11. KEEP-IN-TOUCH ACTIVITIES ON INERTIAL FUSION ENERGY

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11.1. INTRODUCTION

The keep-in-touch activities on inertial fusion energy have been carried out by "Grupo de Lasers e Plasmas" (GoLP) of "Centro de Física dos Plasmas" (CFP).

The research program developed in 2003 covers a wide range of topics:

- Development of high intensity laser technology;
- Target area for high intensity laser experiments;
- High intensity laser-plasma experiments;
- XUV sources and applications;
- Theory and simulations on fast ignition and high energy density physics.

11.2. DEVELOPMENT OF HIGH INTENSITY LASER TECHNOLOGY

11.2.1. Laser status

The laser system is currently capable of delivering broadband (6 nm), 1 Joule pulses. Compression of these pulses result in a peak power of ~ 1 J/200 fs = 5 TeraWatt. The maximum power on target, produced in 2003 was 6 TeraWatt, with a compressed pulse of 180 femtoseconds.

11.2.2. Introduction of a new Pockels cell driver

The performance of the regenerative amplifier was greatly improved thanks to a new high-voltage pulser which is able to drive a single intra-cavity Pockels cell, both for laser pulse seeding and extraction. Losses in the regenerative amplifier, and daily alignment time, are greatly reduced. This up-grade was responsible for a dramatic improvement in the quality and stability of the final laser pulse.

11.2.3. All-reflective grating stretcher

Early in the year, a new, all-reflective grating stretcher was installed and characterized. This became necessary after the previous year's oscillator upgrade. As a consequence, a final compressed pulse duration below 200 fs was attainable for the first time.

11.2.4. Vacuum pulse compressor

Operating the amplifiers at full power with such short durations will require vacuum pulse compression; for this purpose, we designed a new pulse compressor chamber, whose vertical configuration will allow its inclusion in the present set-up without time-consuming geometrical rearrangements. Being the final stage of the laser system, the compressor is connected by vacuum to the target chamber, sharing its vacuum system. The planning and design of the compressor chamber were concluded in September, and the installation is scheduled for next December.

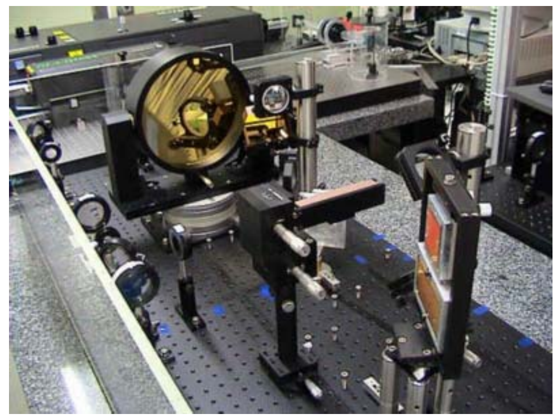

Figure 11.1 – All-reflective grating stretcher

11.2.5. Nd:glass 45 mm amplifier

A new 45 mm Nd:glass amplifier was acquired, with the purpose of boosting the final energy beyond the 10 Joule level. Its impact on the laser performance, at the level of energy, pulse duration and non-linear effects were carefully modelled. The installation of the amplifier is scheduled for next January.

11.2.6. Optical Parametric Chirped Pulse Amplification (OPCPA) development

The L^2I OPCPA program was started this year. Modelling tools for amplification are being developed in order to design an OPCPA chain, both for testing this new concept and for developing a new independent amplification line. This technique allows the amplification of broadband laser pulses with virtually no spectral and spatial degradation, allowing a compact, multi-terawatt laser system for laser pulses under 100 fs.

11.2.7. Diagnostic development

A new single-shot, third-harmonic auto-correlator was assembled. This system will allow high dynamic range characterisation of the pulse duration and contrast at any point in the laser chain, and will be tested later this year.

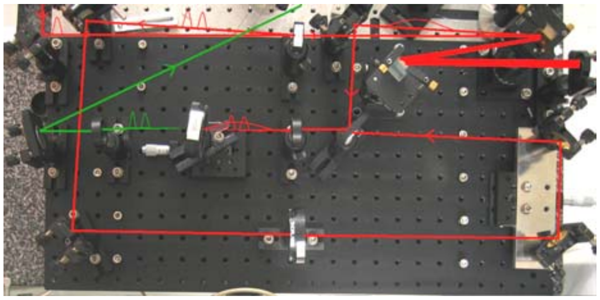

Figure 11.2 - SPIDER diagnostic for spectral phase measurement

A new SPIDER (Spectral Phase Interferometry for Direct Electric-field Reconstruction) diagnostic was also developed, and is currently undergoing calibration. This device allows the measurement of the pulse spectral phase, and is of fundamental importance for characterizing and optimising compressed ultra-short pulses.

