PLASMA MEDIUM AND ITS UNDERSTANDING THROUGH NUMERICAL SIMULATIONS

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Plasma is an interesting complex medium, which offers many exciting research opportunities spanning and catering to applied as well as fundamental interests. The quest for unlimited clean energy through fusion and many environment friendly technologies in areas as diverse as medical, security etc., are based on this particular state of matter. Since, this medium is created by doing violence to matter (heating and/or striking an electrical discharge) it is in general found in a state far from thermodynamic equilibrium. Furthermore, it supports many kinds of waves and instabilities, and displays coherent as well as turbulent nonlinear dynamical behavior. These complex properties of the plasma medium are understood by adopting experimental, observational, numerical and theoretical tools. In this article a brief description of some of the numerical simulation tools, which have been successfully adopted in various contexts of plasma studies, has been provided. An overview of activities in our group in this direction has also been presented.

Introduction

Plasma is considered as a fourth state of matter after solid, liquid and gas. The addition of heat/energy melts the solid to liquid state which when heated evaporates into gas. The gas molecules and atoms get ionized when heated further, creating a collection of electrons and ions. This collection of charged particles constitutes a plasma, which is quasi – neutral and displays complex collective properties. An important feature is the vast range of density (30 orders) and temperature (15 orders) in which matter in plasma state is found to exist. In contrast the other states of matter exist only over a few orders of density and temperature range. This makes the description/understanding of plasma processes pretty challenging.

It is interesting to note that plasma state of matter can provide solutions to many problems (energy, medical, security, environment etc.,) with which the human society is currently struggling. Plasma based technologies are known to be pollution free and environment friendly. For example, the medical and municipal waste can be best handled by plasma incinerators, which burn them at high temperatures to break the molecules of bacteria and other harmful agents. For a variety of other applications (textile, automobile etc.,) plasma based technologies prove to be far superior compared to chemical technologies. Their implementation is not dependent on availability of water and hence one can save water (which is a precious resource nowadays) from getting polluted.

The quest for unlimited energy through fusion is crucially dependent on understanding the behavior of this particular phase of matter. In addition to applications, it also provides rich physics for exploration of fundamental and basic questions in areas as diverse as nonlinear dynamics, non-equilibrium statistical mechanics system etc. It should be noted that always some sort of violence to matter leads to the creation of plasma (heating or striking discharge in it), and hence it inherently exists in a non-equilibrium state.

Particle acceleration is another area where one is bound to rely on plasma based technologies ultimately. The

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conventional accelerators have now hit the material breakdown limit. Therefore, conventional methods are now unable to reduce the accelerator size any further. Plasma (which is already a broken down state of matter) provides an entirely new scheme for particle acceleration. The wake field potential in the plasma triggered by laser or particle beams are used here for acceleration of particles. The plot of wake potential has been shown in Fig.1, obtained from fluid simulations carried out in our group. It holds the promise of building shorter (almost by a factor of thousand and possibly even more with future advancements) and economical particle accelerators for high energy physics studies. Such accelerators with their reduced size would also prove handy for applications in medical science and other areas.

laboratory experiments. The dust species acquires huge charge (about 10^5 to 10^6 electronic charge) as the electrons stick on its surface and then they act as the third charged particle species in the plasma. The plasma is then referred to as dusty plasma when the dust component behaves in a collective fashion. It should be noted that the high charge of the dust particles easily renders them in a strongly coupled state. Also, the micron size of these particles ensures that their tracking does not require sophisticated diagnostics. A camera and laser illumination suffices for the purpose. Such strongly coupled plasma exhibits interesting behavior, similar to crystalline solids, viscoelastic fluids, polymeric systems etc. This demonstrates the interdisciplinary reach of this particular phase of matter. Furthermore, the ease with which the dusty plasma can be

