"GENBU"-Laser Development with Cryogenic Yb:YAG Ceramic for Fusion Energy Reactor Driver

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Abstract. A new diode-pumped laser fusion driver has been conceptually designed. The output power is 1.2 MJ and 0.1 MJ for a compression laser and a heating laser, respectively, at 16 Hz repetition rate and 17% electrical-optical efficiency. We have proposed two new technologies into the laser system to improve its laser output characteristics dramatically. One is cryogenic Yb:YAG ceramics as a laser material and the other is a large-aperture active-mirror as an amplifier architecture. An 1 kJ near-infrared laser is a basic unit for both compression and heating lasers, and its demonstration will become a milestone of the new driver. Recently, "GENBU"-laser has been designed in details for not only a milestone of the new reactor driver but also a tool for advanced application fields. A joule-class laser system of "GENBU-Kid" is under construction for power-scaling up to 1 kJ.

1. Introduction

Recently, the huge laser facilities of NIF and LMJ are under construction for mega-joules pulse energy to ensure compressive central heating. A 10-kJ short-pulse heating laser has been developed for fast ignition in our FIREX-I project. Such high-pulse-energy lasers are single-shot systems for inertial fusion energy (IFE) researches. For a reactor laser driver, in addition to such high pulse energy, repeatable operation and high electrical-optical efficiency are required necessary. Our basic specification for a fast-ignition-based reactor laser is 1-MJ output power at 16-Hz repetition rate with more than 10% efficiency. A diode-pumped solid state laser is a prior candidate today. One of the most significant issues for its realization was, however, no suitable laser material. A cryogenic Yb:YAG ceramic has been proposed as a reactor driver material due to its high tunability of emission cross section, high thermal shock parameter and large aperture feasibility.[1] Using the material, a new reliable diode-pumped reactor laser driver has been designed conceptually. The 1.1-MJ laser pulse energy in nano-seconds at blue and the 0.1-MJ in pico-seconds at near-infrared have been estimated at 16 Hz repetition rate for the compression laser and the heating laser, respectively. The whole efficiency is 17%.[2] Also, an amplification scheme of large-aperture active-mirror has been adopted and unique polygonal main amplifier modules reduces the volume size to less than 3000-m^3. Another advantage of the active mirror is efficient axial conductive cooling, which results in dramatic reduction of laser wavefront distortion. Easy power-scaling of the active mirror is also attractive. Both compression and heating lasers are generated from a 2.5-MJ nano-seconds laser at 1 μm wavelength. The infrared laser consists of forty 8x8-segmented beams. A segmented disk unit supplies an 1 kJ pulse energy, which become a milestone of the new reactor driver development.

On the other hand, in the last few years, the advanced application fields with high power lasers except the IFE research were investigated such as neutron source, ion-beam cancer therapy, positron emission tomography (PET), then the next laser technologies were discussed.[3] As a result, it was concluded that the next laser system should be based on combining an advanced high-power laser technology with an advanced ultra-short pulse laser technology. A "GENBU (**G**eneration of **EN**ergetic **B**eam **U**ltimate)" laser has been conceptually designed for not only laser fusion reactor driver but also the industrial applications. Some laser specifications are, therefore, over those of the reactor driver and improve reliability for the driver more. A joule-class laser system of "GENBU-Kid" is under construction as the first step of the "GENBU"-laser development.

2. Conceptual Design of "GENBU"-Laser

Considering our investigation for the high power laser applications and the recent status of the inertial fusion energy (IFE) reactor driver developments, two goals were set for the next generation of the high power laser development as follows.

(1) Pico-seconds, kilo-joules laser (main laser)
pulse energy ~ 1 kJ, pulse duration 50~100 ps, repetition rate 100 Hz

(2) Femto-seconds, peta-watts laser (OPCPA laser)
pulse energy 30 J, pulse duration 5~10 fs, repetition rate 100 Hz,
peak power > 1 PW, intensity at focusing point > 2 x 10^{21} W/cm^2

The "GENBU"-laser has been conceptually designed to satisfy these goals and consists of two laser systems, a main laser and an ultrashort pulse laser, shown in fig. 1. The main laser is a diode-pumped solid-state laser with high pulse energy, high efficiency, compact system size, long operation lifetime, less maintenance and easy operation. The main laser is also used as the pump source of the ultrashort pulse laser. In the ultrashort pulse laser, an optical parameteric chirped-pulse amplification (OPCPA) technique is used rather than a Ti:sapphire amplifier CPA due to wide spectral range, less thermal loading, high contrast and easy optical construction.