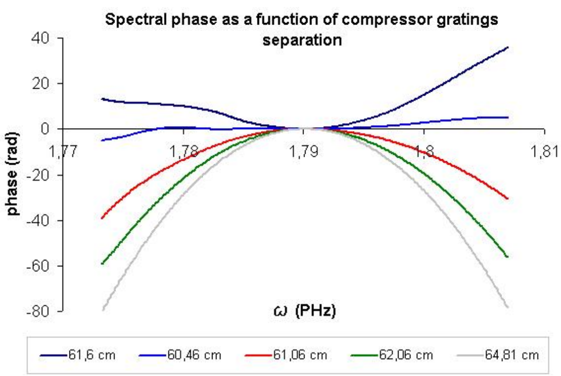

Figure 11.3 - Typical results of a SPIDER measurement

11.2.8 Laser modelling

The laser team started using the *Miro* software package for laser modelling. This powerful modelling tool was originally developed for the CEA *Megajoule* laser project, and is also capable of handling broadband, CPA laser chains. We are currently using it for modelling the next laser system upgrades as well as the OPCPA program.

11.3. TARGET AREA FOR HIGH INTENSITY LASER EXPERIMENTS

11.3.1 Target area development

The target area development activity was focused on the installation of the new compressor vacuum chamber. This consists mainly in a pair of large (120 x 140 mm) diffraction gratings and a set of five mirrors to provide a double pass set-up. These will be installed in a high-vacuum chamber, with optical mounts having a stability in the micrometer range. The compressed, high-power laser pulses should propagate to the target area though vacuum, in order to avoid non-linear pulse degradation. For this reason, a thin film polymer that prevents the contamination of the compressor vacuum will optically connect the two vacuum chambers. The operation of these two vacuum systems as a whole system will be ensured by a custom-developed microcontroller-based system that can be connected to the internet for external access. The hardware and software for this system are being developed, and the final version is expected by the end of the year.

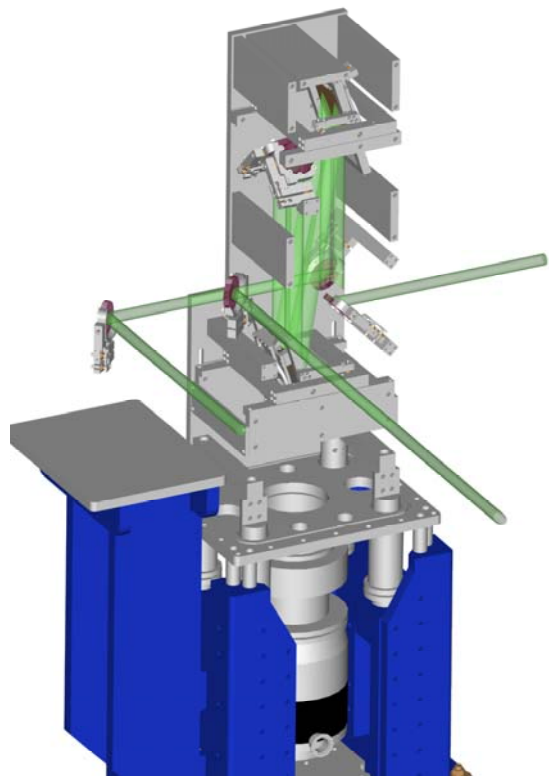

Figure 11.4 - CPA Vacuum pulse compressor for up to 20 TW laser pulses (50 TW for dielectric gratings)

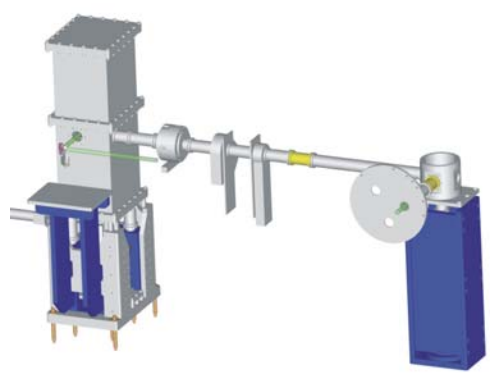

Figure 11.5 - New vacuum pipe between compressor and target chamber for the main laser pulse.

11.3.2. Electron spectrometer development

The existing electron spectrometer was fitted with a vacuum chamber that allows a dramatic increase in its accuracy, since it eliminates the need for a vacuum-air interface before the electrons reach the magnet gap. A new set of twelve ion-implanted silicon detectors was added in order to increase the measurement accuracy. These detectors can be attached to the vacuum chamber in precise locations resulting in a very user-friendly operation. The new up-graded spectrometer will be tested in an experiment to be performed in Oct-Nov 2003.

