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 performed by "Grupo de Lasers e Plasmas" of "Centro de Física dos Plasmas" of IST.

The following sections describe the status of the laser system and target area, the experiments and technologies and the theory & simulations.

11.2. STATUS OF THE LASER SYSTEM

11.2.1. High-dynamic range characterisation of the pulse energy distribution in time

Ideally, all the energy contained in a short pulse should be delivered instantaneously onto the target. In practice, due to the amplification and pulse stretching and compression processes, there may be pre-pulse energy in the form of either weaker replicas of the main pulse or a long pedestal. These spurious effects may be damaging enough to affect the ionisation state of the target, generating a plasma before the main pulse arrives and thereby deteriorating the results of the experiment. For this reason, we undertook a high-dynamic range characterisation of the amplified pulse energy distribution in time, which has allowed us to identify some sources of satellite pulses.

11.2.2. Acquisition of a new ultra-short pulse main oscillator

The use of the optical fibre to enlarge the pulse spectrum was also found responsible for introducing non-linear spectral distortions in the amplified pulse, which translate into a non-uniform pulse profile. For this reason, and given the desirability to operate with shorter pulses, the oscillator and fibre are currently being upgraded to a single-unit, ultra-short pulse oscillator. This is a commercial Kerr-lens mode-locked Ti:sapphire laser (Coherent Mira 900-F) pumped by an all-solid state $Nd:YVO_4$ laser (Coherent Verdi 10), capable of producing ~100 femtosecond pulses at 1053 nm.

11.2.3. Design of a new broadband grating pulse stretcher

The introduction of the new oscillator described above means that the stretching and compression stages must undergo some redesign in order to accommodate the extended bandwidth. In particular, the shorter the pulse, the harder it becomes to perform the final pulse compression as faithfully as possible, so a great level of detail must be placed in this particular aspect. Given that a grating pulse stretcher is essentially an image-relaying element, with the different frequencies playing the role of the optical rays, aberrations must be kept to a minimum in order to avoid spectral distortions in the stretched pulse. We have modelled our new pulse stretcher using commercial ray-tracing codes (OSLO), in order to calculate the optical path differences for the different components. Simultaneously, special optics mounts were designed for the optical relay system. The new stretcher should be assembled and installed before the end of the year (Figure 11.1).

11.2.4. Design and assembly of a vacuum spatial filter

During the amplification process, the laser beam must traverse a considerable length of optical components. Diffraction from inhomogeneities in these media, such as surface spots or clipping, results in sudden changes in the beam profile (corresponding to high spatial frequency components). Through amplification, these irregularities grow into instabilities that can become highly damaging to the beam quality and the optical components. The device known as vacuum spatial filter allows these features to be removed, producing a beam with a smooth profile. During this year, we have designed a medium-sized vacuum spatial filter to be used at the output of the 1 Joule amplifier, before the compression gratings. This should ensure that the beam reaching the target has a soft Gaussian transverse profile.

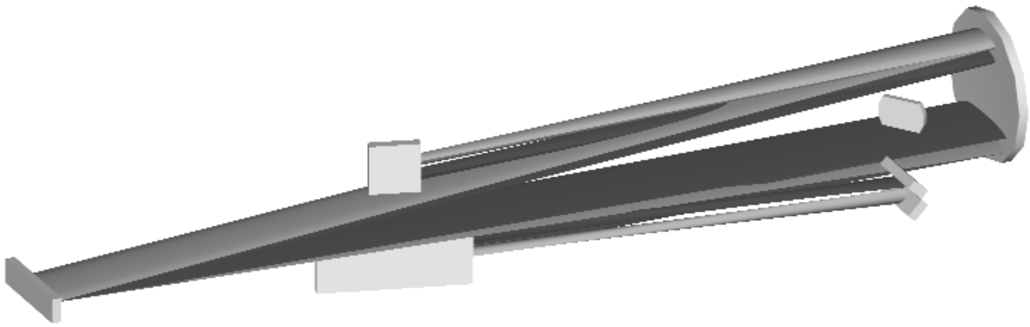


Figure 11.1 – Schematic of the new broadband grating stretcher

11.2.5. Optimisation of the overall shot-to-shot energy stability of the entire system

Several factors were found to account for a progressive decrease in the repeatability of the energy of the amplified shots, such as changes in the alignment of the pumping Nd:YAG for the regenerative amplifier stage, small fluctuations in the room temperature that translated into material expansion of the optical breadboards, and electronic jitter due to heating of the components. These issues were systematically addressed, and a considerable improvement was achieved, resulting in an almost total efficiency of usable Joule-level shots.

