Self-Navigation of Laser Drivers on Injected IFE Direct Drive Pellets

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Abstract. Current status of *stimulated Brillouin scattering* (*SBS) phase conjugating mirror (PCM)* based *inertial fusion energy (IFE)* approach proposed recently as an alternative to the IFE *classical* approach is presented. This technology is of a particular importance to the *direct drive* scheme taking care of *automatic self-navigation* of every individual laser beam on the injected pellets without *any need* for final optics *adjustments*. An upgraded scheme was developed with a low energy *illumination* laser beam (glint) entering the reactor chamber through the *same* entrance window as used subsequently by the corresponding high energy *irradiation* laser beam. Experimental verification of this improved design was performed using a *complete* setup including a pellet - at this stage realized by a static steel ball of 4 mm in diameter. The pellet survival conditions between its low energy *illumination* and high energy *irradiation* were studied and the *upper limits* on the allowed energies absorbed for both *DD* and *DT* fuels were determined.

1. Introduction

One of very difficult challenges to deal with in the *direct* drive IFE integrated approach is connected with the need of *simultaneous irradiation* of injected pellets with thermonuclear fuel inside the reactor chamber by many dozens (or even hundreds) of powerful laser beams. 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 of ~ 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 outside the required margin even in the case of fully *evacuated* reactor chambers - as some time consuming adjustment of heavy *final optics* for every shot and every laser beam is always necessary. This fact is also partially responsible for a rather tight margin (~ 500 µm) on the pellets successful delivery into the above mentioned virtual sphere.

In reality there are even more serious obstacles further complicating this direct drive IFE scheme - putting its practical feasibility *in doubts*. 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 as a more serious IFE candidate - having the corresponding *hohlraum* targets 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 laser navigation difficulties a new approach was recently proposed employing the SBS PCM technique [1, 2]. In the first presentation of this approach [3] it was predicted that a *fully automatic self-navigation* of every individual laser beam on injected pellets with no need for any final optics adjustment could be developed. As an important byproduct, a higher number of less energetic (thus easier to design) laser drivers could be employed. This idea was undergoing a gradual improvement in its theoretical design [4-6] and subsequently it started to be tested also experimentally - proving the principle [7, 8].

The SBS PCM based IFE approach has one *crucial* advantage over the *classical* one: even if the pellets will inevitably reach for every injection slightly *different* (and difficult to *predict* with the *accuracy* required) position within the prescribed area (if missed the shot will be declared as unsuccessful), their subsequent *displacement* from the position in which they will be *illuminated* by low energy lasers (glint) into the position in which they will be *irradiated* by high energy laser drivers would always be the *same* (provided, that the *injection* speed will not vary substantially from shot to shot). For the pellet injection speeds ~ 100 m/s (in practice they might be several timer higher) and 1 μs delay times corresponding to 300 m distance traveled by each laser beam outside the reactor chamber (to reserve enough room for a large number of laser drivers), typical *displacements* between *illumination* and *irradiation* events would be ~ 100 μm (or longer in case of higher injection speeds).

2. SBS PCM Based IFE Approach - Current Design

The *current design* of the SBS PCM approach to the *direct* drive IFE is outlined in the Fig. 1 where one particular laser channel is displayed during the *three distinct stages* of its operation.