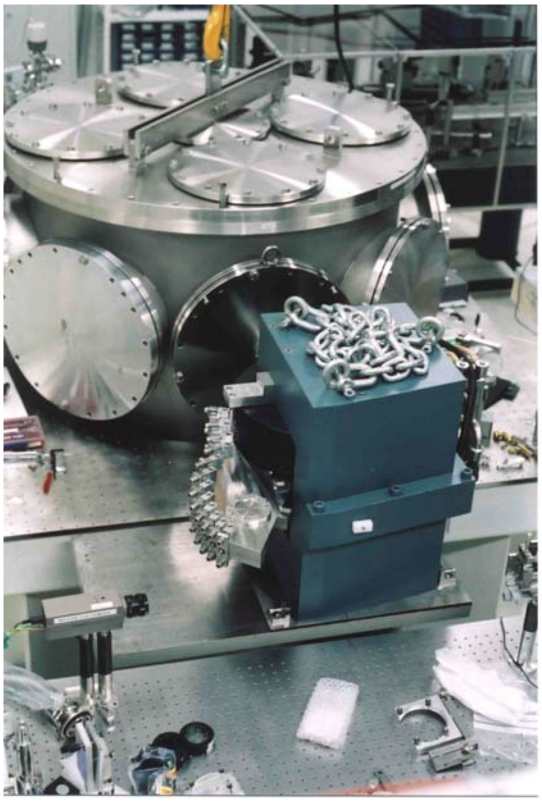

Figure 11.6 - Magnet of the electron spectrometer after the adding of the new vacuum chamber. The vacuum chamber contains an array of 12 silicon electron detectors.

11.3.3. Gas jet development

The Laval nozzle development program was pursued with the development and characterization a new set of two low Mach number (1.5) gas jets. A new double wedge interferometer for laser-aided jet characterization was set up; this allows a 3D characterization of the jet density, by using an automatic profile retriever software package.

11.3.4. Instrumentation

A new mount for 75 mm diameter off-axis parabolic mirrors was developed for use in the target area. The target area "resident" forward optical imaging system was up-graded in order to allow simultaneously electron measurements and forward imaging of the focal spot, as well as to measure the spectra of the forward radiation.

Figure 11.7 - Mach 1.5 Laval nozzle mounted over the alignment target inside the interaction chamber

11.4. HIGH INTENSITY LASER PLASMA EXPERIMENTS

11.4.1. Electron acceleration by propagation of intense laser beams in gas jets

An experimental set-up for measuring the electron beam and forward radiation spectra generated by the propagation of the main laser pulse in a gas jet was developed and assembled in the target area. This experiment will allow the full testing of the electron spectrometer as well as other experimental techniques of laser-plasma interaction. It is now fully operational and is scheduled to run in October and November.

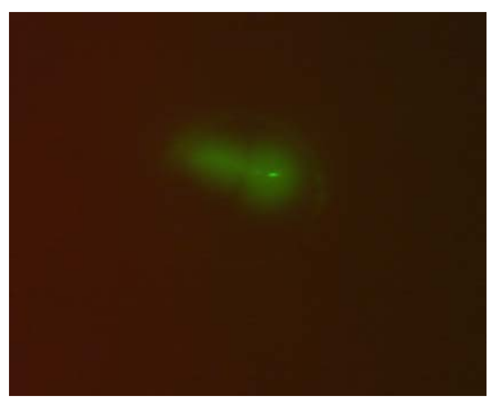

Figure 11.8 - Picture of the light emitted and scattered by the plasma produced by an intense pulse interacting with a Argon jet (the light reflected by the boundary of the nozzle can be observed). Electron acceleration in the sub 10 MeV range was achieved.

11.4.2. Plasma channels by laser-triggered high-voltage discharges

The second experiment on plasma waveguide generation by laser-triggered discharges is scheduled for December 2003 – February 2004. The objectives of this experiment are the testing of a new differential gas cell where the discharge takes place, allowing the vacuum focusing of the main pulse to be guided. A new electrical set-up will be tested in order to achieve a faster channel development.