11.3. STATUS OF THE TARGET AREA

11.3.1. Laser diagnostics

Two new important diagnostics were added this year for the purpose of characterising the temporal behaviour of the laser output: a single-shot, second-order autocorrelator, and a scanning third-order autocorrelator. The first of these devices allows the measurement of the pulse duration at the output of the laser system, in a single-shot fashion. The second is used for characterising the output of the oscillator over a large dynamic range, with the purpose of measuring the initial pulse contrast. Thanks to the use of the third harmonic (351 nm) of the original radiation, measurements with unprecedented accuracy can be obtained. Both these autocorrelators will be extremely useful for characterising the overall performance of the upgraded system, once the new oscillator is installed (Figures 11.2 and 11.3).

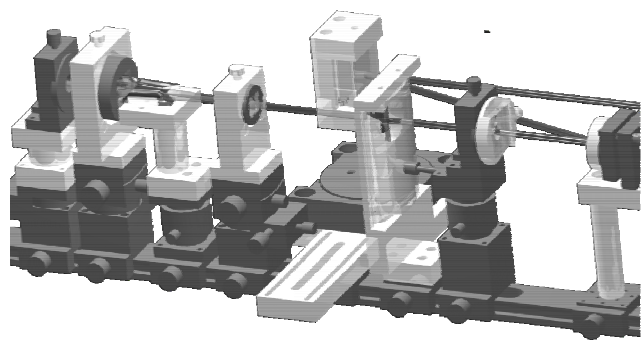


Figure 11.2 – Schematic of second-order single-shot autocorrelator

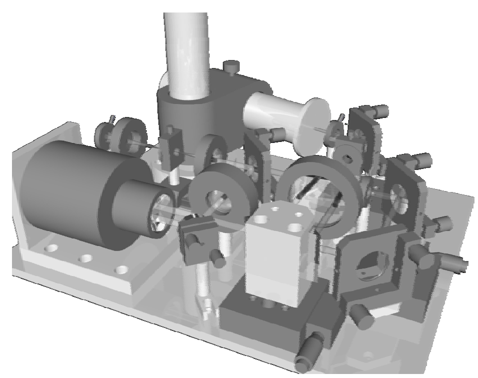


Figure 11.3 – Schematic of third-order scanning autocorrelator

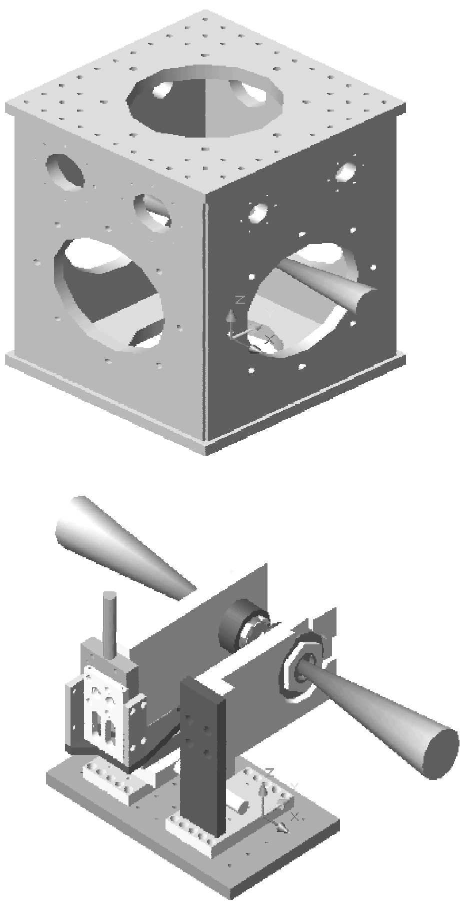
11.3.2. Plasma diagnostics

In order to carry out the L^{2}I experimental program for the remaining of 2001 and the coming years, two new ultra-fast time-resolved plasma diagnostics are needed:

- Fast semi-quantitative analysis of cylindrically symmetric plasma is now possible by optimised shadowgraphy. A ray-tracing program was developed in order to optimise the diagnostic and interpret the shadowgrams. This diagnostic is now fully operational for plasma densities of the order of 10^{18}-10^{19} cm^{-3};
- In order to perform accurate measurements of the radial plasma density profiles a shearing interferometry technique is under development. This diagnostic is more accurate and sensitive than shadowgraphy. Plasma densities of 10^{16}-10^{18} cm^{-3} can be measured in a single shot (for cylindrically symmetric plasmas). In 2002 this diagnostic will be improved with a new automatic interferogram analysis software. This software will allow the extension of the usable plasma density range.

