Development of a Prototype YAG Laser Amplifier for the Edge Thomson Scattering System in ITER

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Design of a high average power Nd:YAG laser system and a prototype laser amplifier for the edge Thomson scattering system in ITER was conducted. The target performance is 5 J of output energy and a repetition rate of 100 Hz for the laser system, and 1.6 J of extracted energy for the prototype amplifier. A prototype amplifier was produced, after which the small signal gain and extracted energy reached up to 12.6 and 1.76 J, respectively.

Keywords: ITER, Thomson scattering, YAG laser, laser amplifier, SBS phase conjugate mirror, Lateral depumping, Sm doped glass

1. Introduction

The edge Thomson scattering system for ITER [1] is a diagnostic system which measures electron temperature (T_e) and density (n_e) at the peripheral region of the plasma. Required measurement ranges for the electron temperature and density are 50 eV < T_e < 10 keV and $5\times10^{18} < n_e < 3\times10^{20}$ m^{-3}, respectively. The spatial and temporal resolutions are 5 mm and 10 ms (period of lasing), respectively [2]. The required measurement area recently was changed from r/a > 0.9 to r/a > 0.85 [2]. A high-energy (5 J) and high repetition-rate (100 Hz) Q-switch Nd:YAG laser system is necessary to satisfy these measurement requirements [3]. Generally, it has been difficult so far to develop a high-energy, high repetition-rate laser system for the following reasons: (1) limitation in laser energy due to the thermal lensing effect of the laser rod; (2) a decrease in laser energy through depolarization caused by thermally induced birefringence in the laser rod; and (3) a decrease in laser energy due to parasitic oscillation. Recently, a high-energy, high repetition-rate laser system for Thomson scattering diagnostics was developed by utilizing a stimulated Brillouin-scattering phase conjugate mirror (SBS-PCM)[4] in the JT-60U [5]. The SBS-PCM effectively compensated for and suppressed the above effects, and the laser system in JT-60U thus far has achieved an output energy level of 7.46 J at a 50-Hz repetition rate.

We have been developing a high-energy, high repetition-rate laser system for the edge Thomson scattering system in ITER. The basic laser design in the JT-60U has been applied to the ITER laser system. This paper is intended to report on the design of a high power YAG laser system for the edge Thomson scattering system, on the design of a prototype amplifier and on related tests.

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2. Design of a high-average-power Nd:YAG laser system for the edge Thomson scattering system in ITER

Optical design of the laser system has been carried out. To achieve the target performance of the laser system for edge Thomson scattering in ITER (5 J, 100 Hz), we have adopted the MOPA (master oscillator power amplifier) configuration. The optical layout is shown in Fig.1.

The SBS-PCM is a key component of a high-energy, high repetition-rate laser system, as mentioned above. In order to obtain high reflectivity of the SBS-PCM, a high Brillouin gain coefficient g_B is necessary. The Brillouin gain coefficient has a relationship of $g_B \propto 1/(\Delta\nu_B+\Delta\nu_L)$, where $\Delta\nu_B$, $\Delta\nu_L$ are the linewidth of an acoustic wave due to Brillouin scattering and the spectral linewidth of the laser, respectively. A single longitudinal mode (SLM) laser enables high reflectivity of the SBS-PCM due to the narrow linewidth. We developed a laser diode (LD) pumped SLM laser oscillator as the master oscillator for the laser system [1]. We have confirmed that the output