The main laser generates an 1-kJ output pulse energy with 100-Hz repetition rate, which is a milestone of the new IFE reactor driver developments. The chirped pulse amplification (CPA) is used for pico-seconds amplification because of the easy energy extraction without optics damages and the high energy fluence operation for reducing a material aperture size.

One of the important issues in the OPCPA laser is to syncronize the seed pulse and the pump pulse. The femtosecond oscillator is the same as that of the main laser. A coherent white light is generated by irradiating a sapphire plate with femto-second pulses and is temporally stretched to 8 ps. By using three OPCPA stages with two BBO crystals and a DKDP crystal, the peak power of peta-watts are obtained in 5~50-fs pulses. The whole size of the "GENBU" laser is 12m x 6m.

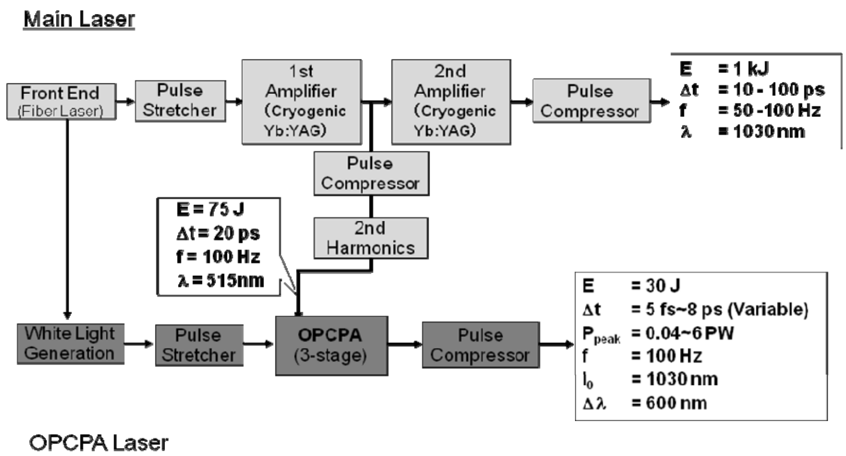

Fig. 1 Systematic diagram of the "GENBU"-laser.

3. Cryogenic Yb:YAG Ceramic

In realizing the "GENBU"-laser, the most significant issue is to find out a laser material which enables both high pulse energy and high repetition rate. The requirements for the laser material are as follows.

(1) High energy storage capability (high saturation fluence)
(2) High thermal toughness (high thermal shock parameter, high thermal conductivity etc.)
(3) Acceptance of a large aperture beam size
(4) Strong absorption at high-power diode emission wavelength

The ytterbium-doped laser materials almost satisfied these requirements. Yb:YAG ceramic[4] is attractive especially in thermal toughness, large aperture beam size and proper absorption spectra. The saturation fluence is a little higher than that of the typical damage threshold of anti-reflection coating (10 J/cm^2 @ 1ns), which results in less energy extraction efficiency. By changing the Yb:YAG temperature, the saturation fluence can be controlled.[5] Additional dramatic improvements at low temperature are to improve the characteristics of the thermal conductivity, thermal expansion and thermal refractive index change.[6,7] Then, at low temperatures, re-absorption of Yb:YAG due to quasi-three-level laser system is reduced, which leads to high gain at a low pump intensity.

