13. THEORY AND SIMULATIONS ON HIGH ENERGY DENSITY SCIENCE AND ASTROPHYSICAL AND SPACE PLASMA PHYSICS

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13.1. INTRODUCTION

Research in theory and simulation at GoLP/CFP was focused on some of the outstanding problems in laser-plasma interactions, basic plasma physics, exploring the connection between laboratory and astrophysical scenarios. The key aspects of research in 2005 dealt with:

- Fast ignition and ICF physics, and laser-solid interactions;
- Ultra intense laser plasma interactions and plasma based accelerators;
- Development of simulation infrastructure for e-Science;
- Relativistic Astrophysics and space plasma physics.

13.2. FAST IGNITION AND ICF PHYSICS, AND LASER-SOLID INTERACTIONS

13.2.1. A coupled two-step plasma instability in PW laser plasma interaction[1]

There is now a growing body of evidence for anomalous ion bulk heating in laser plasma interaction experiments, when the laser power approaches the Peta-Watt (PW) regime, both from experiments and from hybrid code simulations.

We have proposed a possible *explanation for the observed anomalous resistivity*. Our model is based on the existence of two coupled processes. First, the fast electrons created by the laser pulse interact with the resulting return current and produce an intense electrostatic field, by means of a two stream instability. Second, the resulting electrostatic waves become modulationally unstable and decay resonantly into ion-acoustic waves. This mechanism is not efficient for electron heating but leads to an efficient ion heating which could explain the observations.

13.2.2. Laser-Solid Interactions and Fast Ignition Inertial Confinement Fusion

The Vulcan TeraWatt and PetaWatt lasers have produced a vast quantity of data from laser-solid experiments using numerous diagnostics and target materials. We have been able to provide a *coherent interpretation* of much of this data *based on our theoretical work on ion instabilities and magnetic field generation.* Our work on magnetic field generation has been able to explain the increase in the divergence of the electrons accelerated into the target with increasing laser power and the associated appearance of a hollow plasma at the back of the target, in experiments with both the TeraWatt and PetaWatt lasers using both plastic and metal targets (Figure 13.1). We have also worked on magnetic inhibition of electron flow in layered targets.

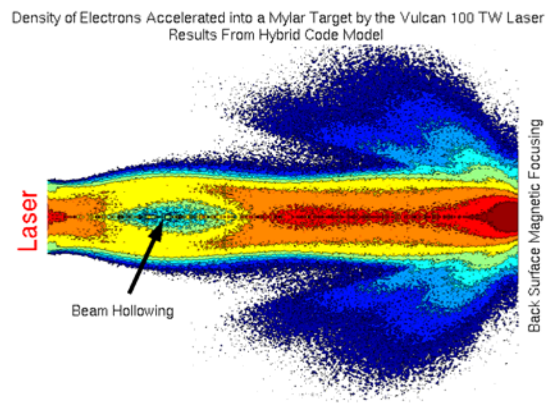

Figure 13.1 - Results from hybrid code modelling of experiments on the Vulcan 100 TW laser with solid, plastic targets (Mylar) that reproduces the electron beam hollowing.

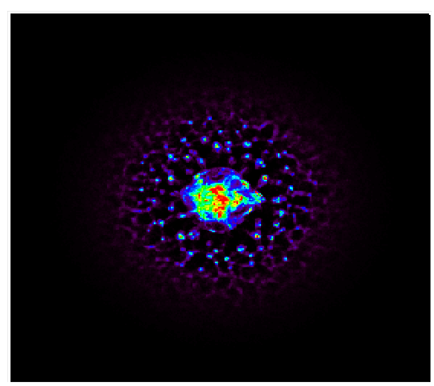

Figure 13.2 - "Finite width beam filamentation due to the Weibel instability"

[1] Work carried out in collaboration with R. Bingham, P. Norreys (RAL).