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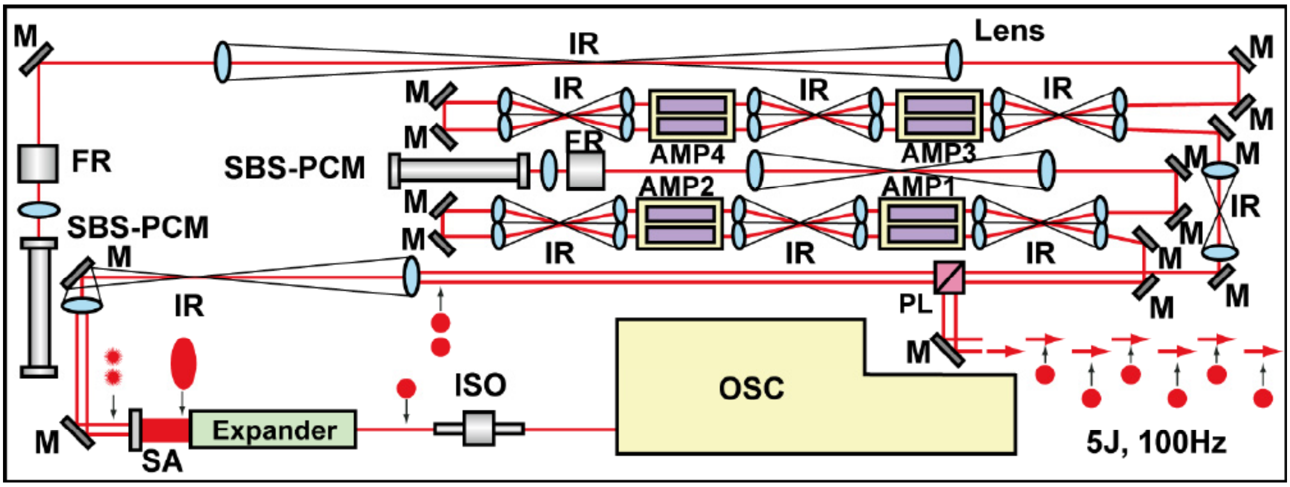

Fig.1 Optical layout of a high average power laser system for the edge Thomson scattering system in ITER

energy is 19.3 mJ at 100 Hz, and the transverse mode is TEM_{00} (Gaussian profile).

The laser beam from the oscillator with a diameter of 3 mm is expanded horizontally to 24-mm and vertically to a 12-mm elliptical shape using cylindrical lenses. The elliptical beam is directed into a spatial filter through a dual-hole serrated aperture. The Gaussian profile beam is converted into dual top-hat shaped beams through a combination of a serrated aperture and a spatial filter. The diameter of each beam is 14 mm. Two amplifier stages have been installed after the spatial filter. Each beam passing a polarizer cube is directed into the amplifier stage by a separation mirror. The amplifier stage consists mainly of two laser amplifiers, a Faraday rotator and a SBS-PCM. To achieve a compact layout, two laser rods have been installed in the amplifier, and the rods have an opposite-tilt wedge at both ends. Therefore, each beam is amplified using four laser rods, and is amplified through a double-pass that employs the SBS-PCM. The double-pass amplification with the SBS-PCM effectively extracts laser energy from the laser

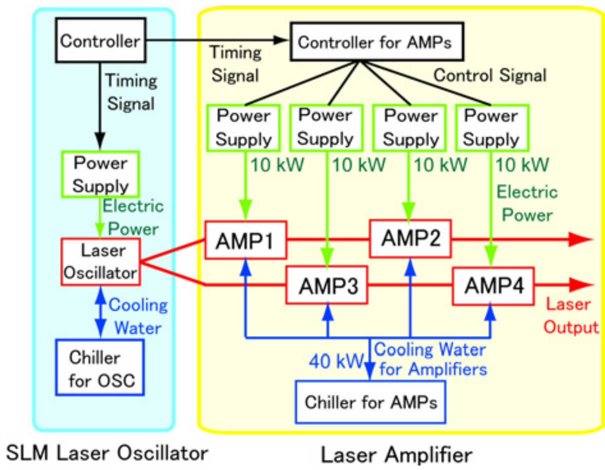

Fig.2 Block diagram of the laser hardware

rods. Furthermore, the thermal effects in the laser rod are compensated by the phase conjugate effect. To relay the image from the serrated aperture to the middle of the laser rod, nine image relay optics with vacuum cells distinct from the spatial filter have been installed at appropriate positions. Each double-pass amplified beam is extracted by the polarizer cube. Each amplifier stage is alternately operated at 50 Hz, the result of which is a 100-Hz pulse beam. Each amplifier stage operates at 50 Hz in order to reduce the heat load on the laser rods. The repetition rate of 50 Hz has been adopted from the JT-60U laser design.

