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# Long term stabilization of the beam combination laser with a phase controlled stimulated Brillouin scattering phase conjugation mirrors for the laser fusion driver

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**Abstract**

Laser fusion requires very high energy/power output with high repetition rate over 10 Hz, which is very difficult with the current laser technologies. However, the recent research work on the phase controlling of the stimulated Brillouin scattering wave enables the realization of this kind of laser fusion driver. The recent progress of controlling the phase has been successfully demonstrated by the self-generated density modulation method proposed by one of the authors (Kong). Nevertheless, it showed a long-term fluctuation of the phase because of the long-term fluctuation of the density of the SBS medium due to the thermal fluctuation. This long-term thermal fluctuation is inevitable a fact in nature. The authors used a specially designed stabilizing system for the phase controlling system, which has the PZT control of the mirror for phase controlling SBS-PCM (the so-called feedback mirror). This system stabilizes the phase controlling system very well for more than 1 h. This technique will help the laser fusion driver to be realized sooner than expected. In addition, we propose a similar scheme to be applied to the ultra-fast pulse laser system, which must operate at high repetition rate for the laser fusion energy power plant.

**Keywords:** Beam combination; High power laser; Laser fusion; Long-term stabilization; Phase conjugate mirror; Stimulated Brillouin scattering

## 1. INTRODUCTION

High power laser development is essential for various laser applications like high energy density physics (Hoffmann *et al*., 2005; Tahir *et al*., 2004), laboratory astrophysics (Gonzales *et al*., 2006), and basic issues of inertial fusion. Laser fusion requires very high energy/power output with a high repetition rate over 10 Hz (Atzeni & Meyer-Ter-Vehn, 2004; Nakai & Mima, 2004). However, the laser facilities NHELIX (Schaumann *et al*., 2005), PHELIX (Neumayer *et al*., 2005), PALS (Jungwirth, 2005), and the Vulcan Petawatt (Danson *et al*., 2005) are just some examples of laser systems that have limitations on the output power, and limitations on the repetition rate due to a thermal problem. To resolve the thermal problem in the solid-state laser system, many researchers have developed their own techniques. Among those techniques, the beam combination technique using stimulated Brillouin scattering phase conjugate mirrors (SBS-PCMs) as proposed by Kong *et al*. (1997, 2001) is the most promising, because the output energy of this laser system can be unlimitedly scaled-up by increasing the number of separate amplifiers. In addition, SBS-PCM gives the phase-conjugated wave (Zel'dovich *et al*., 1972) that can compensate for any optical distortions occurring in the amplifier chain for the best beam quality. Figure 1 shows the schematic diagram of the new beam combination technique as developed by the authors.

Beam combination technique using SBS-PCM, which is to control the phases of the beams to be combined. SBS-PCM reflects the SBS wave within the random phase. For the phase controlling the beam combination with SBS-PCM, there are several different techniques developed. Among those techniques, the self-phase-controlling SBS-PCMs (SFC-SBS-PCM) as proposed by Kong *et al*. (2005*b*, 2005*c*, 2005*d*) is the most favorable, since it is applicable to the unlimited number of beams, and is the most simple among the techniques developed. By employing the phase control technique using a weak density modulation, we have stabi-

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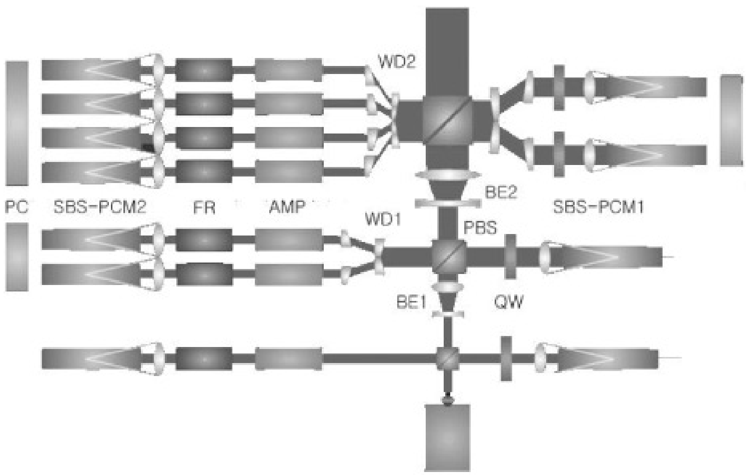