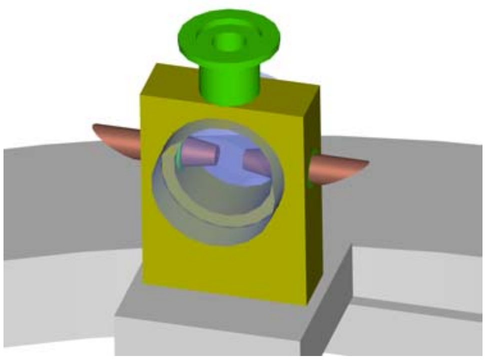

Figure 11.9 - Render view of the differential gas cell for high-intensity guiding experiments

11.5. XUV SOURCES AND APPLICATIONS

The main goals pursued by the XUV sources group is the optimization of XUV short-pulse sources in terms of brilliance for applications. These include probing dense plasmas as with XUV interferometry, but also, if intensities are high enough, creating a plasma from using an XUV monochromatic source, paving the way for future experiments with VUV-Free Electron Lasers now under construction.

The efforts of this team have thus been divided in 3 ways: first, performing experiments at LOA for high harmonic (reaching 30 nm) generation and focusing; second, work on simulations for the interaction of XUV-lasers with solids, and finally, preparing experiments in DESY's VUV-FEL by hosting a VUV-FEL experimental planning workshop at Instituto Superior Técnico.

11.5.1. High Harmonic Generation and focussing

The XUV Sources group has continued its collaboration with colleagues from LOA in Ecole Polytechnique, France, with Drs. Ph. Zeitoun and Ph. Balcou. An experiment was performed at LOA, where high harmonics below 30 nm, generated by interacting "Salle rouge" laser with a gas target, were focused using an off-axis parabola. The outstanding quality of the focal spot, with over 40% of the harmonics beam within a 2 µm focal spot allows us to hope that, with appropriate coating on the parabola, intensities on target should reach 10^{14}Wcm^{-2}, enough for ablation studies with XUV laser. These results have been submitted to Optics Letters.

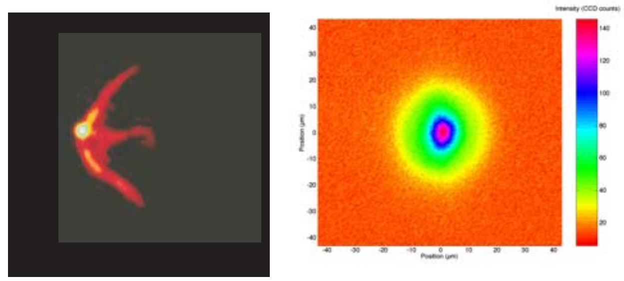

Figure 11.10 - XUV focal spots obtained with a toroidal mirror (left) and an off-axis parabolic mirror (right).

11.5.2. Simulation of XUV laser-solid interaction

With the construction of novel XUV sources, such as VUV FEL's, XUV laser-matter interaction will become available at ultra-high intensities (first experiment scheduled in May 2005). But as shown above, even tabletop facilities such as XUV lasers or High Harmonic Generation, are starting to reach intensities high enough to produce dense plasmas. XUV laser-matter interaction was studied by a 1D hydrodynamic lagrangian code with radiative transfer for a range of interesting XUV sources, in collaboration with J-C. Gauthier's group in CELIA, Bordeaux, and Ph. Zeitoun in LOA, Ecole Polytechnique.

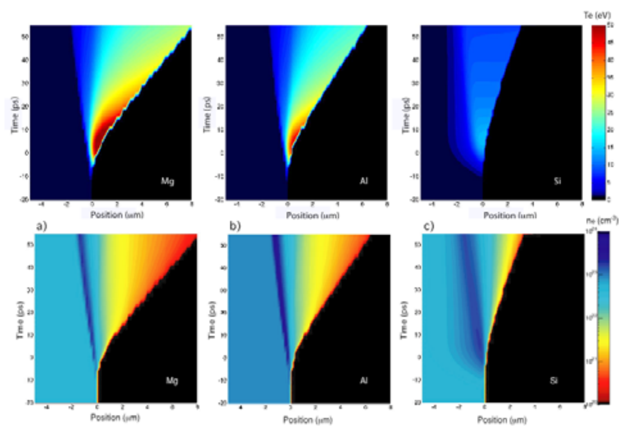

Figure 11.11 - Electron temperature (above) and density, as a function of time and distance to target surface, for a 90 eV XUV laser of 10 ps duration and 1013 Wcm-2 intensity.

The main results were that heating is found to be very different for low close-Z elements having L-edges around the XUV laser wavelength. Possible absorption mechanisms were investigated in order to explain this behaviour, and interaction with cold dense matter proved to be dominant. Plasma sensitivity to XUV laser parameters such as energy, pulse duration, and wavelength was also studied, covering ranges of existing XUV lasers. We found that XUV laser-produced plasmas could be studied using tabletop lasers, paving the way for future VUV-FEL high intensity experiments.