A block diagram of the hardware for the laser system is shown in Fig.2. The flow of timing/control signals, electric power, cooling water and the laser beam between components is illustrated in the diagram. The laser system mainly consists of two parts: a SLM laser oscillator subsystem and a laser amplifier subsystem. The SLM oscillator subsystem is composed of a controller, a power supply of laser diodes for pumping the oscillator head and a chiller for the laser diodes. The laser amplifier subsystem is composed of a controller, four laser amplifiers, four power supplies and a chiller. To maintain a stable energy supply for the SLM, the chiller for the oscillator is controlled to within an accuracy of 0.01 ºC. The chiller for the amplifiers has a cooling capability of 40 kW, and is controlled to within an accuracy of 0.1 ºC. The controller of the oscillator provides a timing signal for pumping the amplifiers.

3. Design of a prototype laser amplifier

Regarding the pumping source for the laser amplifier, there generally are two methods: flash lamp pumping and LD pumping. Although LD pumping enhances laser efficiency, the initial cost is more than ten times that of a flash lamp. Accordingly, we have adopted flash lamp pumping at this time. If the cost of LD pumping decreases in the future, we will consider LD pumping. Laser amplifiers in JT-60U also utilize flash lamp pumping.

Although the JT-60U's amplifiers are designed to attain the highest level of performance, maintainability is not good. For instance, the laser axis is changed when the old flash lamps are replaced with new flash lamps. Consequently, more than one week of realignment work is necessary when replacing the flash lamps. The standard lifetime of a flash lamp is about 10^7 shots. If the flash lamp is flashed at 50 Hz, the lifetime is exhausted in 2.3 days under continuous operation. Considering the expected nature of operations for ITER, maintainability becomes a significant issue. To improve maintainability, the distance between the flash lamp and the laser rod must be expanded to allow for easy flash lamp replacement. However, increasing the distance causes a degradation of the extracted energy. In the ITER prototype amplifier, we have prioritized maintainability over laser performance. The objectives in the development of the prototype amplifier include (1) confirmation of maintainability and (2) confirmation of amplification performance toward the final target (5 J, 100 Hz). As space is limited in this paper, we will describe the design of laser amplification to achieve the target laser performance.

We evaluated the target performance for a prototype laser amplifier for ITER using test data from the laser system in the JT-60U. The laser energy which can be

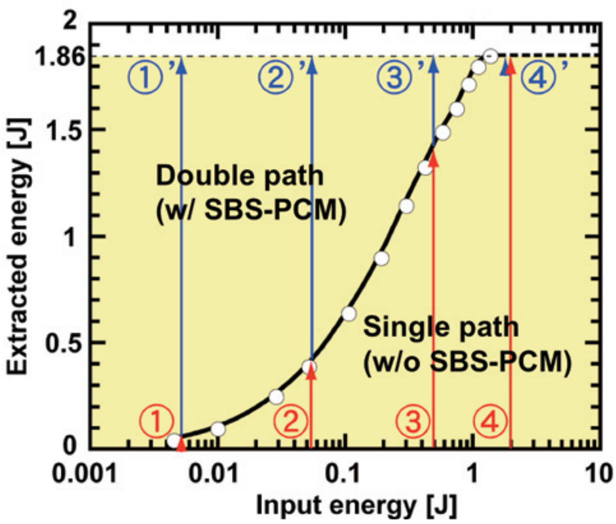

Fig.3 Extracted energy of the JT-60U amplifier. Open circles and the fitted solid line show the extracted energy for single path amplification. The number shows the N^{th} (N=1, 4) rod in the amplification stage. The height of the red arrow shows the extracted energy at the N^{th} rod. The number denoted a prime shows the N^{th} rod on the return path of double path amplification. The height of the blue arrow shows the extracted energy at the N^{th} rod on the return path.

extracted from a laser rod that is 14 mm in diameter has been confirmed to be up to 1.86 J in the JT-60U, as shown in Fig.3. In the ITER laser amplifier, we have determined that the minimum extracted energy is 1.6 J/rod to achieve 5 J of laser energy, keeping maintenance requirements in mind. To attain 1.6 J of extracted energy, four laser rods are necessary, as estimated in Eq.1.

$$1.6 \text{ J} \times 4 \text{ rods} \times (1 - \text{optical loss } 15\%) = 5.4 \text{ J} \qquad (1)$$

The optical loss is estimated by considering the depolarization loss, the reflectivity of the SBS-PCMs and the dielectric multilayer mirrors and the transmissivity of lenses, rods and the Faraday rotator. To extract 5 J of energy efficiently, double pass amplification employing the SBS-PCM's is essential. The laser energy extraction process is shown in Fig.3. It is assumed that the laser rod of the prototype amplifier is saturated at an input level of 1.6 J, and that the relative change of extracted energy is similar to that of the JT-60 amplifier. The 5 mJ of laser energy from the oscillator is amplified up to 50 mJ in the first rod ①. The energy is successively amplified up to 330 mJ in the second rod, 1.04 J in the third rod and 1.55 J in the fourth rod. In the return path of double pass amplification, each rod is saturated, and 1.6 J of energy is finally extracted from each rod.

