Study of the impact of small-scale plasma modulations and the size of the plasma on seeded soft x-ray laser homogeneity.

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Abstract. In the present work, we have used the 2D AMR hydrodynamic code with radiation transport ARWEN to study the plasma homogeneity alteration on small scale (1-10 $\mu$m) that may arise from initial target defects or driving laser intensity modulations. These simulations show that target rugosity imprints strongly the plasma creating a complicated pattern of electronic density. In addition to this, we have done several simulations of plasmas of different size (from 20 $\mu$m to 2 mm height) to study the different stages of a seeded soft x-ray laser amplifier. We have observed that 2D hydrodynamic effects lower the gain in small plasmas. As the main pulse, which creates the population inversion, interacts with a fully developed plasma, we have implemented a ray-tracing subroutine for the laser energy deposition in order to treat correctly the refraction effects of the short pulse. Simulations show that these effects are not negligible in rugous targets. Finally, simulations of the behaviour of the seeded beam in the amplifying plasma have been done with the 3D ray-tracing (amplification in non-homogeneous media) code SHADOX, as a post-processor of ARWEN. Prior ray-tracing, gain calculation is done on the output of ARWEN using a simple 3-level atomic model.

1. Introduction

Ultra intense soft x-ray lasers have many applications in different fields such as femto-biology (diffraction, single shot holography), plasma and astrophysics (core of giant planets, opacity, warm dense matter), atomic physics, soft x-ray physics, surface science (damage, nanotechnology), etc... These applications require short pulses (femtosecond pulses), strong energy (mJ), high spatial coherence and a good wave front. Seeded soft x-ray lasers (SSXRL) have the potentiality to produce a beam with the required characteristics.

A high harmonics beam is seeded on a x-ray amplifier to obtain an amplified beam which conserves the properties of the high harmonics (spatial coherence and a good wave front) and a higher energetic output. Several amplifying stages can be coupled with the appropriate optics in order to obtain the desired energy at the output. An amplifier stage consists of a plasma where a short (ps) infrared laser pulse creates a population inversion. The plasma is created with a long (ns) infrared laser pulse.
The use of solid targets to create the amplification stages allows to obtain more energy than amplification stages based on gas targets. However, amplified spontaneous emission (ASE) may dominate the output beam. In addition to this, as the plasma density is higher in solid targets, strong refraction effects may appear, affecting both the short laser pulse pumping the plasma and the injected beam. The influence of large-scale plasma shaping to enhance the homogeneity and reduce the refraction has been recently studied [1]. In this work, we study small scale (1-10 µm) defects on target surface or in the spatial profile of the laser. In addition to this, several simulations of plasmas of different size have been carried out to study the impact of 2D hydrodynamic effects in the amplifier stages.

In section 2 we describe the computational tools used in this paper and the simple 3-level laser scheme used to calculate the gain of the amplifier. In section 3 we give the results of our simulations of the effects of defects in the spatial profile of the laser. In this same section we also explain the simulations done with defects on target surface. In section 4 we describe the simulations of plasmas of different size. Finally, some final discussion and conclusions are provided in section 5.

2. Computational tools
The simulation of a single stage of the amplification chain has been done with two codes (ARWEN and SHADOX) coupled via a 3-level stationary gain calculation postprocess.

Generation and pumping of the plasma have been simulated with ARWEN [2], an AMR 2D hydrodynamic code with radiation transport and electron heat conduction. A ray tracing subroutine for laser energy deposition was included to take into account the effects of refraction of the pumping pulse in the plasma created by the long pulse.