Also, a collaboration was started with Prof. Pedro Velarde in Instituto Politecnico de Madrid, for the use of an Adaptive Mesh refinement hydro code to describe VUV laser-solid interaction, making the extension of the previous simulations to a bi-dimensional case.

11.5.3. Sub-picosecond X-ray experiments development Workshop

In order to prepare future VUV-FEL experiments, we organized a Workshop in Lisbon, grouping all future VUV-FEL users interested in XUV-laser-plasma interaction. The main goals of the workshop were the following:

(i) Community building and experimental project planning, by informing potential collaborators, and developing working teams;
(ii) Beginning the implementation of projects with main Organization members (e.g., DESY, SLAC, Ultra-Short Pulse community);
(iii) Assistance in Generation of future proposals.

The three goals were fulfilled, with a set of two main experiments (cluster/bio molecules explosion and VUV-FEL-solid ablation) being defined. Material needs (spectrometers, vacuum chambers, manpower etc) were identified, and a “zero-th order” experiment, using available material, was put together. Also, as a full set of possible experiments using additional funding was planned, and three proposals for EU funding started to be written, one of which includes GoLP as an active member, and the other as a leader.

11. 6. THEORY AND SIMULATIONS

11.6.1. Introduction

The main research theme is the physics of intense fields in plasmas, covering a broad range of topics going from laser-plasma accelerators to astrophysics. The unifying aspects of the work is established by the methodology followed when tackling the different problems, with a combination of relativistic kinetic theory, plasma physics, accelerator physics, theoretical astrophysics with state-of-the art massively parallel numerical simulations using particle-in-cell codes or hybrid/reduced codes.

The team has developed a strong expertise in plasma simulation codes, theoretical plasma physics, plasma-based accelerators, and advanced simulation techniques. We are now becoming recognized as the leading plasma simulation group in Europe, and achieving worldwide recognition. Collaboration with the leading research programs in the US in our fields of research is tight and strong, guaranteeing us access to state-of-the-art computing facilities such as the newly commissioned cluster at UCLA (to be ranked #2 or #3 in university supercomputers in the US) or the IBM SP3 at NERSC, Oakland, California.

Our research program has been quite successful in the past years, and the results of our work are now showing up. Among a significant number of publications, we would like to point out that we have published one paper in Physical Review Letters (already in 2004), two additional papers will be published in Physical Review Letters this year (accepted for publication), and other two papers have been submitted to Physical Review Letters (November 2003 and March 2004).

All these papers deal with different aspects of laser-plasma interactions at extreme radiation intensities, ranging from laser-solid interactions to large-scale length plasma accelerators, from fast ignition of fusion targets to shocks in Coulomb explosions of cluster.

On the astrophysical context, we have recently demonstrated the role of the Weibel instability on the generation of magnetic fields in gamma-ray bursters through large-scale numerical simulations. This work is being further explored with the goal of understanding baryon loading effects in magnetic field generation in explosive events.

During 2003, we have also revived the hybrid comet dcomet in order to study the plasma sail concept and the role of magnetic fields in the erosion of planetary atmospheres. This code is being developed in collaboration with the Rutherford Appleton Laboratory, which is supporting one MSc student.

Our research has been widely recognized through several invited talks in Europe and in the United States in the general meetings of the Plasma Physics division of the European Physical Society or the American Physical Society, in all the workshops in the field of plasma-based accelerators or in high intensity laser-matter interactions. Two master thesis have been presented in the last year (one in the University of Bern, and the other in the Politecnico di Torino), and four high quality new PhD students are now preparing their thesis.

We are currently upgrading our cluster to an extra 40 CPU PowerPC G5 over Gigabit Ethernet, for an aggregate cluster size of 80 CPUs, 65 GB RAM. Funding for this cluster has been secured from different grants of the Center for Plasma Physics and the Group of Lasers and Plasmas, mainly from the European Space Agency. This cluster will be the fastest machine for science and technology in Portugal. The new cluster will be featured in press releases of Apple Europe.

Several of our research pictures have been used by RSINC inc., the makers of IDL (Interactive Data Language), visualization software widely used in astrophysics, geophysics, and atmospheric sciences, in their advertisements (e.g. in Physics Today) and promotions (e.g. RSINC Christmas Card). RSINC has provided us three IDL licenses free for the next five years, and access to other RSINC specific resources not available to the general public. Our work was also featured in the French site of RSINC Europe.

Simulation support for the UK collaboration Alpha-X (involving 10 UK university teams and the Rutherford Appleton Laboratory) is also been provided. This collaboration aims to produce a compact source for a 1 GeV electron beam for high brightness coherent radiation, combining plasma accelerators technology with free-electron laser techniques.

