Current status of the SBS PCM approach to self-navigation of lasers on injected IFE pellets

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Abstract. Current status of SBS PCM based IFE approach proposed recently as an alternative to the IFE classical approach is presented. This technology is of particular importance to the direct drive scheme taking care of automatic self-navigation of every individual laser beam on the injected pellets with no need for any final optics adjustment. Conceptual design of one typical laser driver is shown and its features discussed. In comparison with the earlier design an upgraded scheme was developed with the low energy illumination laser beam (glint) entering the reactor chamber through the same entrance window as used by the corresponding high energy irradiation laser beam. Results of experimental verification of this improved design are reported. In these experiments for the first time a complete setup including the pellet (realized by the static steel ball) was employed. The pellet survival conditions in the period between its low energy illumination and subsequent high energy irradiation were studied and the upper limits on the allowed energies absorbed were found for both DD and DT fuels.

1. Introduction
One of the very difficult challenges to deal with in the direct drive inertial fusion energy (IFE) integrated approach is connected with the need of simultaneous irradiation of thermonuclear pellets by many dozens of powerful laser beams inside the reactor chamber. Sophisticated tracking of injected pellets’ trajectories is necessary for prediction of the place most suitable for interaction with the driver beams in order to achieve necessary irradiation symmetry and subsequent fuel compression. For the direct drive scheme the following set of parameters is being currently considered: pellets ~ 4 mm in diameter should be delivered into the virtual sphere ~ 5 mm in diameter located around the center of the reactor chamber ~ 10 m in diameter. Combined precision of tracking and aiming should be ~ 20 μm. Navigation technologies developed so far (despite their gradual progress) are still well outside of the required margin even in the case of evacuated reactor chambers - as some time consuming adjustment of heavy final optics for every shot and every laser beam is always necessary. This last fact is also partially
responsible for the very tight margin (±500 µm) on the pellets successful delivery into the above mentioned virtual sphere. This value was prescribed among other reasons in order to minimize the necessary final optics adjustment.

In reality there are some additional serious obstacles further complicating this direct drive IFE scheme - even putting in doubts its practical feasibility. Among the most serious ones is the insufficient predictability of the injected pellets’ trajectories resulting from their expected interaction with remnants of previous fusion explosions due to the considered 5÷10 Hz repetition rate. This might be one of the reasons why the indirect drive scheme seems to be currently considered a more serious IFE candidate as the corresponding hohlraum targets are by three orders of magnitude heavier compared to their direct drive counterparts thus allowing for much more reliable prediction of their trajectories.

In order to deal with these direct drive IFE scheme laser navigation difficulties a new approach was recently proposed employing the stimulated Brillouin scattering (SBS) phase conjugating mirror (PCM) technique [1, 2]. In the first public presentation of this novel approach [3] it was predicted that a fully automatic self-aiming of every individual laser beam on the injected pellets with no need for any final optics adjustment could be achieved. This idea was undergoing gradual improvement in its theoretical design [4]–[6] and subsequently it started to be tested also experimentally proving the principle [7, 8].

2. SBS PCM based IFE approach - Current Design

Current design of this approach is illustrated in the Fig. 1 where one particular laser channel is displayed during the three distinct stages of its functioning:

![Figure 1](image_url)

**Figure 1.** Three distinct stages of every individual laser channel functioning.

A) at the right moment (determined by careful tracking) 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 the SBS PCM cell; C) amplified pulse is reflected by the SBS PCM cell, amplified once again, converted to higher harmonic (blue line) and automatically aimed at the moving pellet by the target displacement compensation system (TDC) for its final high power irradiation. TDC is a completely passive system having its optical components appropriately designed for every individual channel taking advantage of their index of refraction dependence on the wavelength.
Typical displacements for the pellet injection speeds 100 m/s and 1 µs delay times corresponding to 300 m distance traveled by the laser beam outside the reactor chamber would be 100 µm. It should be noted that in comparison with the previous design presented in Ref. [4] the new scheme of illumination was developed with the seeding laser beam entering the reactor chamber through the same entrance window as used by the corresponding irradiation beam.

This SBS PCM based IFE approach has several important advantages over the classical one. Even if the injected pellets will inevitably reach for every shot slightly different (and difficult to predict with the accuracy required) positions within the prescribed area, their subsequent displacement from the position in which they will be illuminated into the position in which they will be irradiated should always be the same (provided, of course, that the injection speed will not vary substantially from shot to shot). Therefore, optical elements especially designed for taking care of every individual beam shift can be introduced once for all. Featuring no moving parts this technique can significantly simplify design of lasers and beam transport optics allowing for substantial increase in the number of laser beams employed. Every laser beam can operate as an independent sub-beam with much lower energy per pulse thus making the required repetition rate easier to achieve. With many laser beams available any shape of the final irradiating pulse can be realized by considering neighboring sub-beams as creating a required pulse shape when combined together on the pellet surface using different delays and amplifications of individual sub-beams. More details concerning these issues as well as the illuminating and irradiating schemes can be found in Ref. [5].

3. SBS PCM based IFE approach - Experimental Verification

Schematics of the experimental setup used for verification of the proposed design is shown in the Fig. 2.

Figure 2. AMP - amplifier, CCD - CCD camera, CL - collecting lens, DW - dispersion wedge, FI - Faraday isolator, FR - Faraday rotator, KTP - KTP crystal, LAS - laser, PBS - polarizing beamsplitter, SB - steel ball, T - telescope 4x, W - wedge

Compared to the successful experiments performed earlier [7, 8] which confirmed the self-navigation principle (the change of the trajectory achieved by the incorporated conversion to the second harmonic - green line) in these new experiments the complete individual laser channel setup was assembled - including the pellet realized by the static steel ball. It should be noted that during these tests the laser channel was operating with much lower energies compared to the real ones (so far just below 1 J before irradiating the target). Combining description of the Fig. 1 with the Fig. 2 and its captions the results presented above should be self-explanatory.
4. Concluding remarks

In this paper an important upgrade to the IFE scheme employing SBS PCM approach was presented and results from experiments proving the principle of self-navigation of lasers on injected pellets were reported. In these experiments the complete laser channel setup already containing all basic components was used - including pellets realized at this stage of development by stationary steel balls. These were deliberately chosen as capable to withstand much higher illumination energies compared to the real pellets. The higher illumination energies became necessary due to the insufficient amplification available in the laser channel (with only two amplifiers employed).

In this context the injected pellet survival conditions in the period between its low energy illumination and subsequent high energy irradiation were studied. The upper limits on the illumination energies to be used in real experiments for currently considered direct drive pellets (4 mm in diameter, 45 µm thick polystyrene shell, 200 µm thick fuel layer) were calculated. It was found that the absorbed energy which leads to the cryogenic layer temperature increase by 1 K (from 17 K to 18 K) in the area of cryolayer/shell wall contact during 1 µs is \( \sim 6 \) mJ in the case of \( DD \) and \( \sim 14 \) mJ in the case of \( DT \). Knowledge of these energies is crucial for proper design of individual laser channels - in particular their total amplification needed for high quality SBS PCM reflection to take place. The energies found are about ten times higher than those tentatively estimated in our very first laser channel design [7]. This is by all means the move in the right direction.

Encouraged by all these findings a new round of experiments is under preparation when the pellets (still substituted by the steel balls) would be already moving with the speed comparable to that used during the IFE injection.

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