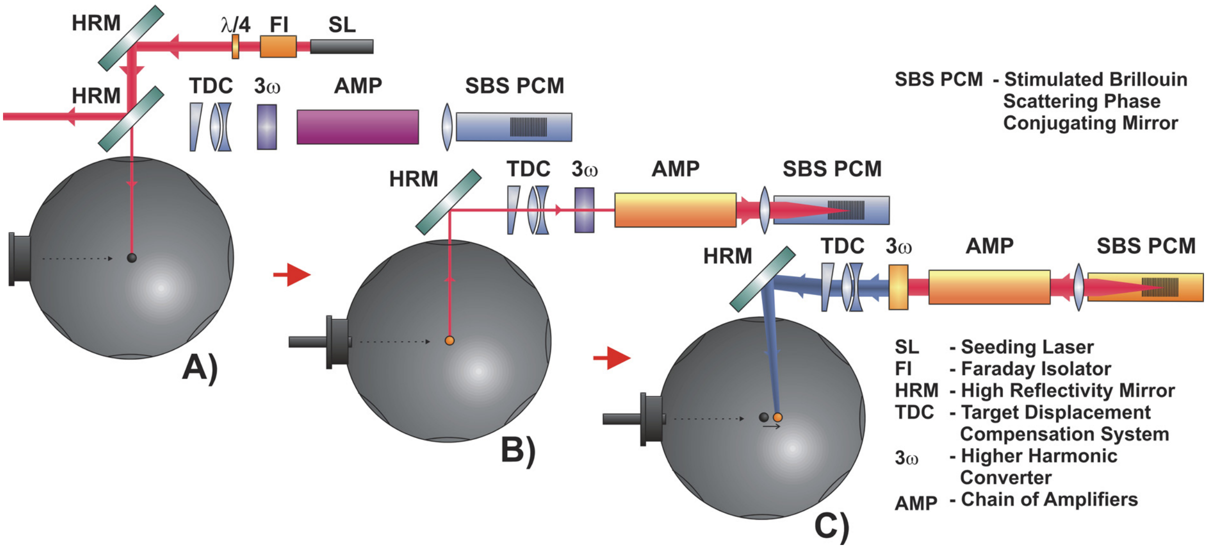


Fig. 1. Three distinct stages of one laser driver channel functioning based on SBS PCM approach.

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. Reflected seeding laser pulse is collected by the focusing optics and amplified on its way to the SBS PCM cell. 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 laser driver channel taking advantage of their index of refraction dependence on the wavelength.

It should be noted that in comparison with the previous design presented originally in Ref. [4] the seeding laser beam is now entering the reactor chamber through the *same* entrance window as used by the corresponding *irradiation* beam, thus increasing the chamber robustness.

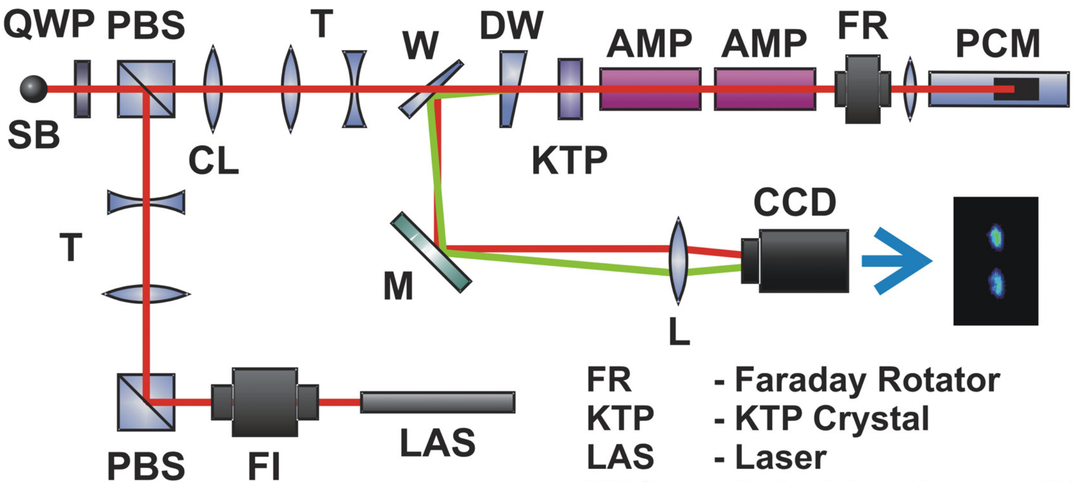
In order to avoid any need for seeding lasers different aiming from shot to shot two scenarios could come into consideration: *(i)* using the seeding laser spot size sufficiently *smaller* than the pellet diameter (say ~ 2 mm) to make sure that in the case of acceptable delivery the whole laser spot will always fit on the pellet surface; *(ii)* using the seeding laser spot size sufficiently *larger* than the pellet diameter. Care should be taken in preventing any part of the laser light (which would not hit the pellet surface) to enter (propagate through) some of the amplifiers. In this geometry the *collection* angle of the low power first harmonic (*illumination* stage) and the high power higher harmonic *focusing* on the pellet (*irradiation* stage) can be designed as *fully independent*. In both scenarios there is no need to move the seeding lasers aiming optics at all. And should it be the case after all, this would be done on a very low level of laser energies, thus working with reasonably small (and light) mirrors compared to the standard approach.