Our effort was concentrated on the following topics: (i) explosions of very large deuterium clusters, (ii) the Weibel instability in astrophysical and laboratory plasmas, (iii) relativistic mirrors for attosecond pulse compression, (iv) one GeV electrons in a 1 cm channel by laser wakefield acceleration, (v) proton acceleration in solid targets, (vi) OSIRIS code development, (vii) dcomet code development (viii) fast electron transport in plasmas and solids.

11.6.2. Explosions of very large deuterium clusters

Our work on very large (10^6 atoms) deuterium clusters demonstrated the possibility to drive shocks in Coulomb explosions. We have also proposed a novel technique to enhance the formation of such shocks, thus capable of increasing the neutron yield in intra cluster reactions

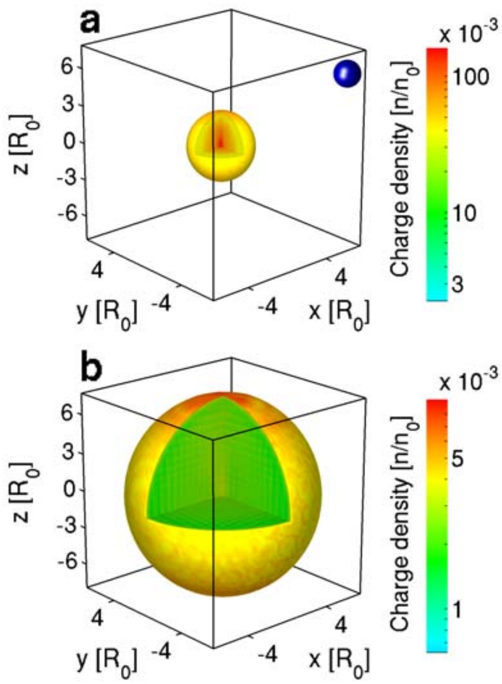

Figure 11.13 – Dynamics of the cluster explosion showing the clear formation of a denser outer shock shell. In blue, and for reference purposes, the initial cluster with ~ 10^6 deuterium atoms. Laser propagates along x and is linearly polarized along z.

11.6.3. Weibel instability in astrophysical and laboratory plasmas

The role of the Weibel instability in gamma ray bursters explosions seems to be now clearly established through the large scale particle-in-cell simulations we have published in 2003. We are also continuing to study the role of this instability in fast ignitor scenarios, where we have performed large scale finite target simulations that clearly demonstrate the role of collisionless electron instabilities, and its coupling to ions dynamics on the overall picture of transport in fusion targets.

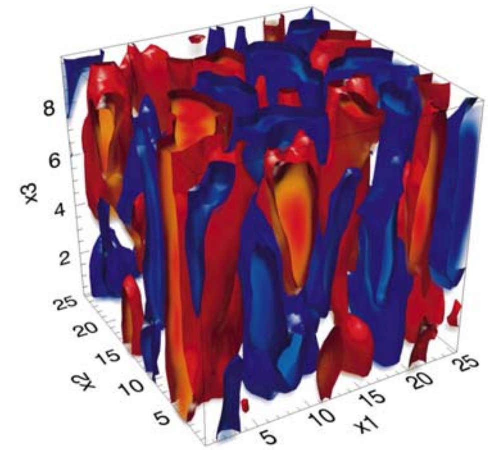

Figure 11.14 – Current density distribution in the early stages of the Weibel (or filamentation) instability from 3D PIC simulation: blue – positive (along x3) current density, while red is negative (along x3) current density.

11.6.4. Relativistic mirrors for attosecond pulse compression

A novel mechanism to compress femtosecond pulses to the attosecond range has been proposed and tested numerically. In this configuration an intense laser pulse drives a strong wake, very close to wave breaking, and a second weaker pulse is partially reflected from the density spike of the nonlinear plasma waves. Reflection efficiencies as high as 10%, with reflected pulses in the hundreds of attosecond have been measured in proof-of-principle numerical experiments.

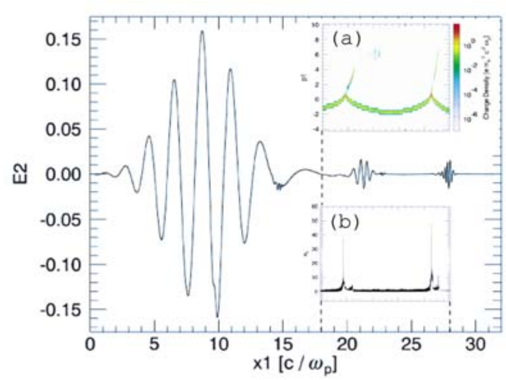

Figure 11.15 – Demonstration of the realtivistic mirror for 1D partice-in-cell simulations, where the electric field on the incoming laser pulse (moving from right to left) is plotted. On the right hand side of the plot the two reflected pulses are already visible (moving from left to right). On the inset, (a) the phase space of the plasma, showing the spikes in the momentum corresponding to the relativistic mirror regions, and (b) the density spikes of the relativistic mirror.

