Scientific report for the ESF short visit grant
Numerical modelling of fast electron transport in a cylindrically laser compressed matter

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1 Objectives

The present study takes part in the HiPER project[1] for a better understanding of the fast-ignitor scheme[2], an alternative approach towards controlled fusion energy. This scheme involves a relativistic electron beam generated by a short and intense laser, and this critical point needs relevant experimental data such as the ones described here.

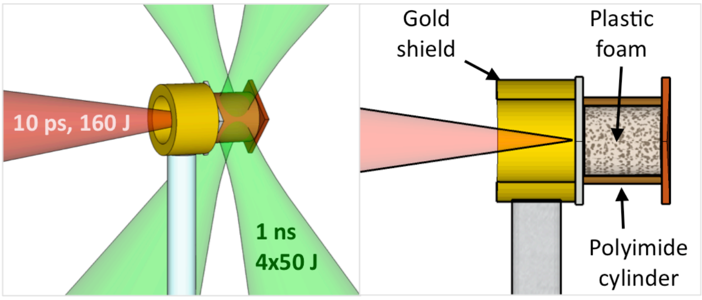

Figure 1: Schematics of the laser and target configuration. The nanoseconds pulses are used to compress the cylinder. In a second phase, the 10 ps pulse generated electrons into the compressed matter. The cylinder was filled with plastic foam at different initial densities: 0.1, 0.3 or 1 g/cm^3.

The visit at the Madrid Polytechnic University (UPM) in the GIFI group (Grupo Interuniversitario de Fusión Inercial) had for main objective to understand the experimental results obtained in october 2008 using the Vulcan laser at the Rutherford Appleton Laboratory (Oxford, UK). This experiment was carried out in two distinct phases[3]. In the first part, four long pulse (nanosecond) lasers were focused onto a plastic cylinder filled with plastic foam, as shown in Fig. 1. Proton and X-ray radiography measured the compression evolution, and those results are reported in upcoming papers by Vauzour *et al.* and Volpe *et al.* In the second phase, the same compression was applied, and an additionnal laser (160 J in 10 ps) was generating an ultra-short relativistic electron beam passing through the compressed plasma. The rear surface (a copper foil) was actually a fluorescent layer, whose x-ray emission gives relevant data about the electron beam divergence and intensity. These measurements were realized for different delays τ between the ns and ps pulses. In other words, the electron beam was generated at different stages of compression and was thus subject to different plasma conditions.

A brief summary of this experimental data follows. The results are presented for different values of the initial foam density. Firstly, the number of electrons reaching the rear surface was measured for various delays τ. As displayed in Fig. 2(left), this quantity decreases when the compression occurs, independently of the initial foam density. Secondly, the size of the electron beam was measured when it reaches the rear surface. In Fig. 2(right), one can clearly see a strong difference between the various initial foam densities). With 0.1 g/cm^3, the size decreases for increasing delays, as if the compression

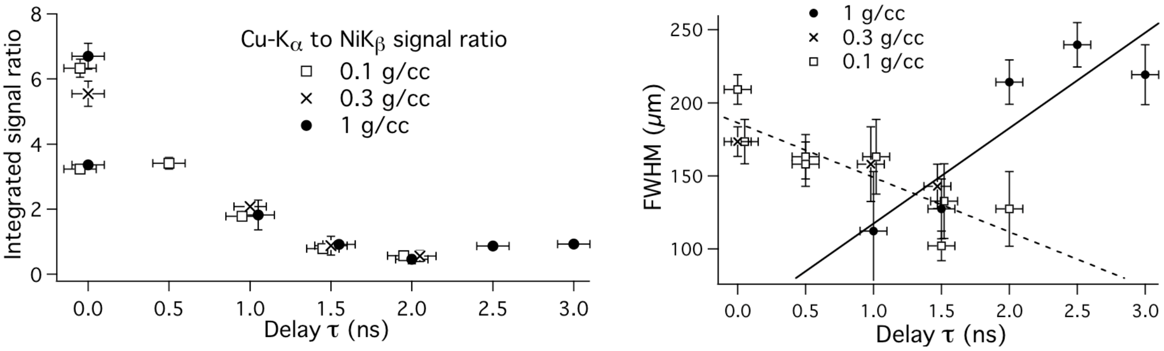

Figure 2: Experimental results of the electron beam characteristics for different initial densities of the plastic foam. Left: a signal proportionnal to the number of electrons reaching the rear surface of the target. Right: the size (Full Width Half Maximum) of the electron beam when it reaches the rear surface. Both quantities are plotted against the delay τ between the long and short pulses.

was collimating the electron beam. With 1 g/cm^3, the opposite trend is observed, as if the compression caused the electron beam to diverge.