13.2.3. Weibel instability in fast ignition of fusion targets[2]

Using relativistic kinetic theory, a *theoretical model for the linear stage of the collisionless filamentation* (Weibel) *instability* has been worked out, analyzing the coronal region of the fuel pellet in fast ignition. We have shown that only at the edge of the compressed pellet, the filamentation instability can develop even at large beam temperature with a small but not negligible growth rate. This is due to the ion presence, which cancels the space charge effects and allows for the instability to occur on the ion time scale.

(i) Finite width beam filamentation due to the Weibel instability

These aspects have been also numerically explored with a very large 2D simulation dealing with both the interaction of a picosecond-long ignition pulse with high-density (40 times critical density) pellet and the pulse driven electron beam propagation. Beam filamentation due to the Weibel instability as well as the role played by ions of neutralizing the space charge effects have been observed.

The propagation of finite width beams through a background plasma has been studied numerically, performing 2D simulations (Figure 13.2). When the simulation plane is perpendicular to the propagation direction, the Weibel instability shows up, filamenting the beam. When the simulation plane is parallel to the propagation direction, evidences of the two-stream instability and the hosing instability have been observed.

13.2.4. Very High Mach-Number Electrostatic Shocks in Collisionless Plasmas

The kinetic theory of *collisionless electrostatic shocks resulting from the collision of plasma slabs with different temperatures and densities* has been developed. The theoretical results are confirmed by self-consistent particle-in-cell simulations, revealing the formation and stable propagation of electrostatic shocks with very high Mach numbers (M >>10), well above the predictions of the classical theories for electrostatic shocks. The theory demonstrates that the shock properties are strongly influenced by Θ, the ratio of the electron temperatures in the two slabs, and by Υ the ratio of the electron densities in the two slabs. The analysis shows that when the electron temperature of the downstream slab (R) is higher than the electron temperature of the upstream slab (L), the shock waves can have very large Mach numbers, which are otherwise not supported by isothermal plasmas. The model predicts that the maximum allowed Mach number increases with Θ, without an absolute upper limit.

The theoretical results have been confirmed by one-dimensional (1D) self-consistent particle-in-cell simulations, demonstrating the formation and the stable propagation of electrostatic shock waves with very large Mach numbers (M ~ 20) (Figure 13.3).

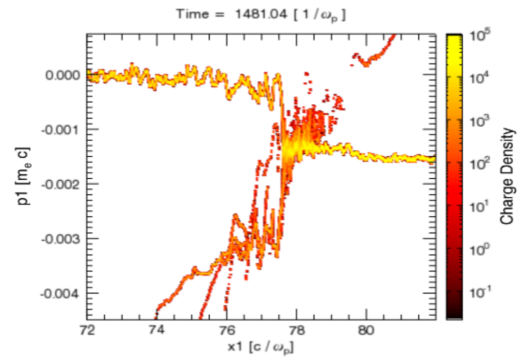

Figure 13.3 - Shock wave in the ion phase space p1x1.

13.2.5 White light parametric instabilities[3]

Parametric instabilities are pervasive in many fields of science with its importance stemming from their close connection to the onset of nonlinear and collective effects such as solitons, vortices, self-organization, and spontaneous ordering. We have employed a *generalized photon kinetics formalism,* directly inspired in the Wigner-Moyal formalism for Quantum Mechanics to establish the general dispersion relation for parametric instabilities driven by electromagnetic radiation, with arbitrary statistics, coupled to the electron collective dynamics in a unmagnetized plasma. The one-dimensional analysis for Stimulated Raman Scattering reveals a growth rate dependence with the coherence width σ of the radiation field scaling as $1/\sigma$ for backscattering, and $1/\sigma^{1/2}$ for forward scattering, and a significant dependence of the instability growth rate on the shape of the power spectrum of the radiation. The results open the way to a full multi-dimensional description of parametric instabilities driven by intense radiation sources, with arbitrary statistics, interacting with plasmas in laboratory and astrophysical scenarios.

13.3. ULTRA INTENSE LASER PLASMA INTERACTIONS AND PLASMA BASED ACCELERATORS

13.3.1 Shock shells driven by layered clusters and explosion of clusters driven by intense x-ray sources[4]

The interaction of ultra-short ultra-intense laser pulses with large deuterium clusters (>10^5 atoms) can lead to the removal of all (or most of) the electrons inducing a Coulomb explosion. During this phenomenon shock shells (multi-branch structures in the phase space) may be formed if ion overtaking occurs.