**Fig. 1.** Scalable beam combination system with the wave-front dividing: PC; phase controller, AMP; amplifier, FR; Faraday rotator, WD1 and WD2; wave-front dividers, BE1 and BE2; beam expanders, PBS; polarizing beam splitter, QW; quarter wave plate.

lized the relative phase difference remarkably to the standard deviation of $\lambda/36(0.028\lambda)$. Figure 2 shows the relative phase difference controlled by SFC-SBS-PCM (Lee *et al.*, 2005*a*).

## 2. EXPERIMENT

Using the self-phase control technique, we have succeeded in controlling the phase of a SBS wave. However, the phase showed a long-term fluctuation due to the density fluctuation by the thermal convection of the liquid SBS medium, which is due to the absorption of the laser energy by the SBS medium.

Figure 3 shows the long-term fluctuation of the output energy and the phase difference of the two-beam combination system for 100 s for the case of $E_{p1,2} \cong 10$ mJ. Since the beam energy reflected by each SBS cell is almost constant (fluctuation of 1.89% and 1.98%, respectively), we can think that the long-term energy fluctuation is originated from the phase fluctuation by thermal convection of the SBS medium. We have stabilized this fluctuation by actively controlling the feedback mirror that was installed for the self-density modulation.

Figure 4 represents the experimental set-up for the long-term phase control of SBS-PCMs. A 1064 nm Nd:YAG oscillator with a bandwidth of ~120 MHz was used for the pump. The pulse width was 8 ns and the repetition rate was 10 Hz. The output from the oscillator is divided into two beams by a polarizing beam splitter (PBS). Both beams are reflected by each SBS-PCM with the concave mirrors for controlling phase. We have used Fluorinert FC-75 as a SBS medium (Yoshida *et al.*, 1997). The length of the SBS cell was 50 cm and the focal length of the concave mirror was −25 cm. Both reflected beams pass through PBS and are divided into two output signals by a wedge. The output beam passing through the quarter wave plate (QWP), experiences the phase changing by $\pi/2$. Therefore, the output energy measured by D1 ($I_{D1}$) and the output energy with phase changed by $\pi/2$ measured by D2 ($I_{D2}$) give us the following expressions,

$$I_{D1} = (I_1 + I_2) + 2\sqrt{I_1 I_2}\, cos\, \Phi$$
$$I_{D2} = (I_1 + I_2) + 2\sqrt{I_1 I_2}\, \sin \Phi, \quad (1)$$

where $I_1$ and $I_2$ is the energy of the SBS beam reflected by SBS cell 1 and cell 2, respectively, and $\Phi$ is the phase differ-

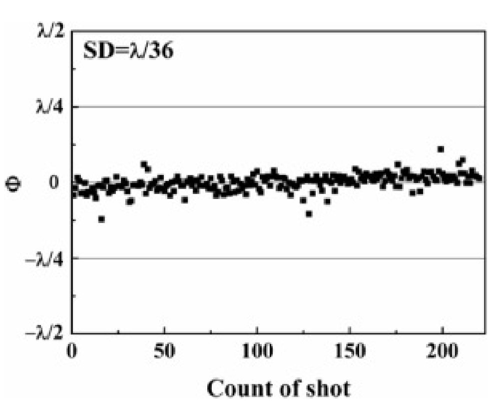


**Fig. 2.** The relative phase difference selected from 220 interference patterns for the cases of both pump energies of 10 mJ ($E_{p1} \cong E_{p2} \cong 10$ mJ).