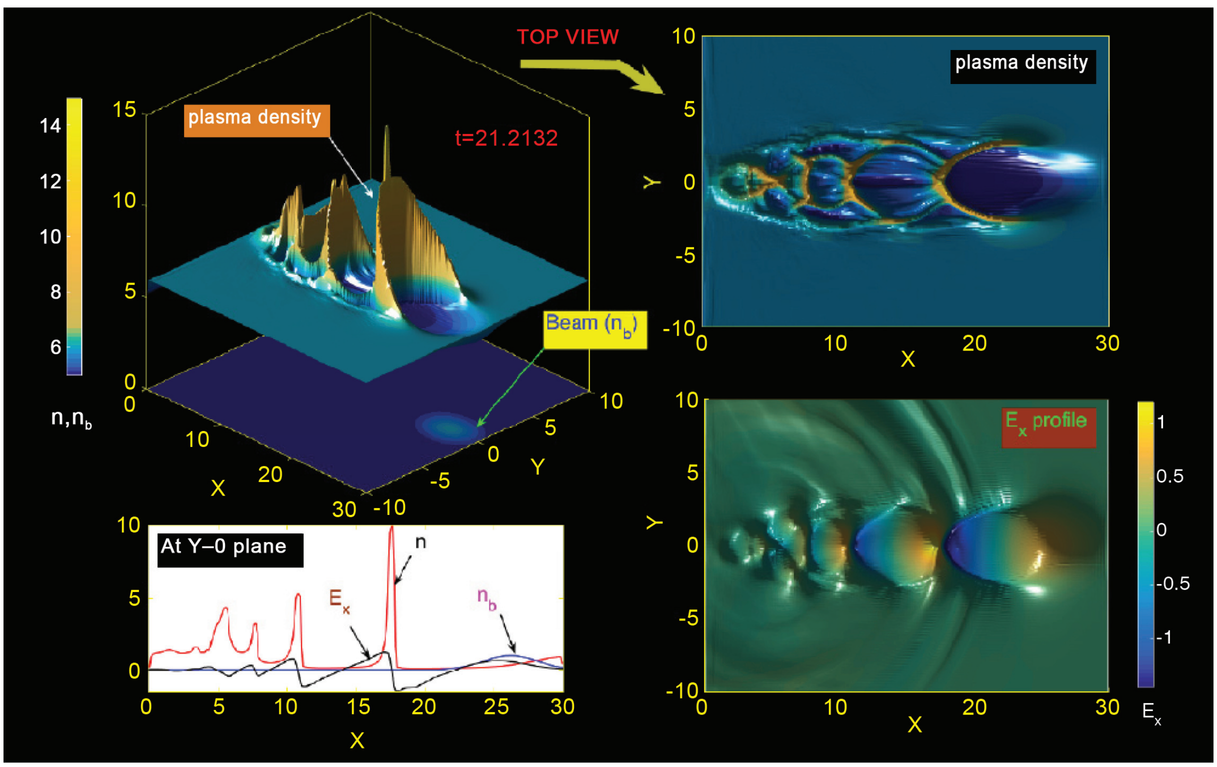

Figure 1. When a laser or an electron beam (denoted by n_b in the figure) passes through a plasma it perturbs the plasma and creates electric field disturbances in its wake. Another group of charge particles when injected appropriately can get accelerated in this wake potential and gain energy. The figure shows the wake field density and electric field structure driven in a 2-D plasma fluid simulation by electron beam. (Courtesy: Ratan Kumar Bera).

In recent times, plasma medium is being studied extensively in strong coupling regime (i.e. when the inter particle potential energy is higher than the average thermal kinetic energy of the particles). This can be achieved either by cooling the plasma, or having very high densities (so that the inter-particle distance reduces) or by having particles with very high charge on it. Often, dust particles of size varying from nano to micro scales, are found in the plasma and/or are deliberately added in certain

prepared and studied demonstrates that many fundamental questions of interest pertaining to other fields can be addressed in a simplified setting.