However, significantly thick shock shells are hard to produce in homonuclear clusters with a single laser pulse. Instead, the use of *heteronuclear layered clusters* has been proposed *as a means of driving shock shells*. This method is based on the fact that the initial ion acceleration profile is a critical issue for the shock formation. Both the number density and the mass profiles can be chosen so as to

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[2] Work performed in collaboration with C. Ren (U. Rochester), M. Tzoufras, W B. Mori (UCLA).

[3] Work carried out in collaboration with R. Bingham (RAL)

[4] Work performed in collaboration with F. Peano (Poli Torino)

produce the desired acceleration profile, the latter being used in this case.

The explosion of layered clusters with light inner species and increasingly heavier species with radial distance was studied. PIC simulations of a three-layer cluster with step-like mass profile were performed with OSIRIS 2.0. It was found that ion overtaking of the outer heavy ions by the lighter inner ones occurs in both of the borders between the layers, even before the total removal of the electrons (Figure 13.4). Density peaks were observed where the overtaking occurs in an analogous manner to what is found in homonuclear clusters. As the core ions continued to expand the two density peaks eventually merged. However, the phase space structure observed in the case of the layered cluster differed from the homonuclear clusters shock shells in that only two branches appeared instead of the three branches seen in the latter.

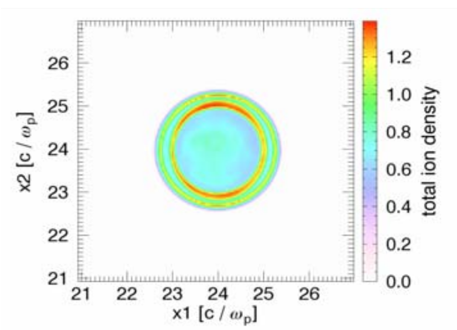

Figure 13.4 - Density peaks due to ion overtaking

In this way, the proper selection of a mass profile offers a method for controlling the phase space of the cluster explosion to induce shock shell formation. The characteristics of this structure can be selected "a priori" by varying the widths, composition and number of layers of the cluster.

The study of the possibility of *producing shock shells in clusters in the x-ray regime* was also initiated. Simulations were made of homonuclear clusters with two pairs of ion and electron populations. These electron populations were initiated at different times and with different energies, representing the two ionization stages expected if the cluster were to be irradiated by two x-ray laser pulses with distinct intensities and frequencies. It was observed that by choosing the laser parameters properly it was possible to induce ion overtaking with the appearance of shock shells in the phase space.

13.3.2 Blowout regime of the laser wakefield accelerator [5]

Studies of electron acceleration in parabolic plasma channels have been carried out. Plasma is a very good medium for accelerating electrons, both injected externally, or self injected from the plasma itself, since the accelerating gradients are orders of magnitude greater than in conventional accelerators. *The primary focus* of the work *is* focused *on the plasma self injected electrons*.

There has been a considerate effort in achieving GeV electrons with this technique, as current experiments place the maximum energy gain of self-injected electrons on a few hundreds of MeV. These experiments operated in the blowout regime, where an intense laser pulse radially expels nearly all plasma electrons. An ion column is left behind the laser pulse and electrons are attracted inwards to the axis, forming an electron void cavity. This cavity is spherical and resembles a bubble that gave its name to the bucket (Figure 13.5).

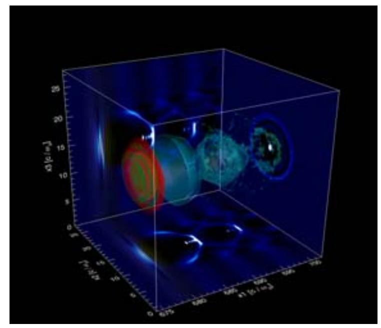

Figure 13.5 - Contour plot of the bubble excited by an ultraintense laser pulse. Blue contours are the plasma density. Red-Green contours are the laser pulse

13.3.3. Wigner diagnostic for photon acceleration [6]

A short intense laser pulse propagating through a gas can generate plasma waves, due to electron density modulation. This mechanism can upshift photons riding the waves, whether they are from a driver pulse or from a trailing low intensity pulse. Such phenomena provide important information about relativistic structures, as well as a novel way to tune radiation (Figure 13.6).