11.6.5. 1 GeV electrons in a 1 cm channel by laser wakefield acceleration

A major milestone for research in plasma based accelerators is the possibility to accelerate electrons up to 1 GeV. We have performed simulations and developed a theory that demonstre that such goal is already possible for available laser technology provided the laser propagates in a preformed plasma channel. High quality beams (energy spread < 10%, with energies in the 500 MeV range) are also predicted in the three dimensional one-to-one simulations we have performed.

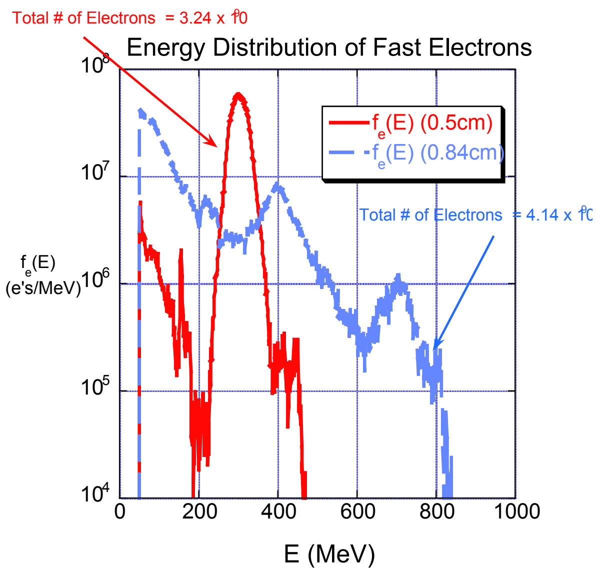

Figure 11.16 – Energy distribution of self-injected electrons in laser wakefield in a channel (in the middle of the channel –red, in the end of the channel – blue) from 3D simulation for currently available laser parameters.

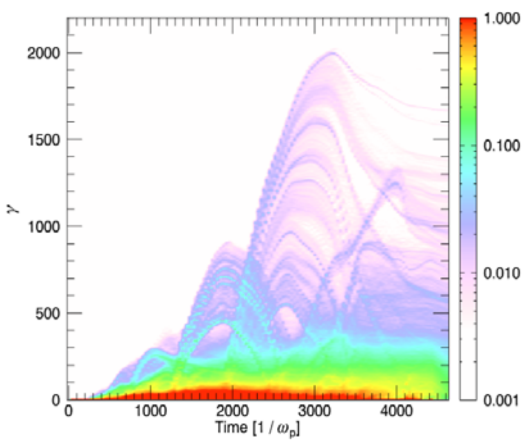

Figure 11.17 – Time evolution of the energy for the laser parameters in the Laboratory for Intense Lasers, demonstrating the possiblity to reach 1 GeV electrons in 1 cm channels (channel parameters also obtained from actual experimental parameters achieved at the Laboratory for Intense Lasers).

11.6.6. Proton acceleration in solid targets

Activity on this topics has been continued, paying particular emphasis to high dimensional effects, in particular the Rayleigh-Taylor like instability growing in the underdense region that can be created by the pre-pulse of an ultra intense laser interacting with a solid target.

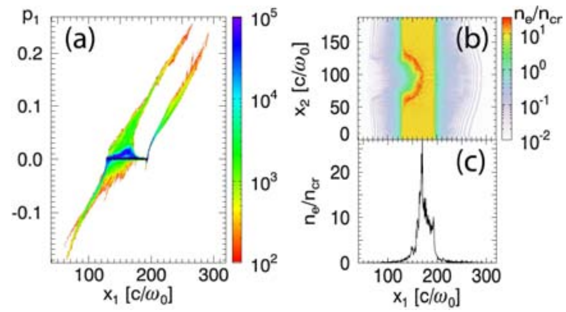

Figure 11.18 - Proton shock acceleration in 2D simulations: (a) ion phase space, (b) electron density, and (c) lineout of the electron density along laser propagation áxis (x1), showing the compressed shocked plasma.

11.6.7. OSIRIS code development

Several new features have been included in OSIRIS, namely, cathodes, external fields, arbitrary profiles, and significant performance improvement and benchmarking has been pursued. The strongest effort was focused on optical field ionization with two ionization models now included in OSIRIS (Barrier suppression ionization and tunneling ionization – ADK model).