11.4. EXPERIMENTS

This year witnessed the beginning of our experimental program in laser channelling inside pre-formed plasmas. A new secondary vacuum interaction chamber was developed for this purpose, inside which a plasma channel is created by means of a laser triggered high-voltage discharge between two electrodes with a special geometry (Figure 11.4). The discharge region, with a linear profile a few millimetres long, is ideal for guiding of high-power picosecond pulses. So far, we have used shadowgraphy and moiré interferometry to characterise the plasma channels, with more complete results pending on ongoing work. Preliminary results point to the creation of plasma channels with lengths up to 2 cm suitable for high intensity laser guiding (Figure 11.5).



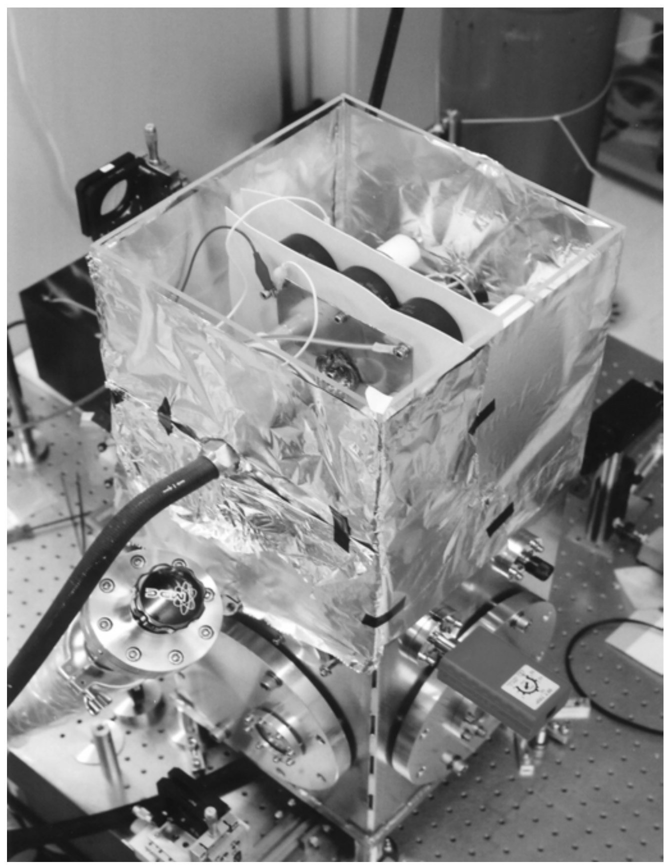


Fig. 11. 4 – Rendering of the vacuum chamber and insulated electrode mounts for the channeling scheme by laser-triggered HV

discharge and photography of the vacuum chamber and capacitor bank

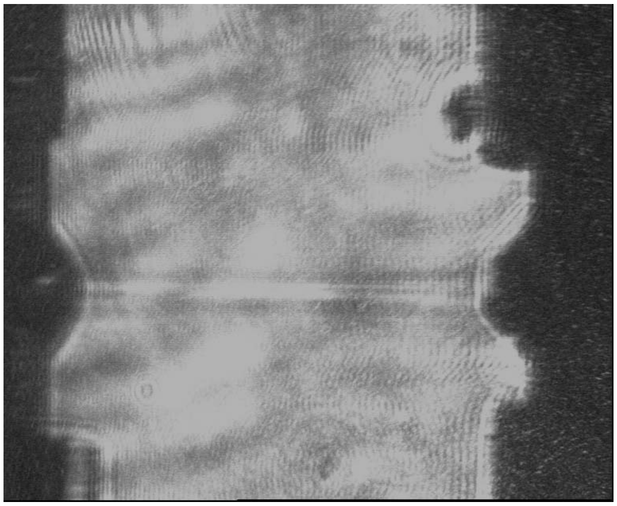


Fig. 11.5 – Shadowgraphy of the first channel produced by the laser-triggered high voltage discharge channeling scheme

11.5. TECHNOLOGY

The experiments on the laser-triggered high voltage discharge channelling scheme required the development of a shielded high voltage power supply, capacitor bank and discharge vacuum chamber. This system is now working producing 20 kV discharges with electromagnetic noise sustainable by the remaining laboratory systems. A new system, using a differential pump technique to allow the main beam focusing in vacuum and channel lengths up to 10 cm is now in project stage.

11.6. THEORY & SIMULATION

Beginning January 2001, was installed an infrastructure for intensive numerical particle-in-cell simulations. The computational infrastructure is built around a 32 node Macintosh cluster, the fastest Macintosh cluster in the World, and the fastest cluster for Science and Technology in Portugal (as of November 2001), the state-of-the art fully relativistic parallel particle-in-cell code OSIRIS, and the IDL-based visualization package Zamb.

The cluster epp (Figure 11.6) was installed in the middle of February 2001 in less than two days, and OSIRIS has been running in the cluster, in production mode, without major glitches, since the end of February.