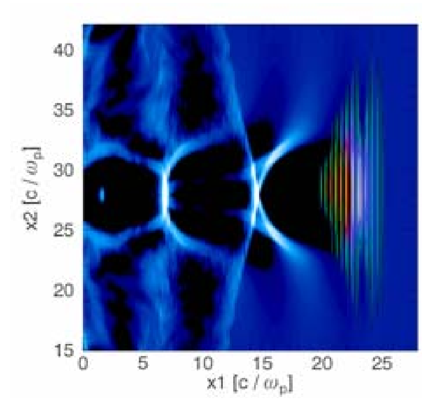

Figure 13.6 - Wakefield generated by an ultra short intense laser pulse (laser pulse in red/green).

[5] Work carried out in collaboration with W. Lu, M. Tzoufras, C. Joshi, W. B. Mori (UCLA)

[6] Work performed in collaboration with J. P. Bizarro, A. Figueiredo (CFN), R. Trines, and R. Bingham (RAL)

Several kinds of *Wigner transforms* were implemented *to analyze photon acceleration.* PIC simulations were preformed with OSIRIS 2.0, revealing that in 1D simulations, where the interaction length is comparable/longer than photon dephasing length in wake (regime achievable for very long Rayleigh lengths), different initial delays between the driver and probe pulses do not lead to different signatures in Wigner distribution (Figure 13.7). However, in 2D simulations, a tight focus leads to short interaction time with wake, thus different probe displacements lead to different final conditions. On the other hand, the FFT failed to reveal detailed internal dynamics of laser pulse.

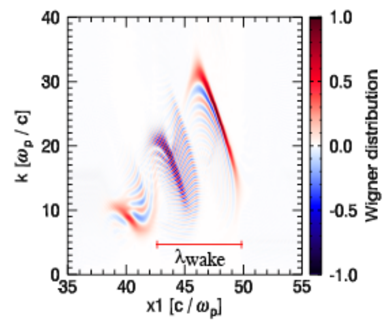

Figure 13.7 - Wigner transform of ultra short laser pulse riding a laser wakefield.

13.4. DEVELOPMENT OF THE SIMULATION INFRASTRUCTURE FOR E-SCIENCE

13.4.1 osiris 2.0 development[7]

The OSIRIS 2.0 framework is an integrated framework for particle-in-cell (PIC) simulations. This framework is based on a three-dimensional, fully relativistic, massively parallel, object oriented particle-in-cell code, that has successfully been applied to a number of problems, ranging from laser-plasma interaction and inertial fusion to plasma shell collisions in astrophysical scenarios.

The main development milestone achieved in 2005 was the *full implementation of the dynamic load balancing algorithm in OSIRIS.* A binary tree algorithm for finding best problem partition solution was implemented to this end. During runtime, OSIRIS will dynamically analyze the load of each computing node, and reshape the parallel partition whenever needed to maintain an evenly balanced node.

The OSIRIS code structure was also updated, with significant changes to the object hierarchy, and new current deposition modules are under development that will result in a significant performance boost.

Standard PIC "collisions" occur between finite sized particles. It is an inherent property of the PIC algorithm that collisional effects therefore are not properly reproduced in a standard PIC algorithm, due to limitations in grid size possible with available computing power. In order to fully deal with collisional effects the standard PIC algorithm must be extended. Several extensions were proposed. For osiris, we follow the approach of binary collisions [Takizuka and Abe 1977, Nanbu 1997], generalized for the fully relativistic scenario.