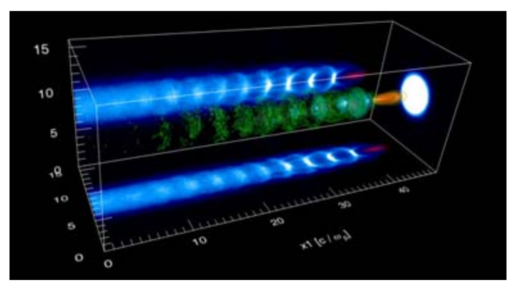

Figure 11.19 – Ionization front and plasma wakefield generated by a 30 GeV electron beam (with the parameters of SLAC) in a gás chamber of Li.

11.6.8. dcomet code development

During 2003, we have revived the hybrid code dcomet (R. Bollens, UCLA PhD thesis, 1993). This hybrid code examines the self-consistent dynamics of kinetic ions in a MHD electron background (massless electrons, but including the Hall term). The legacy code was modernized, and several new features have been included (arbitrary number of species, different charge to mass rations) getting the code ready to be parallelized.

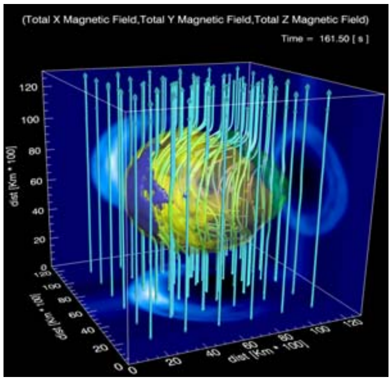

Figure 11.20 – Magnetic field structure generated from the interaction of the solar wind with an expanding plasma cloud (e.g. AMPTE release) from dcomet simulations.

11.6.9. Fast electron transport in plasmas and solids

Theoretical work on fast electron transport in plasmas and solids, relevant to laser-solid interactions and fast ignition inertial confinement fusion, has been continued.

An analytical model of field generation and Ohmic heating by fast electrons propagating in conductors was developed, which includes a resistivity with an arbitrary power law dependence on temperature. It clearly demonstrated the significant effect of target heating on the field generation, the effect being particularly pronounced for the magnetic field. Field generation is enhanced when the resistivity increases with temperature, as occurs in metals, and reduced when it decreases, as occurs in plasmas. If the resistivity falls faster than linearly with temperature then the magnetic field will eventually change sign, causing beam expansion and hollowing. The implications for laser-solid interactions and the fast ignitor were considered. It was found that the minimum fast electron density required to achieve ignition by Ohmic heating is prohibitively high. This work was published in Physical Review E and featured in the Virtual Journal of Ultra Fast Science.

The limitation of the current of a charged particle beam due to its self-generated magnetic field, first considered by Alfvén in 1938 in terms of particle trajectories, was reconsidered in terms of energy conservation. An absolute upper limit on the net current was derived by equating the kinetic energy of the particles to the magnetic field energy within the beam. It depends only on the current profile, is directly applicable to beams that are not mono-energetic, and can be expressed in a simple, general form, unlike Alfvén's approach. Calculations for various current profiles using both approaches gave similar results. Alfvén only considered a uniform current density. The limit is lowered if the current is concentrated on-axis, and increased if it is concentrated off-axis. In particular, an arbitrarily large current can propagate in a narrow, ring shaped profile. Magnetic field limitation only applies to beams that are, at least partially, charge neutralised, that is beams propagating in a conductor. In this situation the beam current is also initially neutralized, allowing forward currents much greater than the Alfvén limit to propagate. However, current neutralisation is temporary, as the return current decays due to collisions and the currents separate due to their mutual repulsion. The resistive decay of the return current was calculated, and a magnetic inhibition time was defined for beams that exceed the Alfvén limit, as is the case for laser-generated fast electrons. This work was published as a brief communication in Physical Review E. It was then applied to fast ignition, and it was found that the proposed ignition beam parameters are not viable. The possible solutions to this are increasing the mean energy, increasing the temperature to which the fuel is heated by lowering the beam radius and duration, using multiple beams, and using an annular beam. Taking into account the laser wavelength required showed that increasing the mean energy and the number of beams are the most practical solutions.

This work has been submitted as a rapid communication to Physical Review E. An alternative fast ignition scheme using a spherically converging heat wave, rather than a beam, was proposed in both this article and that on field generation, and it is intended to follow up on this, and other, ideas for fast ignition.

We also collaborated in the interpretation of proton emission measurements from solid targets obtained on the Astra laser at the Rutherford Appleton Laboratory, UK, by groups from Glasgow and Imperial College. This work was published in Physical Review E.