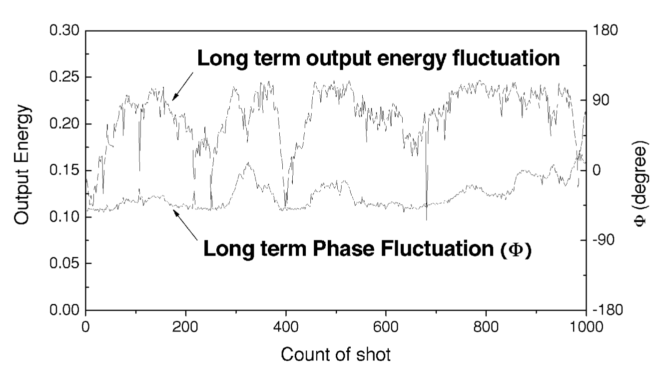


**Fig. 3.** The long-term fluctuation of the output energy (arbitrary unit) and the phase difference of the two beam combination system without active control for 1000 s for the case of 10 mJ pump beam.

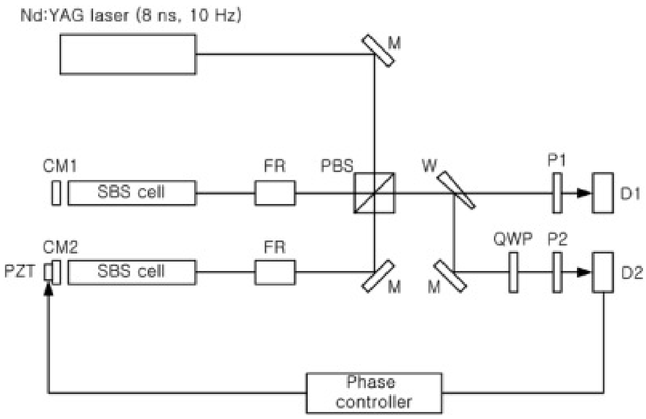


**Fig. 4.** The experimental setup for the long term phase control of SBS-PCMs: M, mirror; PBS, polarizing beam splitter; FR, Faraday rotator; PM1&PM2, feedback mirror; PZT, piezoelectric transducer; W, wedge; P1&P2, polarizer; QWP, quarter wave plate; D1&D2, detector.

ence between the two SBS beams. Therefore, we can make the phase difference zero by maximizing the output energy $I_{D1}$ or controlling the output signal $I_{D2}$ as $I_1 + I_2$ using the feedback system. However, the output energy $I_{D1}$ cannot be used as the feedback signal, since it is impossible to find the sign of the phase variation from the energy variation, cos $\Phi$ is the even function. On the other hand, the output energy $I_{D2}$ can be used as the feedback signal, since the sign of the phase variation can be found from the energy variation, sine is the odd function. Therefore, the output signal with the phase changed by $\pi/2$ ($I_{D2}$) is fed-back to the PZT controlling system of the feedback mirror, for compensating the density variation of the SBS medium.

Figure 5 shows the output energy and phase difference of the two SBS beams controlled by this active controlling system. The result shows a 3.21% long-term energy stability and 0.009 $\lambda$ long-term phase stability of the two 10 mJ beam combination system. This system stabilizes the phase controlling system very well for a long time.

The waveform of the SBS wave is known to be distorted by the SBS intrinsic process (Shen, 1984). The deformation

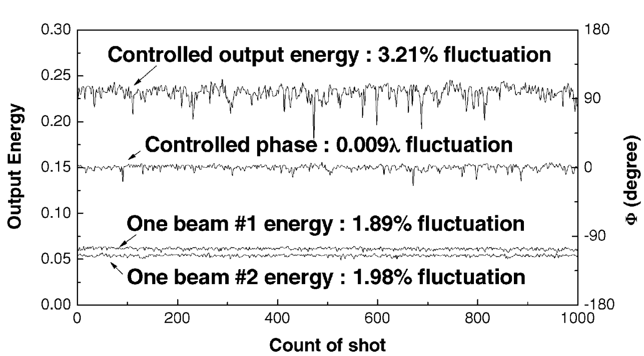


**Fig. 5.** Experimental results for active control of the output energy (arbitrary unit) and the phase difference of two SBS beams (10 mJ pump beams).