As is the rest of OSIRIS the implemented algorithm is fully relativistic. Osiris uses different weights for different particles. The collision algorithm is able to deal with this circumstance without violating any of the conservation laws (i.e. energy- and momentum- conservation) [Nanbu and Yonemura 1998].

13.4.2 dHybrid[8]

A hybrid code called dHybrid has been used in the study of space plasma interactions. Hybrid codes, due to the use of kinetic ions and fluid electrons, allow an intermediate step between full particle codes and fluid codes. The applicability of such codes ranges from low density plasmas like space plasmas to denser plasmas like the ones found in tokamaks.

The first massively parallel version of dHybrid is now ready to completion. This code, originally written to study the solar wind interaction with an artificially created plasma cloud (AMPTE release experiments) has now new important features that broaden its applications (Figure 13.8). Studies such as solar wind interactions with artificial magnetospheres and coronal mass ejection interactions with the solar wind are now possible.

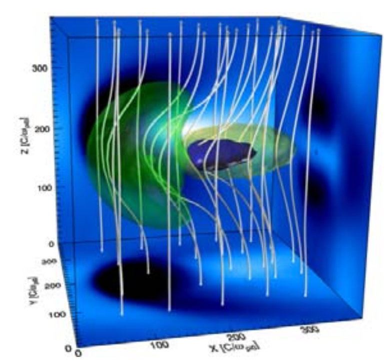

Figure 13.8 - Magnetic field isosurfaces and field lines of the artificial magnetosphere at time 72 (simulation units). The solar wind flowing from the left exerts pressure on the system and creates asymmetry.

The new version of the code allows better results due to improved statistics in these runs, which is possible only due to the use of massively parallel machines. New problems like the solar wind interaction with planetary exospheres (e.g. Mars, Venus) and planetary magnetospheres (eg. Earth) can now be considered.

[7] Work carried out in collaboration with F. Tsung and W. B. Mori (UCLA)

[8] In collaboration with R. Bingham (RAL)

13.4.3 Visualization infrastructure

Visualization is an essential part of any numerical laboratory. The data being produced by our simulations is both large and complex, and requires an appropriate set of tools for the adequate understanding of the results obtained. We therefore developed a custom visualization and analysis infrastructure for our needs, that has been successfully used with several simulation and experimental data sources, most notably the OSIRIS code, the QUICKPIC code and the dHybrid code.

The development of this infrastructure continued over 2005, and as a result of user feedback led to the development of new visualization tools, Significant work also went into the development of the new version of the visualization and data analysis routines, that will allow for better user-data interaction, and also provide a unified interface for representing data and metadata in encapsulated objects (Figure 13.9).

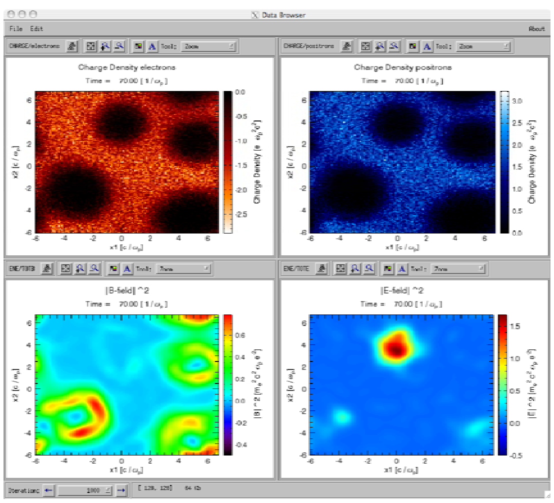

Figure 13.9 - Simulation Browser. This simulation tools allows for quick access to multiple diagnostics for the same time step. The navigation tools (zoom/pan) for all the plots are linked.

Different new visualization software for very large datasets was evaluated (VTK, OpenDX, SciRun), and finally VisIt was chosen (a visualization program from Lawrence Livermore National Laboratory, USA), because it was the only one to offer all the features needed: parallel data processing and rendering (distributed and shared memory), scriptable, expandable, high performance and scalability, multi platform, uses VTK and it is Open Source (Figure 13.10).