In the structure of the JT-60U laser amplifier, the amplifier consists of one laser rod between two flash lamps, and light from the flash lamps is focused toward the center of the rod axis by a double-ellipsoidal reflector. The prototype amplifier has a similar design. However, the two amplifier units are arranged in one amplifier unit for a compact optical layout, as shown in Fig.4. Therefore, two laser rods, four flash lamps, and two reflectors are included in the amplifier.

Nd:YAG crystal rods with a concentration of neodymium of 1.1 at% are used as the laser medium in

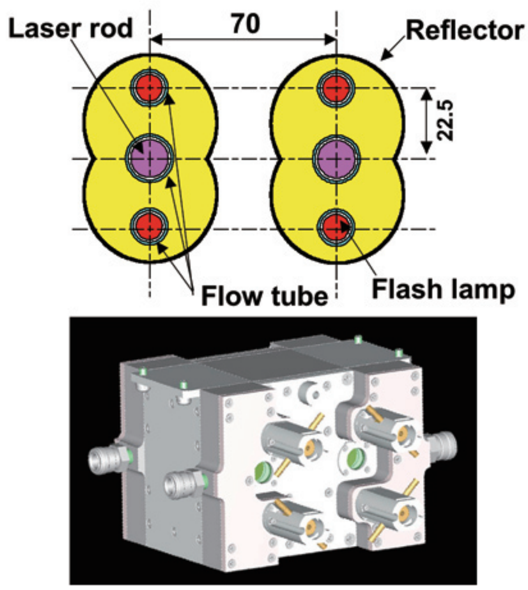

Fig.4 Cross section and exterior of the prototype laser amplifier

the amplifier. The length and the diameter are 100 mm and 14 mm, respectively. The opposite-tilted wedge angles of the rods at both ends are ±5.35°, respectively. Flash lamps are filled with a xenon gas at 450 torr. The inner diameter and the arc length are 8 mm and 63.5 mm, respectively. Flow tubes made of bolosilicate (BC) glass are used for effective cooling of the laser rods and the flash lamps. The thickness is 1 mm, and the gap between the rod and the flash lamp is 1 mm. Water-cooled, gold-plated double-ellipsoidal reflectors are used for focusing the pumping light on each rod.

For optical pumping, 100 J of electric energy is input to two, serially connected flash lamps per rod. The repetition rate is 50 Hz for 100-J operations, and average electric power to the two flash lamps is 5 kW. A total of 10 kW of electric power is input to the amplifier. Since the laser efficiency of a solid-state laser pumped by a flash lamp is not very high generally, a large proportion of the electric power is converted to heat in the amplifier. Therefore, cooling is important to maintain high laser performance. Cooling impacts not only the thermal effect from the laser rod as mentioned above, but also the beam axis. The amplifier is cooled by pure water flowing at 20 L/min at a temperature of 20°C in order to remove the heat of 10 kW.

4. Performance tests of the prototype laser amplifier

We measured the small signal gain (SSG) and extracted laser energy for the prototype amplifier, and compared with the JT-60U amplifier. The SLM laser oscillator mentioned in section 2 is utilized to measure the SSG of the prototype amplifier. Since a wide range of input laser energy is necessary for the measurement of extracted energy, the laser system in the JT-60U is used. Figure 5 shows the initial results of the SSG and the measurement of extracted energy. All data is for 50-Hz lasing. The SSG of the JT-60U increased with an increase in the charge energy of the condenser bank, yielding a maximum value of 8.2 at 94 J pumping. The extracted energy for the JT-60U attained a maximum of 1.86 J. On the other hand, the SSG of the prototype amplifier was saturated when the charge energy exceeded about 70 J; the maximum value was around 7. The extracted energy did not reach the target value of 1.6 J; the maximum value was 1.3 J.