of the SBS wave can cause the optical breakdown in the optical components, for it causes a temporal spike in the rising edge (Dane *et al.*, 1992). We have found that the deformation is due to the effect of losing a front part of the pumping energy to create the acoustic Brillouin grating for the SBS process. And the authors expected it will be possible to keep the temporal waveform, if the acoustic grating is generated before the main-pulse enters the SBS interaction region by using the "pre-pulse technique." In this technique, the incident wave is divided into two pulses, the pre- and the main-pulses, and the pre-pulse is sent to the SBS medium before the main-pulse with some delay in time. It has been shown successfully in a previous paper that the main-pulse shape can be well preserved by this method (Kong *et al.*, 2005*a*).

The scheme of the proposed set-up is presented in Figure 6a. Pockels cell (PC) is used for adjusting the proper ratio of the pre- and the main-pulse energies, by adapting high voltage (HV), and HV applies to the PC for the passing time of the incoming pulse through the PC. The PC is in the off state when the pulse returns back. PBS2 and PBS3 reflect the S-polarization and pass the P-polarization. The incident wave is split into two paths after PBS3, path 1 (pre-pulse) and path 2 (main-pulse). The main-pulse cannot pass through path 1, similarly, pre-pulse cannot pass through path 2, and vice versa. The pre-pulse is initially S-polarized and reflected when it reaches PBS2 after the SBS process, because the PC is in the off state when the pulse returns back. The main-pulse which has initially a P-polarization follows the very similar process as the pre-pulse. So it takes the P-polarization to pass through PBS2. But in this experiment, we did not have the PC available, and the set-up of the experimental scheme as shown in Figure 6b for its alternative. We put HWP2 and the Faraday rotator (FR) (45 degree rotator), instead of the PC in this experiment. Figure 6b produces double pulses corresponding to the pre-pulse and the main-pulse. This problem will be resolved if we employ PC as shown in Figure 6a.

Let us define $E_{main}$, $E_{pre}$, and $T_{delay}$ as the energies of the main- and the pre-pulses, and the delay in time between the pre- and the main-pulses, respectively. Figure 7a shows the incident wave, and Figures 7b, 7c, and 7e correspond to the waveforms for delay times of 3 ns, 5 ns, 7 ns, and 10 ns, respectively, with the fixed values of $E_{main}$ = 10 mJ and $E_{pre}$ = 5 mJ. For $T_{delay}$ = 5 ns, the waveform preservation is the best among these conditions.

It has been shown that the pre-pulse technique is quite powerful for preserving the SBS waves. This system can be applied to the beam combination laser system using SBS-PCM.

It is a well-known fact that the pulse width should be longer than the phonon life-time of the SBS medium for the SBS. In addition, we propose a new idea for the fast ignition laser operating at the high repetition rate over 10 Hz by this technique. This self-phase controlling technique can be applied to the ultra-fast pulsed laser system whose pulse width is much lower than the phonon life-time of the SBS