The purpose of the visit in Madrid was to reproduce and understand numerically these interesting results using the 2D cylindrical hybrid code developped by Javier Honrubia[4].

2 Progress and results

Before simulating the electrons propagation into the compressed cylinder, we needed to know the state of the compression for various values of the delay τ. This was achieved using two different hydrodynamic codes: CHIC from the CELIA laboratory[5] and MULTI3D from UPM[6]. The first ones takes more physical features into account but is only two-dimensionnal. The second one is three-dimensionnal, but contains less radiative effects.

2.1 Effect of the electron beam divergence

The electron beam characteristics have to be explicitly input in the code. Most importantly, the electrons energy and divergence have to be chosen. The mean energy was experimentally measured around 300 keV, so we started by the study the divergence. A sample case was chosen from the CHIC results and several divergence values were input.

Those tests shown that the electron beam induced a surprisingly intense magnetic field after a few picoseconds. This implied an efficient collimation of the electrons. As a consequence, the beam shape was not very much dependent on the initial divergence because the magnetic fields forced the electrons to follow a central channel. At most, we could observed a reduced signal due to electrons escaping the target before being trapped by the fields.

This test already indicated that the pulse duration (10 to 20 ps) had an important effect on the electron transport because this unusual duration allowed the magnetic fields to grow.

2.2 Taking into accound 2D effects

The previous test had to be carried out with 1D profiles of the plasma density and temperatures, as the CHIC code didn't produce the 2D effects in the right direction. To investigate the effects using 2D density and temperature maps, the results from MULTI3D were input in the hybrid code. We then started a systematic study for the electron transport inside the compressed cylinder at different delays. We chose delays τ from 0 to 3 ns with a 0.5 ns interval, and targets filled with 0.1 or 1 g/cc foam. It gives 14 cases to be studied under various electron beam conditions.

Several modifications of the code had to be implemented to understand the contributions of different effects. Indeed, we tested the influence of fields, collisions, resistivity and refluxing. The collisions had some noticeable influence on the beam dilution, but didn't change dramatically the results. The

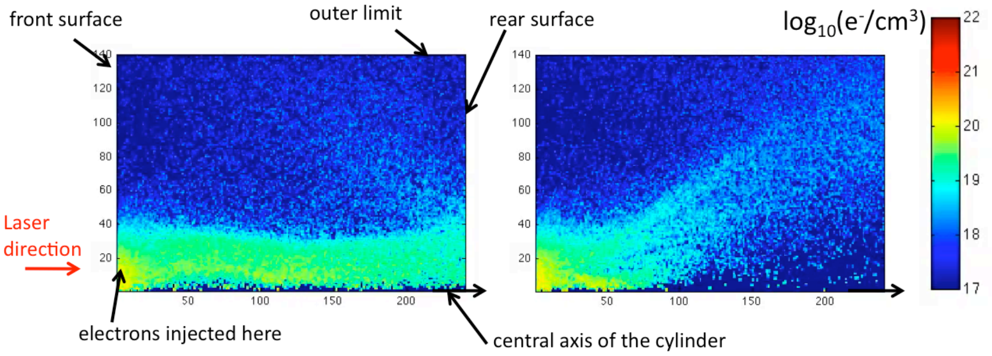

Figure 3: Example of simulated electron collimation for the 1 g/cm^3 targets, at $\tau = 1.5$ ns (left) and $\tau = 2$ ns (right). The maps represent the fast electron density in cm^{-3}, in log$_{10}$ scale. The first case shows an efficient collimation contrary to the second one. Note that only one half of the cylinder is plotted, as the other half is symetric.

refluxing made the signal somewhat higher and blurred. The resistivity effect is definitely the most important for the magnetic fields generation, and depends mostly on the initial temperature map. Indeed, without going into the details, the electrons are confined into the high resistivity zones of the plasma. As illustrated in Fig. 3, some cases produce an efficient collimation. They correspond to plasmas containing a high resistivity channel in the center of the cylinder.