A database plugin was developed for VisIt, that allows the full exploration and rendering, in parallel, of Osiris and dHybrid simulation results, in particular of very large datasets of 3D vectorial data (Figure 13.11).

Research has been done in *the development of general purpose algorithms for the modern graphics processor* (GPGPU). Simulation algorithms can be accelerated by passing some of them to the shader unit of the GPU and taking advantage of its vectorial capabilities. A development system has been set up on the visualization cluster that allows for general research on this kind of algorithms and for research on parallel versions (distributed memory) of GPGPU.

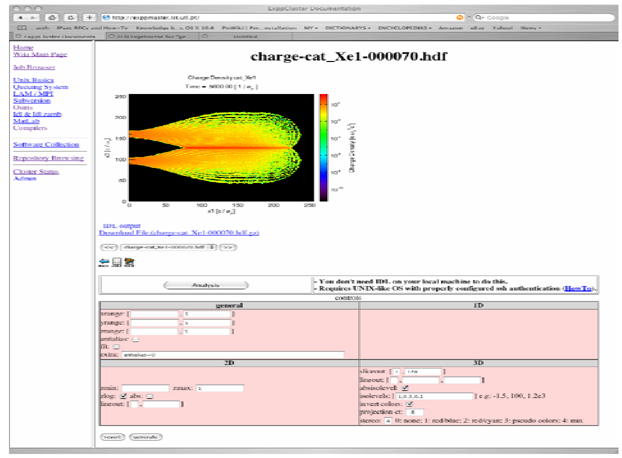

Figure 13.10 - Data visualization and users interface as seen in a web browser.

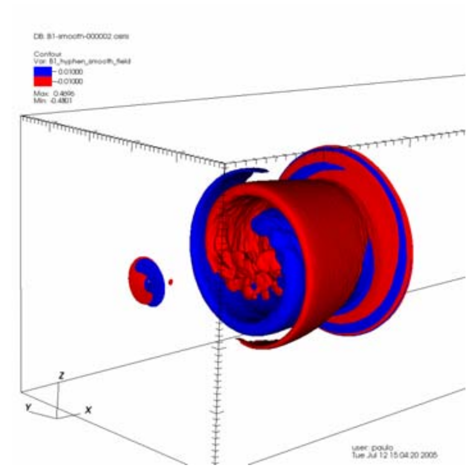

Figure 13. 11 - Visualizing the inverse Faraday effect in VisIt.

13.5. ASTROPHYSICS AND SPACE PLASMA PHYSICS

13.5.1 Plasma thruster dynamics and charge exchange collisions

With the goal of *understanding the full kinetic dynamics of the charge exchange back flow originating from the plume injected from a spacecraft,* and to understand how relevant the electron dynamics is in such scenario (in particular, to understand if a Boltzmann equilibrium for the electrons can be assumed in such configurations) several multi-dimensional particle in cell simulations have been performed in osiris 2.0 (Figure 13.12). In these scenarios charge exchange (cex) collisions play an important role, as they are responsible for the slowing down and thermalization of the fast ions originating from the thruster plume. Consequently a cex-module has been written and tested for osiris 2.0. This module is an extension of the existent neutral module and allows for cex collisions to occur between multiple neutral and multiple charged species. Different models for the cross-section of interaction are available and fully parameterized. Proper accounting for the charge and mass transfer between the collision partners is conducted.

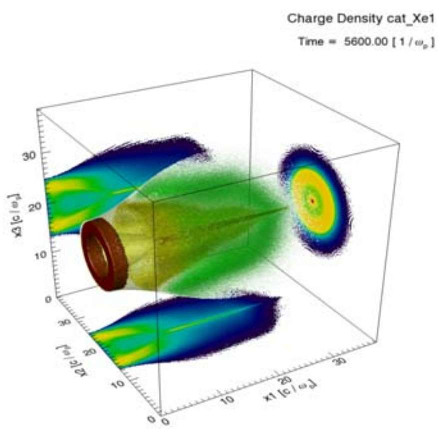

Figure 13.12 - Xe+ ions originating from the thruster. The thruster plum pinches after a stage of free expansion leading to higher flow velocity. Densities [e ω03c3]: red 1, yellow 0.3 and green 0.1.