The data obtained from ARWEN are postprocessed to calculate the gain. A three level scheme for Ne-like iron (λ = 25.5 nm) is supposed. A stationary calculation of the level populations is done with the rates of collisional excitation obtained from [3]. Only Doppler broadening is taken into account in this calculation. Finally, the injection of harmonics in the amplifier is simulated with SHADOX, a 3D ray-trace code. Varying different parameters (focal point, injection angle) we can optimize the seeding in order to reduce the refraction undertaken by the x-ray beam.
3. Effects of laser profile modulations and surface defects
Small scale defects may imprint the plasma, thus destroying the homogeneity of the amplified beam. This effects may arise from an inhomogeneous deposition of the laser energy or from defects in the target. We have studied separately the defects on the long pulse creating the plasma, the short pulse pumping the plasma and the roughness on target surface. Defects on laser have been implemented as a sinusoidal modulation of different amplitude and a wavelength of $10 \mu m$ in the energy profile. Roughness of the target is simulated as a sinusoidal perturbation of an amplitude of $5 \mu m$ and a wavelength of $10 \mu m$.

3.1. Defects on long laser pulse
The plasma is created with a perturbed laser pulse. Three different amplitudes (5%, 2.5% and 1%) have been used. As a measure of the inhomogeneity imprinted by the laser, we plot in figure 2 the contrast of temperature (the difference between the maximum and minimum temperature, divided by its sum) measured in a horizontal cut at a quarter the critical density versus time.

![Figure 2](image)

**Figure 2.** $\Delta T/T$ vs time for three different amplitudes: 5% (blue circles), 2.5% (red squares) and 1% (yellow triangles).

As it can be seen, laser defects imprint the plasma and smoothing the laser will ameliorate the plasma homogeneity (there exists a great difference between amplitudes of 5% and 2.5%) but it is not worth to obtain a perfectly homogeneous long pulse energy deposition, as the benefits will be negligible (there are not many differences between 2.5% and 1% curves in figure 2).

3.2. Defects on short laser pulse
Now the plasma is created by a smooth long laser pulse and it is pumped with a perturbed short laser pulse. In this case, gain profiles have been calculated to evaluate the impact of the perturbations.

![Figure 3](image)

**Figure 3.** Gain map for 2.5% (left) and 7.5% (right) amplitudes.

As it is shown in figure 3, a great perturbation imprints the plasma and the gain profile whereas small perturbations may be allowed (like in long pulse case) as the homogeneity of the gain is good enough (oscillations are hardly visible in the left figure).

3.3. Defects on target surface
In this case, both lasers have no perturbation and the roughness is simulated with the sinusoidal perturbation described in this section. Early in the simulation, a very complicated pattern of velocities and temperatures appears, imprinting strongly the plasma and the seeded beam, as a SHADOX post-process showed. To evaluate the refraction undertaken by the short laser pulse pumping the plasma, a ray-tracing subroutine was added to ARWEN. SHADOX post-processing showed that the plasma simulated with the ray-tracing subroutine was more homogeneous. In addition to this, the output beam was three times more energetic and also the gain zone was greater, so refraction effects of the short pulse in the perturbed plasma must be taken into account if we study the effects of roughness.

4. Effects of target size
As the different stages of the amplification chain will not have the same size, plasmas of 20 µm, 50 µm, 200 µm, 1 mm and 2 mm height have been simulated, using the same laser intensity.

For big plasmas (from 200 µm to 2 mm) the maximum gain has the same value, as the intensity of the lasers is the same. However, for 50 µm and 20 µm the maximum value of gain is smaller than expected. Simulations show that electronic density and temperature are lower in the gain zone, thus decreasing collisional pumping rates and reducing the population inversion. The lateral expansion of the plasma (which is seen clearly in simulations) can explain this effect, lowering density and temperature of the plasma in the gain zone in small plasmas, whereas in greater plasmas, the gain zone is not affected by this 2D effects.

5. Conclusions
The amplifying chain of a seeded soft x-ray laser must be designed carefully, to obtain a beam with the properties required. Plasma homogeneity plays a fundamental role so amplifier stages must be designed carefully. We have coupled the hydrocode ARWEN with the ray-tracing code SHADOX, allowing us to simulate the amplification chain.

Simulations of perturbations both in driving laser and target surface show that the last are the most important, imprinting strongly the output beam, whereas we can allow some perturbations in both driving lasers. Refraction effects must be taken into account if we want to study the effects of roughness.

Finally, we have showed that 2D hydrodynamic effects lower the gain in small plasmas and must be taken into account in the design of the amplification chain.

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