Late Professor Predhiman Kaw recognized the importance of this field and spearheaded an indigenous program for Plasma and Fusion Science and Technology. The Institute for Plasma Research (IPR) was founded by him in the late 1980s. The autonomy and free scientific atmosphere of the Institute under the visionary leadership of Prof. Kaw made rapid advances in the short span of about 30 years. Two indigenous Aditya and SST1 Tokamaks (machines in which plasma is magnetically confined) were built and made operational for carrying out magnetic confinement experiments relevant for fusion studies. These developments led to India's entry as a full partner in the International Fusion program where the "International Thermonuclear Experimental Reactor" (ITER) is being made by seven participating countries. The scientists and industries in India gained experience in a variety of cutting edge technologies, such as Ultra high vacuum systems, advanced materials, Cryogenic and Mega Joule class superconducting magnets, RF, microwave and beam technologies, Power Engineering etc. Prof. Kaw also envisaged the immense potential of plasma technologies for industrial applications. Thus, when Prof. John came up with an idea of establishing a "Facilitation Centre for Industrial Plasma Technology (FCIPT)" for developing plasma based technologies and facilitating its transfer to industries with an ultimate goal of having the center as a section 25 company (now section 8 in the new company act), Prof Kaw supported the idea whole heartedly.

Prof. Kaw also ensured that the Institute had a vibrant culture of research in basic and fundamental science. Thus, innovative ideas were conceived and they flourished in the IPR environment under his leadership. A strong theory and simulation group thrived at IPR, which collaborated extensively with experimentalists from national (TIFR, BARC) and some International laboratories (ILE Osaka) as well. Excellent research and development work were carried out at IPR resulting in research articles in international peer reviewed journals. Some of those,concerning simulation studies on plasma carried out by us, will be discussed in subsequent section of this article.

It is evident from the discussions above that plasma medium has an important and extensive role to play in the scientific and technological scene as well as the environment friendly and pollution free development of any country. It is, therefore, imperative that the behavior of plasma medium should be understood well. For this purpose one needs to adopt all possible tools at hand, e.g. experimental investigations, observational studies, numerical simulations and theoretical analysis. Each of these techniques have their own importance and an assessment, based on a proper synergistic understanding gleaned from them, can lead to unraveling the behavior of this particular state of matter in a best possible fashion. I would, however, concentrate here only on the role of numerical simulations. The challenges involved, the diverse techniques of simulations, and the advancements in understanding led by them,would be discussed. In this short article, however, I cannot give exhaustive and complete information but can only hope to provide a small glimpse on this topic.

Numerical Simulations for Plasma Medium: The Challenges, Required Simplifications and Diverse Approaches

Simulating any physical process numerically is like conducting experiments with the help of a computer. In the case of plasmas there are many challenges involved. As stated in the introduction the density and temperature range is too huge for this system. The charge particles in the plasma not only respond to the electromagnetic fields but also generate them. The electrons and ions have huge difference in mass (a factor of 1840 or higher). Thus there is a vast difference in their response time scales. For dusty plasma, with the much heavier dust as the third species, another extremely slow time scales of dust response becomes relevant. Plasma medium is known to support many normal modes in the form of oscillations and waves which have their own characteristic time and length scales associated with them. Ideally, one would like to simulate plasma in its full glory. However, this turns out to be too demanding, as one would need to resolve the fastest time scale and yet cover the slowest possible phenomena. Similarly, it is desirable to resolve the smallest spatial scale and the simulation domain should cover the longest spatial length scale of the phenomena of interest. As we would see simplifications are desirable and adopted for the task.

If one wants to simulate the trajectory of a single particle, one specifies its initial position and velocity and then uses Newton's Law of motion which equates the rate of change of momentum to force:$M d\mathbf{v}/dt = \mathbf{F}$. Here M is the mass, **v** is the velocity and **F** is the force acting on the particle. This helps in evaluating the velocity and position of the particle at subsequent times, thereby ascertaining its future course. Can one, therefore, simulate the plasma medium, which consists of many charged particles, by evolving all the particles?