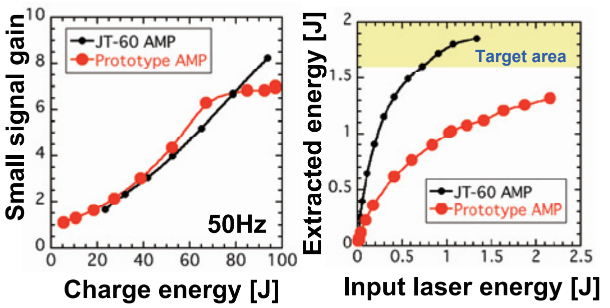

Fig.5 Small signal gain and Extracted energy of the prototype amplifier in initial tests

We investigated the reason for the SSG saturation. First, we considered the spectral gain shift due to the rising temperature of the rods. Kaminskii reported that the fluorescence spectrum of an optically pumped Nd:YAG rod shifts to a longer wavelength with a rise in rod temperature [6]. The fluorescence spectrum corresponds to the laser gain spectrum. From heat analysis, we calculated that the temperature near the

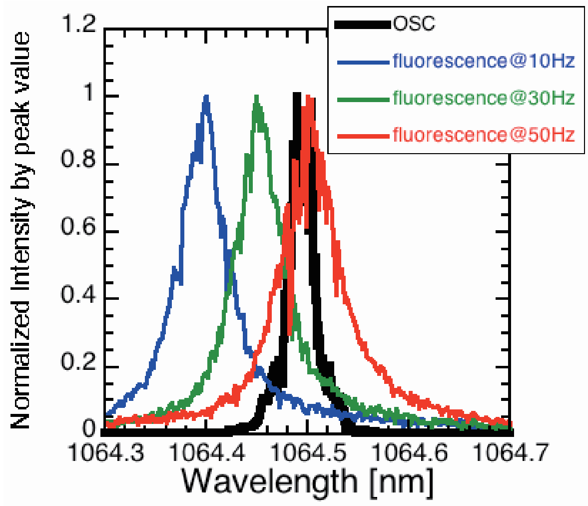

Fig.6 Fluorescence spectra for the SLM oscillator and the prototype amplifier

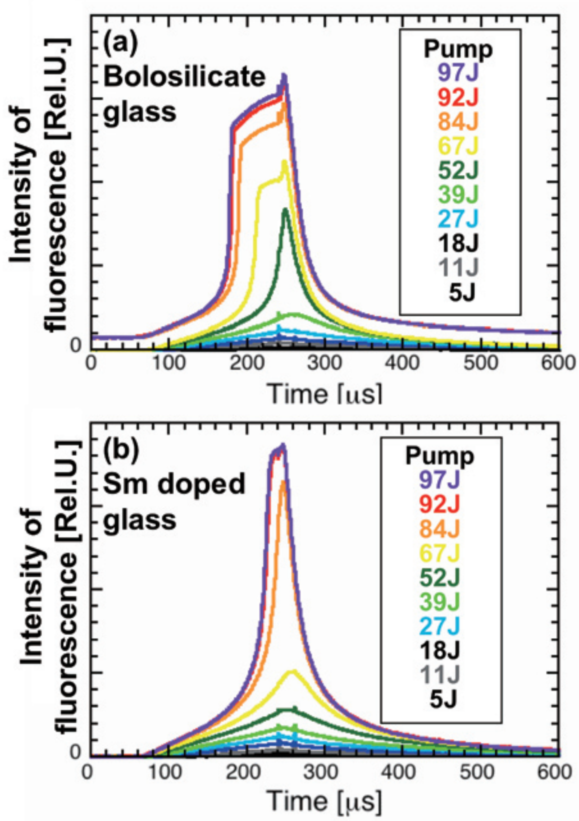

Fig.7 Time evolution of fluorescence for two kinds of flow tubes. (a) Bolosilicate glass, (b) Sm doped silicate glass

central axis of a laser rod increases up to 101 °C at 50 Hz, 100 J pumping. In the SSG measurement, the pumping energy changes in a manner corresponding to the heat load on the rod. Therefore, we consider that the spectrum of the oscillator and the gain spectrum of the amplifier may have deviated. The spectrum of the oscillator and the fluorescence spectra of the amplifier are measured as shown in Fig.6. The spectrum of the oscillator was measured at 50Hz; the fluorescence spectra were measured at 10, 30 and 50Hz. Because the repetition rate corresponds to the heat load, we can see that the fluorescence spectrum is shifted to a longer wavelength with increasing heat load. However, the fluorescence spectrum at 50Hz closely accords with the oscillator spectrum. As such, the spectral gain shift seems not to be the reason for the SSG saturation.