2.3 Overall results

The final size of the electron beam as well as the number of electrons reaching the rear surface was measured numerically and compared to the experimental data, as summarized in Fig. 4.

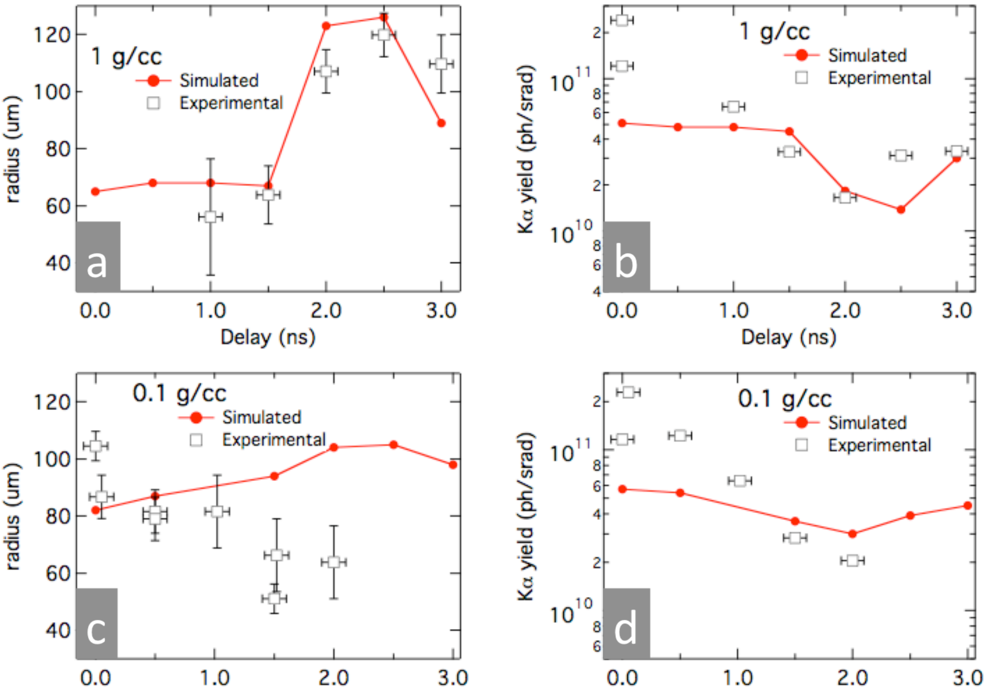

Figure 4: Overall results for 1 g/cm^3 (a, b) or 0.1 g/cm^3 (c, d) targets. The electron beam radius (a, c) and yield (b, d) are compared to the experimental data.

For 1 g/cm^3 targets, the simulation and experiment show a good agreement, especially for the beam size. This result is very interesting because it may constitute an experimental confirmation of the magnetic field effect on fast electron transport. Indeed, the small sizes measured at early delays, compared to the late ones, show that a confinement of the electrons on the cylinder axis is possible under the right conditions.

The 0.1 g/cm^3 targets results don't match the experimental measurements. Additionnal studies will be needed to find the causes. We already have plans to investigate several effects, as modifying the electrons initial energy or initial beam size. We are also thinking about getting a better estimation of the resistivity in cold materials, which is a critical parameter, although very uncertain.

It is worth noticing that the agreement on the electron yield needed an overall adjustment factor of 3 to match the experimental results. This could be due to the unprecise absolute calibration of the corresponding spectrometer, or to the wrong input value of the electron divergence. THis points will be investigated.

3 Projected work

Great progress has been made for understanding the experiment, and the different issues found during the visit will be further investigated from both laboratories in order to complete the analysis. More precisely, modified values of the electrons parameters and of the resistivity will be tested for a better agreement. An article, and possibly conference proceedings, will then be prepared when the remaining work is done.

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