Remarks to SBS PCM based self-navigation of laser drivers

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Abstract. A novel technology of self-navigation of laser drivers on injected inertial fusion energy pellets employing phase conjugating mirrors based on stimulating Brillouin scattering was recently proposed. Its feasibility as well as various implications were gradually studied and working solutions to potential problems were always suggested. As this technology could help to overcome several burning key issues of inertial fusion (e.g., a sufficiently precise navigation of laser drivers on injected pellets in the case of a direct drive scheme and decreased requirements on high-repetition high-power lasers) it gradually started to attract a carefully measured tentative interest among the major inertial fusion oriented laboratories and projects. In this paper the next step in this research path will be reported. It concerns the resulting phase and amplitude structures created by multiple low energy drivers (glints) illuminating the pellet during the first stage of the process after their reflection and a subsequent superposition on the collecting/focusing final optics. It was demonstrated that with a large number of such drivers acting simultaneously from many angles the situation gets somewhat complicated and requires more detailed studies/suggestions of suitable configurations.

1. Introduction

There are still many problems to be solved in inertial confinement fusion development, before a functional inertial fusion power plant can be built. An ignition has not been achieved, yet, not even on stationary pellets with indirect drive. Despite the fact that some encouraging progress has been recently reported by NIF. However, a stationary pellet is not suitable to be used in a power plant. One possible solution is to inject the pellet into the reaction chamber and irradiate it during its fly at the right moment by many laser beams. This might highly improve the repetition rate, but also brings the question of how to aim the lasers on the moving pellet with a necessary accuracy and timing. Tracking the pellet and aiming at it either by moving heavy final optics or by adjusting refractive index of suitably chosen optical elements is an option for consideration. But it might prove to be too difficult to handle in practice.

Therefore, an alternative approach was recently proposed for evaluation. This approach employs phase conjugating mirrors (PCM) generated by stimulated Brillouin scattering (SBS). If successfully mastered, it might require no active aiming at all. For more details regarding a graduate development of this technology kindly see the following papers \([1, 2, 3, 4]\). An existence of this technology was already acknowledged by major international specialists in their overview paper dedicated to inertial fusion \([5]\). It might be interesting to mention that recently a different
phase conjugation based beam steering technology started to be studied by another group. In their approach the laser beam-steering mechanism is controlled by a four-wave mixing process [6].

Principles of SBS PCM self-navigation technology is schematically illustrated in Fig. 1.

**Figure 1.** A scheme of one laser channel during three different stages of its operation [4]

A) When the injected pellet is approaching its best interaction position, a low energy seeding laser pulse (glint - red line) is sent to illuminate the pellet.

B) Reflected seeding laser pulse is collected by the focusing optics and amplified on its way to SBS PCM cell. Its energy is below threshold thus no higher harmonic conversion occurs.

C) Amplified pulse is reflected by SBS PCM cell, amplified again on its return, major part of its energy (now above the threshold) is converted to higher harmonic (blue line) and automatically aimed at the moving pellet by the target (pellet) displacement compensation system (TDC) for its final high power irradiation. The unconverted part is removed from the system by a specially designed Faraday insulator (red line).

In order to ensure a sufficient symmetry of the final high energy irradiation of the injected pellet, it seems unavoidable that the pellet would have to be, at first, illuminated by many low energy laser beams (glints) from many directions as well. In an ideal case using the same number of glints as it would be the number of the high energy beams. Therefore, the resulting light on any of these entrance windows (on its way out) would consist of contributions created by reflections of many glints from the pellet (approximately one half of their total number), which would superimpose. A crucial question thus arises: would the characteristics of the collected light be suitable for its amplification and PCM reflection? Providing some light to this question is the main purpose of this paper.