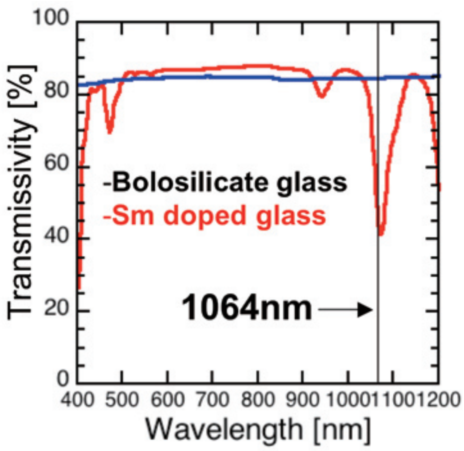

Fig.8 Transmissivity of Bolosilicate glass and Sm doped silicate glass flow tubes

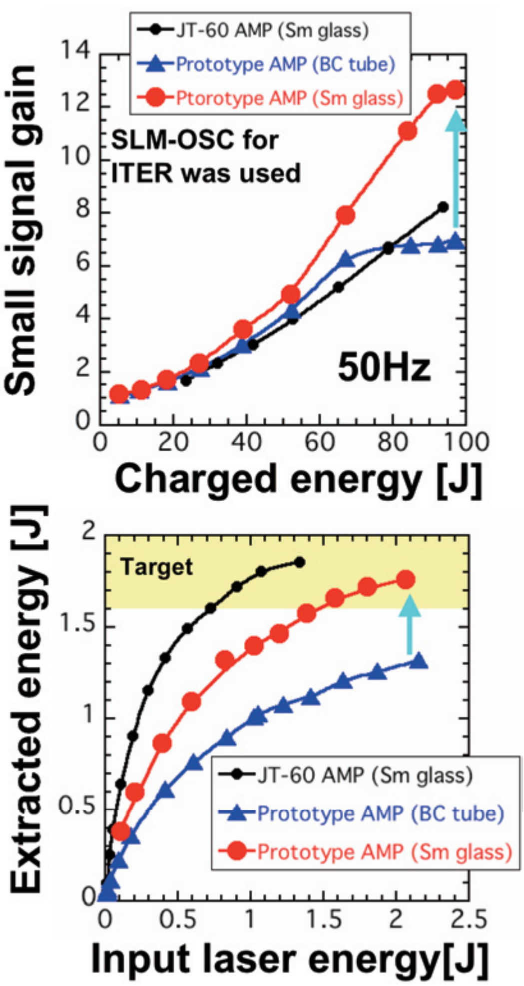

Fig.9 Small signal gain and extracted energy for the prototype laser amplifier

Next, we considered the amplified spontaneous emission (ASE). To investigate the effect of ASE, the temporal change in the fluorescence of the prototype amplifier was measured. The temporal evolution of the fluorescence at various pumping levels is shown in Fig.7 (a). Measurements indicate a flattening of the waveform near the peak when the pumping energy exceeded 52 J. We considered structural differences between the prototype amplifier and the JT-60 amplifier. There is only one difference aside from the configuration of the rod and flash lamps as shown in Fig.4: The JT-60U amplifier does not use a flow tube made of BC glass but rather of samarium doped silicate glass. The concentration of Sm is 10%. The original JT-60U laser system also used BC-glass flow tubes. Since the Sm-glass flow tube absorbs ultraviolet radiation from the flash lamp and emits fluorescence, it was deemed to be useful for producing fluorescence for the pumping. A Sm-glass flow tube was used for the laser rod, while the flow tube for flash lamp was conventional BC glass. Figure 7 (b) shows the time evolution of fluorescence for the prototype amplifier using the Sm-glass flow tube. The flattening of the waveform near the peak disappeared for the Sm-glass flow tube. The radiation from the flash lamp has a broadband spectrum and includes the wavelength (1064 nm) of the laser light. In the case of the BC flow tube, it seems that the 1064-nm light from the flash lamp is amplified in the radial direction in the rod and then the laser gain in the rod is lost. Since the laser gain is high as is the intensity of the 1064-nm light from the flash lamp for high energy pumping, it seems that the phenomenon of lateral depumping occurs quite easily. Figure 8 shows the spectral transmission of BC and Sm glass flow tubes. The transmissivity of BC glass has a flat profile. On the other hand, there is an absorption band around 1064 nm for the Sm glass. It seems that lateral depumping is suppressed by this absorption. Further experimental investigation is needed to provide a qualitative evaluation of the lateral depumping.