The charged particles are acted upon by the Lorentz force: $\mathbf{F}=q(\mathbf{E} + \mathbf{v} \times \mathbf{B})$, where **E** and **B** are electric and magnetic fields present in the system. In addition to externally applied electric and magnetic fields, the charged particles, can themselves also generate these fields. The evolution of the self consistent electric and magnetic field are governed by the Maxwell's set of equations. Thus, one needs to solve the Newton's equation of motion for each particle in the plasma coupled with the Maxwell set of equations to describe the evolution of the plasma medium. This turns out to be very expensive as a small calculation on number of mathematical operations needed for a simple system of N charged particle interacting with Coulomb force demonstrates below. The equation of motion of i^{th} particle due to the remaining (N-1) particles (represented by *j*) interacting by Coulomb force is given by:

$$\frac{d^2 r_i}{dt^2} = \frac{q_i}{m_i} \sum_j \frac{q_j (r_i - r_j)}{\left| r_i - r_j \right|^D}$$

Here *D* represents the space dimension. The summation *j* is over all other (N-1) particles. For a system of N particles even a simple force evaluation on a single particles involves summing up N terms (N-1 ~ N as the total number of particles N should be typically quite large for a realistic system). Each term on the other hand involves 8 mathematical operations for D=2. Thus for a simple force evaluation at any time step one requires to perform at least $8N^2$ operations. With the current high performance computers of PFLOPS (peta flops ~ 10^{15} floating point operations per second) the value of N would turn out to be very small for carrying out simulations within a reasonable time duration. Let us for the sake of estimation, consider $N=10^{17}$ (It should be noted that at Standard Temperature and Pressure the number of particles per cubic centimeter is 1.9 x 10^{19}). This means that around 10^{35} floating point operation would be required in two dimensions for merely force calculation for a single time step. For a Petaflops scale computer this would require a duration of ~10^{20} seconds. It thus appears that it is impossible to simulate systems even for such small number of particles. Particle simulations can thus be carried out when the particle numbers are restricted to the order of millions or even smaller, as in the case of complex chemical/biological molecules etc. For plasma system, clearly there is a need for some smart thinking. The discovery of Particle – In – Cell (PIC) scheme in early 60s[1] provided a nice way of circumventing this problem and is best suited for simulating plasma medium.

Two important considerations are the hallmark of the PIC technique. First relates to the use of pseudo particles, which are not point particles, instead their charge is smeared out over a finite size. These pseudo fat particles represent many real particles, thereby reducing the total number of particles in simulation. Secondly, the space is divided in a grid with resolution of '$\delta \mathbf{x}$'. A two-step process in employed to first calculate the fields only on the grid points from particle locations. Thereafter, to evolve the particles interpolating the fields at the particle location leads to the force calculation on each particle. This results in tremendous reduction in the number of mathematical operation required at each time step.The grid points are much less in number compared to the number of pseudo-particles. The choice of '$\delta \mathbf{x}$' (grid spacing) and '$L_x = n_x \delta \mathbf{x}$' (here L_x and n_x are the simulation box size and the number of grid points respectively) is governed by the smallest and largest scale of physical phenomena that one wishes to simulate.

The PIC simplification in effect sacrifices the short-range collisional interaction amidst the charged particles. The collective features exhibited by the plasma medium are, however, captured extremely well by this simulation method. So when the plasma can be considered collision-less, the scheme works perfectly fine. At high temperature it is well known that the Rutherford collisional cross section reduces, thus such a plasma can be understood remarkably well by this numerical technique. In fact the entire community working on laser/beam plasma system heavily relies on this particular scheme of simulation.

Repeated laboratory experiments are expensive and often the entire parameter domain is not accessible for exploration. PIC technique has been proven to be very successful for laser plasma interaction studies. For instance, in the context of plasma based acceleration schemes, particles are accelerated by riding on the potential of plasma wake field. PIC simulations have in this regard provided crucial inputs to improve the accelerated beam quality (in terms of energy, mono-energetic quality of the beam, etc.). A new bubble regime of operation was identified in the simulation, which helped experimentalists in attaining much better quality of the accelerated beam.