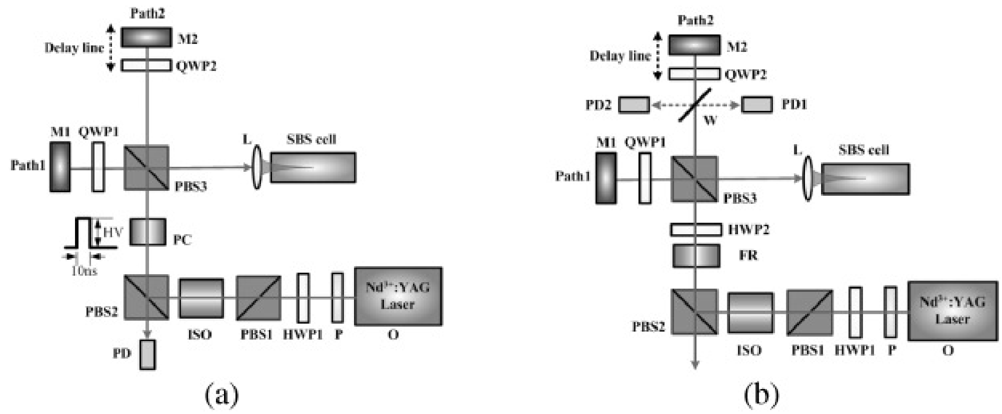


**Fig. 6.** (**a**) The proposed system for preserving a temporal SBS pulse shape, and (**b**) the experimental set-up for this experiment: O, Nd3+:YAG Laser Oscillator; P, linear polarizer; HWPs, half wave plates; PBSs, polarizing beam splitters; ISO, Faraday isolator; FR, Faraday rotator; QWPs, quarter wave plates; PC, Pockels cell; Ms, full mirrors; W, wedge; L, convex lens (f = 15 cm); PDs, photo diodes; SBS cell (FC-75, 30 cm long).

medium, by (1) applying this technique in the chirping stage in the OPCPA stage or (2) applying the pre-pulse technique.

For the first method, we can apply this technique in the chirping stage of OPCPA. For the single-mode pumping regime of the SBS (Lee *et al*., 2005*b*), the line-width of the pumping laser, $\Delta\nu$, is shorter than the Brillouin gain width of the SBS medium, $\Gamma$. Let the threshold of the SBS of the medium be $E_{th}$. If the line-width of the chirped pulse is $\Delta\nu_l$, we can consider the laser spectrum with a bandwidth of $\Gamma$ as a single mode composition. Then, the energy of this composition should be larger than $E_{th}$ for SBS. Therefore, the total pumping energy should be larger than $E_{th}\,(\Delta\nu_l/\Gamma)$, which is the threshold of the chirped pulse. For the FC-75 SBS medium, $E_{th}$ = 3 mJ and $\Gamma$ = 300 MHz. Assuming the spectral width of the chirped pulse as $\Delta\lambda \sim 10$ nm at $\lambda = 1$ $\mu$m for the pulse-width ($\tau_l = 300$ fs), then $\Delta\nu_l \sim 3\times10^{12}$ Hz. The threshold of this chirped pulse is 30 J. For the reflectivity of 50%, we need 100 J pumping energy. For the reflectivity of 80%, we need 500 J pumping energy. For the multi-mode regime ($\Delta\nu > \Gamma$), we can expect the threshold energy to be 3 mJ, and the energy for the reflectivity of 75% to be 30 mJ.

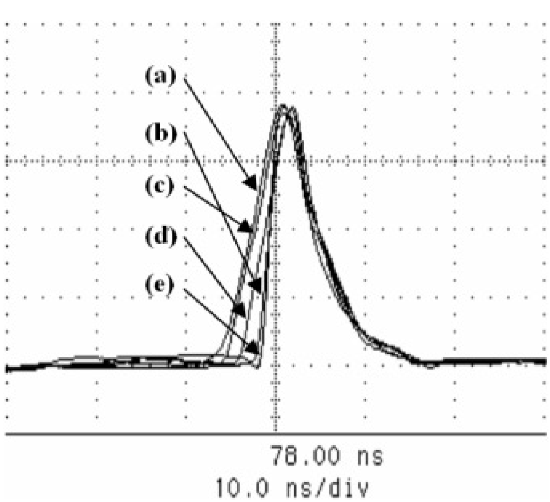


**Fig. 7.** The waveforms of the reflected wave for the delay times: (**a**) Incident wave, (**b**) 3 ns, (**c**) 5 ns, (**d**) 7 ns, and (**e**) 10 ns.

For the pre-pulse technique (Kong *et al*., 2005*a*), the pre-pulse can generate the Brillouin grating, the main-pulse can be reflected by this pre-existing acoustic grating, and can give the SBS wave. We can apply this idea to the ultra-short pulse laser system also. The pre-pulse might generate the acoustic grating during the phonon life-time after the excitation occurred, even if it is much shorter than the phonon life-time. Therefore, we can expect that the main-pulse can interact with the pre-existing grating for the SBS process, if we inject the pre-pulse to generate the acoustic grating (Brillouin grating) prior to the main-pulse.