Amplification tests for the prototype amplifier were carried out again after installing the Sm flow tube, as shown in Fig.9. The SSG and extracted energy significantly improved, reaching up to 12.6 and 1.76 J, respectively. Since the extracted energy exceeds the target value of 1.6 J, we have the prospect of realizing the laser system for the edge Thomson scattering system in ITER.

The focal length of the thermal lensing effect in the laser rod was measured. To identify the focal point, a CCD camera of a laser beam profile analyzer was swept along the laser axis, and the diameter of the beam pattern at each position was plotted, as shown in Fig. 10. As a result, the focal length is evaluated to be 120 cm. On the other hand, the focal length for the JT-60U amplifier is 170 cm. This difference may have implications for heat removal. It seems that the central temperature of the laser rod in the prototype amplifier is higher than that of the JT-60U amplifier. Note that it is possible that the thermal lensing effect may be compensated by the SBS-PCM. However, rod temperature is an important factor in obtaining high laser performance because the gain spectrum shifts according to the rod temperature.

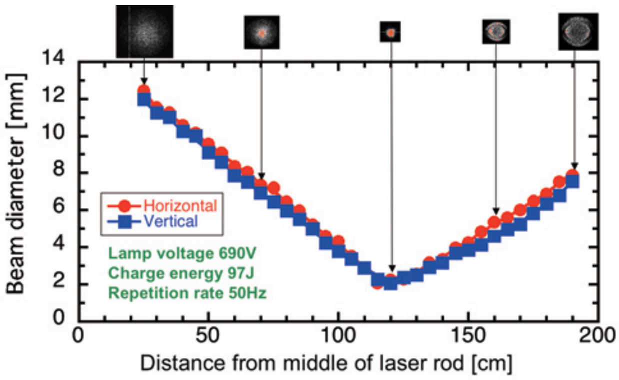

Fig.10 Focal point of the thermal lensing effect for the prototype laser amplifier

5. Conclusions and future plans

A high average power Nd:YAG laser system (5 J, 100 Hz) is necessary for the edge Thomson scattering system in ITER. A high average power laser system was designed, and the prototyping of components has started. A prototype laser amplifier for the laser system was designed and produced. The prototype laser amplifier contains two laser rods and four flash lamps for a compact layout. Specifications for the laser rods, the flash lamps, and the pumping energy are almost identical to those of the JT-60U laser system. In the ITER prototype amplifier, we have prioritized maintainability over laser performance. To improve maintainability, distance between the flash lamp and the laser rod was expanded to allow for easy flash lamp replacement. In the initial test, the SSG was saturated in a high pumping regime. One possible explanation is that light from the flash lamp in the wavelength of 1064-nm is amplified in the radial direction in the rod, with the result that the laser gain in the rod is lost. Since the laser gain is high as is the intensity of the 1064-nm light from the flash lamp for high energy pumping, it seems that this phenomenon of lateral depumping occurs quite easily. A flow tube made of samarium doped silicate glass significantly improves the SSG and reduces energy degradation. We found that the use of the Sm-glass flow tube is essential for achieving optimal performance from a high average power laser system pumped by flash lamps. Results indicate a significant improvement in the SSG and extracted energy compared to the use of a BC-glass flow tube, reaching up to 12.6 and 1.76 J, respectively. Since the extracted energy exceeds the target value of 1.6 J, we have the prospect of realizing the laser system for the edge Thomson scattering system in ITER.

At the current point in laser development, four amplifiers have been manufactured on the basis of the prototype amplifier, and we continue to test laser components. Assembly of the prototype YAG laser system for the edge Thomson scattering system in ITER has started. Optimization leading to the achievement of 5 J, 100 Hz will commence following assembly.

Acknowledgments

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