In addition to PIC there are many other numerical techniques by which plasma behavior is routinely unraveled. For instance, often fluid model depiction[2] where groups of particles represent a continuum density, are adopted. Though the kinetic effects associated with the particle nature gets lost in such a description, crucial understanding of collective and nonlinear properties of the plasmas have been gleaned from such a description. Due to the long-range character of forces acting on the charged particles even a tenuous collision-less plasma is very well represented by the fluid treatment. Many simplified fluid models are available. For laser plasma interaction, the lighter electron species has the dominant role in the dynamics. The heavier ion species in this case are considered to be immobile and merely providing a charge neutralizing background. On the other hand at slow time scales ion response is crucial and electrons are assumed to follow inertia-less instantaneous response. Thus, many kind of simplifications are adopted dependent on the kind of phenomena one wishes to explore, which not merely reduces numerical efforts but has often been suitable at extracting and identifying the essential physics germane to the problem.

It is worth mentioning here that for the dusty plasma medium with three distinct charged species and the dust being the heaviest a major simplification is adopted by considering inertia-less response of electrons and ions where their density is determined by the Boltzmann distribution of the form $n_{e,i} = n_{0e,i} \exp(\pm e\Phi/KTe,i)$. Here, 'n' and 'T' are the density and temperature corresponding to electrons and ions depicted by the suffix 'e' and 'i' respectively. The scalar field potential is denoted by Φ and K is the Boltzmann constant. The dust particles number being small (of the order of million or smaller) can then be directly evolved using Molecular Dynamics (MD) codes[3] which evolve individual particles. The MD simulations do not have the restriction of PIC and can treat the strong coupling limit appropriately.

We have discussed three schemes, namely Molecular Dynamics (MD)[3], Particle – In – Cell (PIC)[1] and simulation technique based on fluid models[2] which are adopted for studying plasma processes routinely. In our group also we employ all the three schemes to study various phenomena of interest. We will discuss some of them in the next section.

Simulations for Plasma Research in Our Group

Our group primarily engages in the study of nonlinear plasma phenomena, instabilities and turbulence, in the context of laser plasma interaction, dusty plasmas etc.

Some of the important issues in the context of laser plasma interaction that we have focused upon are on the efficient process of laser energy absorption, energetic electron/ion generation, propagation of energetic electrons in plasma medium, magnetic field generation, plasma heating etc. These studies have been performed keeping in mind plasma processes involved in plasma based particle acceleration schemes[4], fast ignition mechanism of laser fusion[5], astrophysical applications etc.

In the early 2000 we had developed simple fluid codes in our group on Electron Magneto-hydrodynamic (EMHD) fluid model[6] and its generalizations for the depiction of fast electron time scale phenomena in plasmas. The ions merely provided a stationary neutralizing background in this model. Since, the high power short pulse lasers typically interact with the lighter electron species, this model was used to understand the subsequent dynamics of electron fluid. Using these simulations we were able to show an important result that the presence of plasma density inhomogeneity creates ashock in the energetic electron flow leading to rapid dissipation of electron energy[7]. This new mechanism of shock dissipation was important in the context of fast ignition[5] where it is desirable to create a hot spot in the plasma by transferring the energy of fast electrons in a compressed fusion pellet. Since the Rutherford cross section for electron ion collision drops off with increasing electron energy, the classical collisional processes were found to be inadequate for the task. Our mechanism of inhomogeneity induced shock was able to explain an experiment conducted at ILE Osaka[8]. Moreover, Prof. G. Ravindra Kumar's group at TIFR also demonstrated the presence of anomalous dissipation of electron currents by studying magnetic field evolution in their lab leading to a turbulent state[9,10,11]. The important part of fluid simulation was that it provided a clear understanding of the physical processes involved in creating such a shock. The PIC simulations subsequently confirmed some of our observations which were made using simplified fluid approach.