## 3. CONCLUSION

Using the self-phase control technique, we have succeeded in stabilizing the phases of the SBS waves remarkably to the standard deviation of $\lambda/36$ ($0.028\lambda$). However, SBS phase shows a severe long-term fluctuation due to the density fluctuation by the thermal convection of the liquid SBS medium. Therefore, we stabilized this fluctuation by the active controlling system of the feedback mirror for compensating the density variation of the SBS medium. This system stabilizes the phase controlling system very well for a long period of time at the standard deviation of $0.009\lambda$. This long-term stabilization technique will be useful for the ultra-high power/energy laser operating at high repetition rate, and can be realized for the laser fusion energy. The pre-pulse technique for preserving the pulse shape is very important for the beam combination system that has serial SBS-PCMs, for the rising edge of the SBS wave becomes steeper and steeper every time it experience the SBS reflection. This steep rising edge is dangerous for the optical damage, and this pulse preserving is very important. Together with the pre-pulse technique, this self-phase controlling system can be applied to the real laser fusion driver.

In addition, this self-phase controlling technique can be applied to the ultra-fast pulsed laser system whose pulse width is much lower than the phonon life-time of the SBS medium, by (1) applying this technique in the chirping stage in the OPCPA stage or (2) applying the pre-pulse technique. In the chirping stage, the pulse width should be longer than the phonon life-time of the SBS medium for this technique. For the pre-pulse technique, the pre-pulse can generate the Brillouin grating and the main-pulse can have the SBS process by this pre-existing acoustic grating and can give the SBS wave.

## REFERENCES


Atzeni, S. & Meyer-Ter-Vehn, J. (2004). *The Physics of Inertial Fusion*. New York: Oxford University Press.

Dane, C.B., Neuman, W.A. & Hackel, L.A. (1992). Pulse-shape dependence of stimulated-Brillouin-scattering phase-conjugation fidelity for high input energies. *Opt. Lett.* **17**, 1271.

Danson, C.N., Brummitt, P.A., Clarke, R.J., Collier, I., Fell, B., Frackiewicz, A.J., Hawkes, S., Hernandez-Gomez, C., Holligan, P., Hutchinson, M.H.R., Kidd, A., Lester, W.J., Musgrave, I.O., Neely, D., Neville, D.R., Norreys, P.A., Pepler, D.A., Reason, C., Shaikh, W., Winstone, T.B., Wyatt, R.W.W. & Wyborn, B.E. (2005). Vulcan petawatt: Design, operation and interactions at $5 \times 10^{20}$ $Wcm^{-2}$. *Laser Part. Beams* **23**, 87–93.

Gonzales, M., Stehle, C., Audit, E., Busquet, M., Rus, B., Thais, F., Acef, O., Barroso, P., Bar-Shalom, A., Baudin, D., Kozlova, M., Lery, T., Madouri, A., Mocek, T. & Polan, J. (2006). Astrophysical radiative shocks: from modelling to laboratory astrophysics. *Laser Part. Beams* **24** (in press).

Hoffmann, D.H.H., Blazevic, A., Ni, P., Rosmej, O., Roth, M., Tahir, NA., Tauschwitz, A., Udrea, S., Varentsov, D., Weyrich, K. & Maron, Y. (2005). Present and future perspectives for high energy density physics with intense heavy ion and laser beams. *Laser Part. Beams* **23**, 47–53.

Jungwirth, K. (2005). Recent highlights of the PALS research program. *Laser Part. Beams* **23**, 177–182

Kong, H.J., Baek, D.H., Lee, S.K. & Lee, D.W. (2005*a*). Waveform preservation of the backscattered stimulated Brillouin scattering wave by using a prepulse injection. *Opt. Lett.* **30**, 3401.

Kong, H.J., Lee, J.Y., Shin, Y.S., Byun, J.O., Park, H.S. & Kim, H. (1997). Beam recombination characteristics in array laser amplification using stimulated Brillouin scattering phase conjugation. *Opt. Rev.* **4**, 277.

Kong, H.J., Lee, S.K., Kim, J.J., Kang, Y.G. & Kim, H. (2001). A cross type double pass laser amplifier with two symmetric phase conjugation mirrors using stimulated Brillouin scattering. *Chinese J. Lasers* **B10**, I5–I9.