2. Model, calculations and results

Geometry in which the problem was studied is similar to (at least some) NIF parameters. The target chamber was assumed spherical with 10 m in diameter. The pellet was a 100 % reflective sphere 4 mm in diameter positioned exactly in the center of the target chamber. The light reflected from the pellet was superimposed on the plane outside the target chamber were the final optics would be placed. The selected distance from the center of the target chamber
was in our calculations set to 10 m. Every collecting area was a square 400 x 400 mm (this particular shape was selected only to simplify the calculations). The laser beam (glint) cross-section was a square (not particularly important), aimed at the center of the chamber, wide enough to illuminate the whole pellet. In practice, for safety reasons, it would be wise (unless some specific care taken using other means) to distribute the windows in such a way that no laser light (not reflected by the pellet) could be fired directly into another window. A proper positioning of collecting areas (depending on their number) was dealt with by a special software developed for this purpose. Collecting areas were not considered flat for the calculation, but spherically curved due to the fact that behind every such area there has to be a lens to make the beam parallel.

As for the SBS PCM reflection the most suitable polarization of the incoming light is linear, a need for having polarizers in the beam line arises. A simple way to ensure the amplitude of the reflected glint would always stay the same, and yet the light would remain linearly polarized after it has been collected, is to use a circularly polarized light for the glints.

Due to the fact that analytical solutions for the phase and the amplitude (intensity) would be difficult to find even in the most simplified scenarios, and because it would be beneficial that the same approach could be used to analyze even more complicated scenarios later on (narrow beam, non-spherical target displaced from the center of the target chamber etc.), a numerical model based on Monte Carlo simulations was developed. Its principle is rather a simple one. A random ray from the beam is selected and followed to the target. If the target is hit, the ray is reflected according to the law of reflection and followed to the collecting area. Provided this area is hit as well, all necessary parameters are calculated and saved. This is repeated until enough rays hit the collecting area. Parameters that have to be calculated are the path traveled by the rays before hitting the collecting area (to calculate the phase) and the amplitude. The amplitude of the ray would normally stay unchanged (total reflection), but as it would eventually pass through a polarizer behind the collecting area (final optics), its orientation must be taken into account (not needed for the circularly polarized glints).

It is relatively easy to calculate the path traveled by every ray that hits the selected collecting area. However, working this way means we only know the traveled path in the points that were actually hit. And these are essentially randomly scattered. It is necessary to divide the collecting area into a regular grid, and calculate the traveled path (and any other quantity that might be needed) on this grid. Typically 10 million randomly selected rays were tested for every collecting area, and the rays that actually hit that area were counted. Subsequently, contributions from individual glints were superimposed over the whole grid one by one using the following formulae:

\[
E = \sqrt{E_1^2 + E_2^2 + 2E_1E_2 \cos(\alpha_2 - \alpha_1)}
\]

\[
\tan \alpha = \frac{E_1 \sin \alpha_1 + E_2 \sin \alpha_2}{E_1 \cos \alpha_1 + E_2 \cos \alpha_2}
\]

Here \(E\) and \(\alpha\) are the amplitude and the phase of the resulting wave and \(E_1, E_2, \alpha_1, \alpha_2\) are amplitudes and phases of the two interfering waves (in a given point).

Due to space limitation only a very brief description was provided. For details kindly see [7].

3. Conclusions

As it was found (see Fig. 2), the amplitude of the light after superposition changes rapidly across the collecting area (and its quick variations are present regardless of the number of beams used). In order to verify whether the proposed self-navigation technology can work, further research needs to be done in order to find out how would the collected light behave in amplifiers, whether the resulting beam would be able to reflect successfully on the phase conjugating mirror, and whether the phase and the amplitude structure of the light after its
Figure 2. Amplitude structure in the collecting area after illuminating the pellet with 400 beams (expressed as a ratio to the amplitude of one beam only).

SBS PCM reflection would be good enough for the beam to compress the target. It seems likely that the amplitude structure (as well as the phase - not shown here) might pose an issue during these steps, and methods will have to be looked for to make the parameters of the laser driver more even. The most promising scenario seems to be when every driver beam line could work with just one (directly backwards) reflection (as illustrated in Fig. 1). However, such scenario might not be easy to realize in practice. It should be also noted that all the calculations were done in geometrical optics approximation. Thus reality might not be so unfavorable after all. But under any circumstances our findings might attract some attention to this particular issue.

Acknowledgments
On the Czech side funding from MSM 6840770039, RVO 68407700 is gratefully acknowledged. On the Korean side this work was supported by "Dual Use Technology Program" at Agency for Defense Development (ADD) of the Republic of Korea (UM12012RD1) and by the National R&D Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Education, Science and Technology (2013-036083).

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