Many other studies and basic understanding of the magnetized[12] and relativistic character of sheared flow Kelvin Helmholtz instability[13] for a sheared electron flow configuration was developed by using such fluid codes[14] and subsequently also studies with PIC were performed[15]. The KH vortices from a PIC studies in our group can be seen from Fig.2. The possibility of guiding, trapping etc., of the electron current pulses with the use of appropriately tailored plasma density inhomogeneity has also been demonstrated by us.

The coupled system of laser plasma displays highly nonlinear interaction. We have, therefore, sought exact coherent nonlinear localized solutions for this system in the form of a variety of envelope solitons. The solitons are exact solutions for which nonlinear effects are balanced by the dispersive terms in the equations. Such solutions are known to propagate undistorted and preserve their shape after undergoing collisional interaction with other solitons. In the context of laser plasma coupled system it has been observed that the light pressure can evacuate the electron density and get trapped inside the evacuated cavity giving rise to a structure having a form of envelope solitons.

Detailed fluid and PIC simulations have been carried out to study the evolution, collisional interaction, stability in longitudinal propagation direction as well as transverse to the structure. The development of transverse modulations in 1-D solitonic structure and its eventual break up in the form of filaments has been shown in Fig.3, which has been

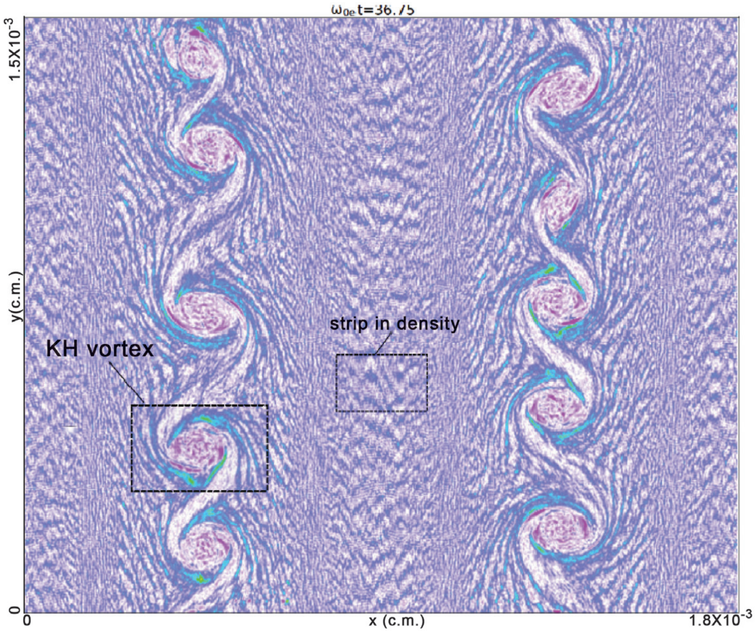

Figure 2. The Kelvin Helmholtz vortex pattern which develop in a sheared electron flow in PIC simulations. (Courtesy: Chandrasekhar Shukla).

obtained from our fluid simulations[16].

The fluid simulations are simple and provide incisive physics underlying the phenomena. Thus, even now when we have acquired expertise with PIC codes in our group, the fluid simulations are employed and are very helpful for throwing light on the underlying physics associated with the phenomena.

In the mid 2010s we acquired the capability of using PIC simulations for our studies. We worked initially with a code PICPSI developed by Dr. Kartik Patel from BARC. The role of structured targets on instabilities associated with electron beam propagation and laser absorption in plasmas was extensively studied by this code[17,18]. We also got access to the OSIRIS code developed by the UCLA group and another code EPOCH is also now frequently used which is freely available. Recently, with the help of all the available tools with us (namely theoretical analysis, fluid simulations, PIC simulations with variety of codes carried out by different groups and experiments) we have been able to identify a new mechanism which generates magnetic field in a beam plasma system at long scale (at the beam spot size which is longer than the electron skin depth where the well known beam plasma instabilities like Weibel and KH generate magnetic fields). This overturns the 50-year-old understanding of the beam plasma system[19].