Kong, H.J., Lee, S.K. & Lee, D.W. (2005*b*). Beam combined laser fusion driver with high power and high repetition rate using stimulated Brillouin scattering phase conjugation mirrors and self-phase-locking. *Laser Part. Beams* **23**, 55.

Kong, H.J., Lee, S.K. & Lee, D.W. (2005*c*). Highly repetitive high energy/power beam combination laser: IFE laser driver using independent phase control of stimulated Brillouin scattering phase conjugate mirrors and pre-pulse technique. *Laser Part. Beams* **23**, 107.

Kong, H.J., Lee, S.K., Lee, D.W. & Guo, H. (2005*d*). Phase control of a stimulated Brillouin scattering phase conjugate mirror. *Appl. Phys. Lett.* **86**, 051111.

Lee, S.K., Kong, H.J. & Nakatsuka, M. (2005*a*). Great improvement of phase control of the entirely independent stimulated Brillouin scattering phase conjugate mirrors by balancing the pump energies. *Appl. Phys. Lett.* **87**, 161109.

Lee, S.K., Lee, D.W. & Kong, H.J. (2005*b*). Stimulated Brillouin scattering by multi-mode pump with a large number of longitudinal modes. *JKPS* **46**, 443.

Nakai, S. & Mima, K. (2004). Laser driven inertial fusion energy: Present and prospective. *Rpt. Prog. Phys.* **67**, 321.

Neumayer, P., Bock, R., Borneis, S., Brambrink, E., Brand, H., Caird, J., Campbell, E.M., Gaul, E., Goette, S., Haefner, C., Hahn, T., Heuck, H.M., Hoffmann, D.H.H., Javorkova, D., Kluge, H.J., Kuehl, T., Kunzer, S., Merz, T., Onkels, E., Perry, M.D., Reemts, D., Roth, M., Samek, S., Schaumann, G., Schrader, F., Seelig, W., Tauschwitz, A., Thiel, R., Ursescu, D., Wiewior, P., Wittrock, U. & Zielbauer, B. (2005). Status of PHELIX laser and first experiments. *Laser Part. Beams* **23**, 385–389.

Schaumann, G., Schollmeier, M.S., Rodriguez-Prieto, G., Blazevic, A., Brambrink, E., Geissel, M., Korostiy, S., Pirzadeh, P., Roth, M., Rosmej, F.B., Faenov, A.Y., Pikuz, T.A., Tsigutkin, K., Maron, Y., Tahir, N.A. & Hoffmann, D.H.H. (2005). High energy heavy ion jets emerging from laser plasma generated by long pulse laser beams from the NHELIX laser system at GSI. *Laser Part. Beams* **23**, 503–512.

Shen, Y.R. (1984). *The Principles of Nonlinear Optics*. New York: John Wiley & Sons.

Tahir, N.A., Udrea, S., Deutsch, C., Fortov, V.E., Grandjouan, G., Gryaznov, V., Hoffmann, D.H.H., Hulsmann, P., Kirk, M., Lomonosov, I.V., Piriz, A.R., Shutov, A., Spiller, P., Temporal, M. & Varentsov, D. (2004). Target heating in high-energy-density matter experiments at the proposed GSI FAIR facility: Non-linear bunch rotation in SIS 100 and optimization of spot size and pulse length. *Laser Part. Beams* **22**, 485–493

Yoshida, H., Kmetik, V., Fujita, H., Nakatsuka, M., Yamanaka, T. & Yoshida, K. (1997). Heavy fluorocarbon liquids for a phase-conjugated stimulated Brillouin scattering mirror. *Appl. Opt.* **36**, 3739.

Zel'dovich, B.Ya., Popovichev, V.I., Ragul'skii, V.V. & Faizyllov, F.S. (1972). Connection between the wave fronts of the reflected and exciting light in stimulated Mandel'shtam-Brillouin scattering. *Soviet Phys. JETP Lett.* **15**, 109.