4. Main Laser Design

The specifications of the main laser are shown for 100-J and 1-kJ system in Table 1. The laser material is a cryogenic Yb:YAG ceramic and the laser wavelength is 1030 nm. The pulse duration is several ten pico-seconds and the repetition rate is 100 Hz. The front-end is a fiber system to obtain high operation stability. A mode-lock fiber oscillator generates 30-fs pulses and a pulse picker with a combination of a pockels cell and polarizers reduces the repetition rate to 100 Hz. A fiber stretcher expands the pulse duration from 30 fs to 1 ns. The pulses are then amplified to several milli-joules with a large-mode-area (LMA) fiber amplifier. Then, the pulses are temporally stretched again to 3-ns with a grating pair, and are amplified to 200 J with a pre-amplifier and a power amplifier, both of which use cryogenic Yb:YAG ceramics in an active mirror architechture. A rough image of the 200-J first main amplifier is shown in Fig. 2. A seed pulse is amplified via four active mirrors and reflected for the second pass by a deformable mirror to compensate its wavefront distortion. A Pockels cell is used to prevent spontaneous emission from amplifying. The amplified laser energy is 200 J with a 104-mm beam diameter. The second amplifier with seven active mirrors gives 2 kJ with a 326-mm diameter. After the pulse compressor, a 10~100-ps pulse is obtained with an output energy of 1 kJ. The main laser is also used as a pump source for the OPCPA laser. A 200-J laser pulse is extracted after the first main amplification, and by using a pulse compressor and a frequency converter, a 75-J green laser is generated in 20 ps. The size is compact at 1-m x 0.7-m. Excluding electric power and cooling units, the size for the whole laser system with 1 kJ at pico-seconds is laboratory size at 12-m x 6-m.

The laser material temperature is distingushed as (1) < 100K, (2) 100~160 K, (3) 160~200 K, (4) > 200 K. Over 200 K, the re-absorption of Yb:YAG due to quasi-three-level laser system is significant, and a high pump intensity of several ten kW/cm^2 is necessary for a laser gain. Below 100 K, the Yb:YAG operates as a four-level laser material, resulting in an efficient laser operation. A fluorinert is useful as a refrigerator between 160 K and 200 K. There are no refrigerator between 100 K and 160 K. By decreasing the temperature, efficient laser operation becomes easier. The overall efficiency is, however, decreasing due to less efficiency of the cooling unit for Yb:YAG and vice versa. The overall efficiency in (3) is higher than that in (1) now. Considering the improvements in cooling technologies and refregerators in the future, (1) < 100 K is choosen. Damage threshold of the anti-reflection coat of Yb:YAG was assumed at 2 J /cm^2 under considering an interference with incident and reflected beams. The small signal gain was calculated at $g_0L < 3$. The pump intensity was about 2 kW/cm^2 based on our experimantal data, which was comparable to the averaged surface intensity of stack laser diodes. The temperature rise of the Yb:YAG is theoretically calculated when the pump intensity is 1.7 kW/cm^2. The four-level laser system is maintained for a thick disk of 20 mm when the heat sink temperature is 50 K, shown in fig. 3.

Table 1 Basic specification of main laser.

	100 J-system	1 kJ-system
Wavelength	IR (1030 nm)	
Pulse energy	100 J	1 kJ
Pulse duration	20 ps	10 ~ 100 ps
Beam number	1	
Repetition rate	100	
Efficiency	>0.03	
Laser material	Cooled Yb:YAG ceramic	
Amplifier architechture	Active mirror	

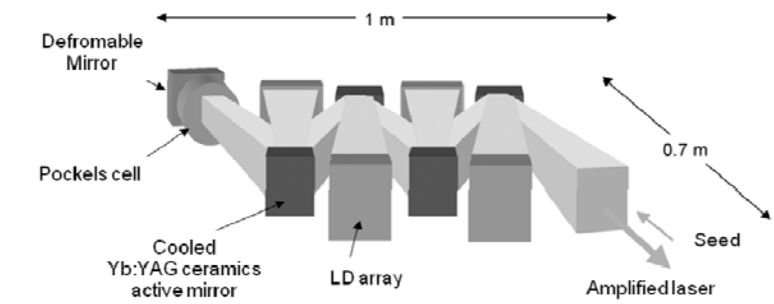

Fig. 2 Brief design of a 200-J main amplifier of "GENBU"-main-laser.