13.5.2 Development of Plasma Reflectometry for In-Flight Aerothermodynamic Research[9]

The reflectometry for in-flight aerothermodynamic research project is a new comprehensive project involving theory development, instrument design and prototype development. The principal objective of this project is *the measurement of plasma density profiles surrounding a re-entry vehicle* as it comes into the atmosphere. Use of electromagnetic waves constitutes a powerful plasma diagnostic method. Due to the large electron to ion charge to mass ratio, it is primarily the electron properties of the plasma which can be obtained at microwave and higher frequencies.

The physical parameters of relevance to plasma reflectometry in the shock layer of a re-entry vehicle, are the plasma density, neutral density and temperature. These are characterized on the basis of computational fluid dynamics (CFD), in order to define a reference environment and to set up an optimum measurement strategy.

A typical case is the European Experimental Reentry Testbed (EXPERT) vehicle scenario. For this vehicle, the ionization shocked layer and the plasma sheath is thin, roughly at most 20 cm thick on the side and 1/3 of that in the nose region. The expected plasma frequencies for a 6.8 km/s re-entry speeds appears in the figure 13.13. The plasma distribution along a normal line to the vehicle surface is approximately parabolic. The electron density goes to zero at the surface, in the catalytic case, while it is the electron density gradient that goes to zero in the non-catalytic case. Plasma gradients can be very high with 1 GHz frequency change over a 1 cm distance fairly common.

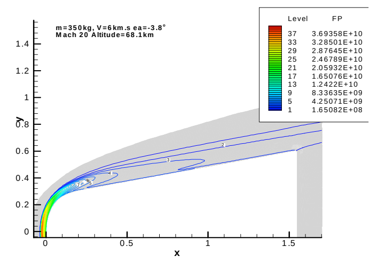

Figure 13.13 - Predicted plasma characteristics for a 6 km/s re-entry speed for EXPERT.

13.5.3 Magnetic field generation in clusters of galaxies[10]

Magnetic fields are ubiquitous in cosmic objects, from stars and galaxies, to galaxy clusters, the largest gravitationally bound objects in the Universe. The origin of these fields, observed to be as strong as a few micro-Gauss in a number of clusters, remains one of the outstanding problems of modern cosmology. Conventional explanations involve the amplification of a very weak seed field of possibly primordial origin by turbulence and gas compression during the formation of the cluster. However, the origin of the nano-Gauss seed field that is required remains a mystery. We have *demonstrated that cluster magnetic fields could have been produced by shocks* propagating through galaxy clusters and in the intercluster (ICM) medium during the formation of large-scale structure. We have performed three-dimensional particle-in-cell simulations of a nonrelativistic shock in a electron-proton plasma that show that such shocks generate a magnetic field via the counter-streaming (Weibel) instability (Figure 13.14). The strengths of the shock-generated fields range from tens of nano-Gauss in the ICM through few micro-Gauss inside galaxy clusters. Thus, cluster magnetic fields may be explained without resorting to amplification of a primordial magnetic field.

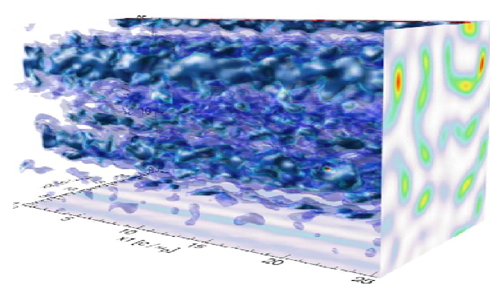

Figure 13.14 - The three-dimensional structure of the magnetic field generated at nonrelativistic collisionless shocks.

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9 Work carried out in collaboration with G. Vecchi, V. Lancelloti, R. Maggiora (Poli Torino), M.E. Manso, and L. Cupido (CFN)

10 Work performed in collaboration with M. Medvedev and M. Kamionkowski (Caltech)