The whole cluster operating system was upgraded to Mac OS X in early June: at the same time, we have also evolved to the LAM MPI implementation, and the total RAM was upgraded to 18 GBytes. The success story of our cluster was featured in several computer related news sites, including slashdot.org, and MacCentral, as well as in press releases in the United States and Germany from the companies that supplied the Ethernet switch (Asante, San Jose, California) and KVM switches (Dr Bott, Germany). Table 11.1, we presents the benchmarks of our cluster, performed by Professor Viktor Decyk during his visit to Lisbon.

Fig. 11.6 - Epp cluster

Even though self-made clusters are still far from the raw computational power of a supercomputer, it must be stressed that the performance for small to medium scale problems is comparable, and the turn over time is, of course, much shorter on a few-users machine.

In connection with inertial confinement fusion, has been examined in detail the propagation of intense electron beams with currents in excess of the Alfven current generated from the interaction of intense laser pulses with solid targets. Such intense currents might be of relevance for neutrino factories and fast ignition of fusion targets, and are also present in astrophysical scenarios. Our work was focused on electromagnetic collisionless instabilities (Weibel instability) that lead to the generation of intense magnetic fields and beam filamentation, thus loss of beam quality. We have performed three-dimensional massively parallel numerical simulations of finite width electron beams as well as fully periodic simulations of wide relativistic beams in plasmas to demonstrate that this instability is not relevant for high temperature beams such as the ones produced from laser-solid interactions. These simulations were supported by theoretical work based on relativistic kinetic theory, and a generalization of relativistic fluid theory including the self-consistent plasma dynamics on the collisionless time scale. Our theoretical results predicted a new instability regime, from the multidimensional coupling of the two-stream instability with the Weibel instability that leads to strong filament tilting due exclusively to kinetic effects on the Weibel instability. These analytical results were fully confirmed by three-dimensional and two-dimensional particle-in-cell simulations.

Computer	Push Time (in nsec)	LoopTime (in sec)
IBM SP3, w/MPI, 128	13	65.2
IBM SP3, w/MPI, 64	17	73.1
IBM SP3, w/MPI, 32	30	117.2
IBM SP3, w/MPI, 16	57	214.8
IBM SP3, w/MPI, 8	107	396.5
IBM SP3, w/MPI, 4	206	760.2
Cray T3E-900, w/MPI, 128	13	53.8
Cray T3E-900, w/MPI, 64	24	92.6
Cray T3E-900, w/MPI, 32	48	173.5
Cray T3E-900, w/MPI, 16	93	335.7
Cray T3E-900, w/MPI, 8	173	629.6
Cray T3E-900, w/MPI, 4	334	1212.9
SGI Origin2000/R12000, 64	17	70.5
SGI Origin2000/R12000, 32	53	191.5
SGI Origin2000/R12000, 16	101	358.6
SGI Origin2000/R12000, 8	200	708.1
SGI Origin2000/R12000, 4	396	1405.4
Mac G4/450, IP cluster, 16	120	477.5
Mac G4/450, IP cluster, 8	218	847.0
Mac G4/450, IP cluster, 4	418	1577.0
Mac G4/450, IP cluster, 2	814	3025.8

Table 11.1: Benchmark of the epp cluster against some of the fastest supercomputers in the World, with a PIC skeleton code (Decyk, 1997). The IBM SP3 (NERSC) is ranked #3 in the TOP500 list released November 2001

The propagation of fast electron beams with density much lower than that of the background plasma, or solid, where the background is collision dominated. Has also been studied a hybrid code that treats the fast electrons kinetically, using the Fokker-Planck equation, and the background as a resistive fluid, using Ohm's law was used. The fields are found by solving Maxwell's equations in cylindrical geometry, neglecting the displacement current. Modelling the propagation of fast electrons in solid targets is essential in determining the generation of fast electrons in laser-solid interactions from measurements of X-ray emission, the main diagnostic for fast electrons. Most experiments have been interpreted considering only collisional effects, field generation was ignored. It is these results on which the Fast Ignitor proposal was based. The collisional part of the hybrid code has been just compared with the full code in the interpretation of layered target K α emission experiments. We found that ignoring the fields can lead to an apparent two temperature distribution and to underestimation of the laser absorption into fast electrons, the mean fast electron energy can be either over or under estimated. Work on the interpretation of experimental results from the Vulcan laser, in collaboration with Imperial College, London, has continued.

The possibility of a fast ignitor using fast protons instead of fast electrons has been widely discussed. The nature of the generation of fast protons in high-intensity laser-solid interactions is not yet fully understood. We have developed a simple, one-dimensional, analytic model of proton acceleration inside solid targets by the electric field generated by fast electrons. It gives very similar results to the well-known models of fast electron driven plasma expansion into vacuum. An invited review of proton and neutron generation by terawatt lasers has also been published.