In this self-navigating illumination/irradiation concept the *optical elements* taking care of each particular laser beam *shift* can be especially designed once for all. Featuring *no moving parts* (at least on the *high power* side) this technique can significantly *simplify* design of lasers and the 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].

In designing individual laser drivers several *key parameters* need to be taken into consideration*: (i)* to keep the energy of initial *illumination* of the injected pellet *low enough* to ensure that *no harm* (e.g. preheating) would be done to the pellet itself, *(ii) amplification* achieved by the chain of amplifiers would be *sufficient* to bring the energy of the pulse to the level ~ 1 J before entering the SBS PCM cell (this particular value was selected to ensure that the actual SBS PCM reflection will be performed for the energy values with low dependence of the *reflection coefficient* on the incident energy in order to minimize the energy *fluctuation*), *(iii)* the *final energy* of the pulse for the pellet *irradiation* would be ~ 1 kJ (this effectively assumes ~ 1000 individual channels). As an important parameter to be also taken into consideration is the *energy extraction efficiency* from individual amplifiers. One such (very preliminary) design of the channel can be found in [9] (se also Ref. [8]).

3. SBS PCM Based IFE Approach - Experimental Verification

In order to test this SBS PCM approach to IFE a new series of experiments was performed. A diagram of the experimental setup used for verification of the proposed design is shown in the Fig. 2. 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 a *complete* individual laser channel setup was assembled - including the *pellets* realized by the static *steel balls* 4 mm in diameter [10]. This kind of pellets was deliberately chosen as capable to withstand much *higher illumination energies* compared to the real ones as the higher illumination energies became necessary due to the *insufficient amplification* available in the laser channel (with only two amplifiers employed). It should be noted that during these tests the laser channel was operating with much *lower* energies compared to the real ones (just below 1 J after amplification and frequency conversion).



AMP - **Amplifier**
CCD - **CCD Camera**
CL - **Collecting Lens**
DW - **Dispersion Wedge 3°**
FI - **Faraday Isolator**
FR - **Faraday Rotator**
KTP - **KTP Crystal**
LAS - **Laser**
PBS - **Polarizing Beamsplitter**
PCM - **Phase Conjug. Mirror**
QWP - **Quarter Wave Plate**
SB - **Steel Ball**
T - **Telescope 4x**
W - **Wedge**

Fig. 2. Schematics of the experimental setup used for verification of the SBS PCM approach to IFE. As the steel ball was stationary the amplified beam was on its way back to the target deflected in order to verify the displacement feature of the scheme.

Temperature Increase	**Energy Absorbed**	**Energy Absorbed**
ΔT (K)	**D2 (mJ)**	**DT (mJ)**
0.1	0,45	0,68
0.2	0,94	1,52
0.3	1,48	2,54
0.4	2,05	3,72
0.5	2,66	5,08
0.6	3,28	6,58
0.7	3,94	8,19
0.8	4,62	9,95
0.9	5,33	11,86
1.0	**6,03**	**13,82**

Table 1. Graphs of the pellet cryogenic layer temperature increase in the area of the cryolayer/shell wall contact during 1 µs as a result of the amount of the energy absorbed through illumination.

In this context the injected pellet *survival conditions* in the period between its low energy *illumination* and subsequent high energy *irradiation* were also studied. The upper limits on the acceptable amount of energy *absorbed* during the *illumination* stage for the direct drive pellets with parameters close to those currently considered (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 ~ 6 mJ in the case of DD and ~ 14 mJ in the case of DT (see Table 1). Knowledge of these energies is *crucial* for a proper design of individual laser channels - in particular their *total amplification* needed for high quality SBS PCM reflection. The acceptable energies obtained are about *ten times higher* than those conservatively estimated in our very first laser channel design [8, 9].

Acknowledgements

This work was supported by the International Atomic Energy Agency (IAEA) as a part of the coordinated research project “Pathway to Energy from Inertial Fusion – An Integrated Approach” (Research Contracts No. 13781 & 13758); by the Ministry of Education, Youth, and Sports of the Czech Republic Research Project LC528 & by the grant KONTAKT No. ME933. It was also supported by the Nuclear Research & Development Program of the Korea Science and Engineering Foundation (KOSEF) grant funded by the Korean Government (MEST) - grant code: M20090078160 and by R&D Program through the National Fusion Research Institute of Korea (NFRI) funded by the Ministry of Education, Science and Technology.

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