In our study of Dusty plasma medium (in both weakly as well as strongly coupled regime) we have employed fluid as well as MD (particle) codes. The lighter ion and electron species are assumed to respond instantaneously and instead of following them in numerical simulation a Boltzmann form of their density is used in the Poisson equation. This results in a major simplification. The strongly coupled behavior of the dust medium is modeled with the help of visco–elastic relaxation in fluid models. Unlike PIC, the particle code MD which follows real dust particles can depict the regime of strong coupling in the dusty plasma medium.

Interesting observations on excitation of transverse shear waves and Poynting like theorem associated with these waves in the dust fluid[20], novel shock formation etc.,[21] have been shown in the strong coupling limit. An interesting interplay between single particle effects and collective properties of the dusty plasma was shown recently[22]. Furthermore, the excitation of 2-D spiral waves in dust medium was shown and the deformation of the spiral wave front to hexagonal form in the crystal phase was clearly demonstrated by us[23].

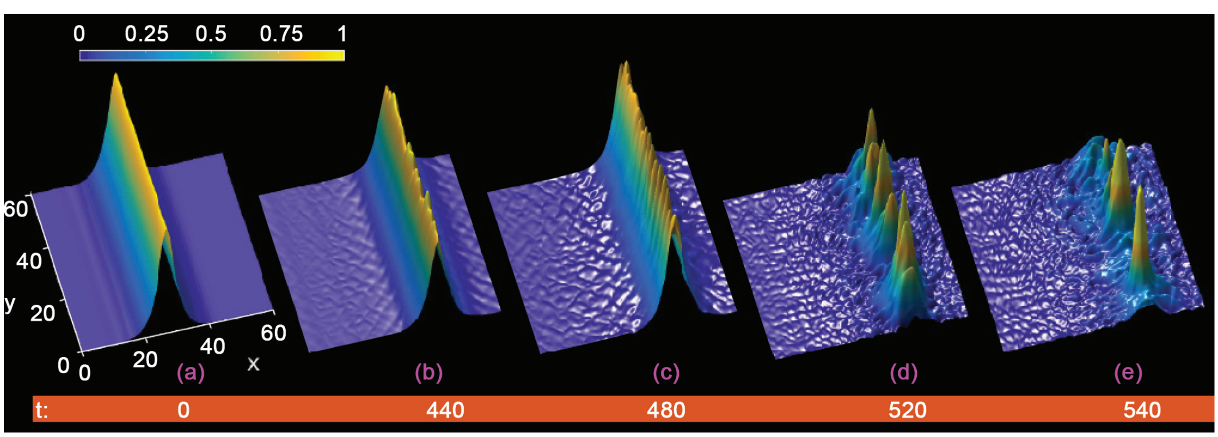

Figure 3. The evolution of laser plasma coupled soliton showing the development of transverse filamentation instability obtained from fluid simulations. (Courtesy: Deepa Verma and Ratan Kumar Bera).

Final Remarks and Future Scope

The importance of plasma medium in applications and research area of fundamental interest have been outlined in the article. Numerical simulation is one important technique of unraveling the behavior of plasma system. Three major numerical techniques to study plasma processes have been discussed in the article. A glimpse of how these techniques have been successfully utilized for simulating laser plasma interaction studies as well as the study of dusty plasma medium has been provided.

The future of numerical simulation for the study of plasma medium seems very promising. In a couple of years from now many new laser facilities are poised to come up at various places (e.g. ELI in Europe, SACLA in Japan, XFEL etc.) which will open up newer regimes of laser power and frequency for investigation. The radiation reaction and QED (Quantum Electrodynamics effects) could be tested in laboratories. Many new applications can then be envisaged. Accordingly, the simulation requirements have to keep pace with it. The simulation tools are already being developed and numerical studies with these effects are being carried out to study plasma in such exotic regimes. ❐

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Author's Note : *This article is my personal tribute to late Prof. P. K. Kaw who introduced me to the rich and diverse field of plasma physics. I cherish every moment of my collaboration and discussions with such a great thinker and a gentle person.*