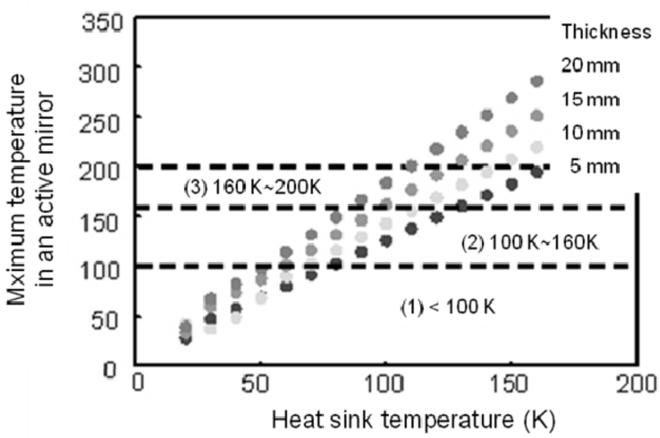

Fig. 3 Brief design of a 200-J main amplifier of "GENBU"-main-laser.

The total electric power is estimated to be 1.7 MW for 1 kJ, ps-system. The overall efficiency is 5.8%, which is improved with a magnitude of more than one order compared with an existing flashlamp-pumped kJ-laser system. The electric power required for laser operation and over all efficiency are shown in table 3. Most of the electric power is consumed by the main amplifier. The electric power for cooling the laser diodes is comparable with that for cooling Yb:YAG. The whole system costs about 20 million dollars under our hopeful expectation, especially, concerning mass effect of laser diodes.

Table 3 Electric power required for laser operation and overall efficiency.

Laser output	
Pulse energy (J)	1000
Repetition rate (Hz)	100
Average power (W)	100
Electric power	
Electric input of main amp. pumping (kW)	1010
Electric power for material cooling (kW)	323
Electric power for diode cooling (kW)	404
Total electric power for main amp. (plug) (kW)	1737
Efficiency	
Electrical - laser power conversion efficiency	0.058

The average power at a high pulse energy of 1 kJ and a high repetition rate of 100 Hz is about four orders higher than commercial lasers. There are various issues to be settled. The most significant issues are various kinds of large aperture optics and their thermal problems such like a Pockels cell, a Faraday rotator, a deformable mirror, a grating and so on. An advanced coating technology for high damage strength reduces the requirements of large aperture by high energy fluence operation. For the laser material, the characteristics of the coating at low temperature should be evaluated. Increasing the brightness of the laser diodes gives us the possibilities for reducing the system size and improving the operation stability. The efficient cryostat will help the overall efficiency and the system size.

3. Laser Demonstration : “GENBU”-Kid

1 J, 100 Hz laser of “GENBU-Kid” is under construction as a pre-amplifier of “GENBU”-laser. “GENBU-Kid” is a MOPA system, which consists of a fiber oscillator with pulse shaping optics, a Yb:YAG regenerative amplifier and a Yb:YAG main amplifier. Both the regenerative amplifier and the main amplifier uses cryogenic Yb:YAG active mirror.

By the aid of a pockels cell and 2 crossed polarizers, the laser output from a CW fiber oscillator was sliced with 10 ns pulse duration and a repetition rate of 100 Hz. The produced 10ns pulses were then amplified up to several milli-joules using thirty round trips of the regenerative amplifier arrangement. A folding caivity length is long at 4.9 m due to avoiding laser pulse overlap on the active mirror. The regenerative amplifier had a compact size of 0.8

m x 1.2 m in spite of the long cavity length. The laser material was a 10 x 10 x 2mm 9.8% doped Yb:YAG ceramic used in an active mirror arrangement. One surface was HR-coated for both 1030nm and 940nm, and its other surface was uncoated. It was mounted on a copper holder with 100 µm thickness indium foil and was directly cooled with liquid nitrogen. The pump source was a 140 W fibre-coupled laser diode with a pump duration of 1000 µs. The obtained pulse energy was 4.7 mJ at maximum. The pulse energy was saturated over 85 mJ input power due to a amplified spontaneous emission. The optical efficiency was as low as 4% due to a poor spatial beam coupling between pump laser and amplified laser. Using a thinner Yb:YAG, it will be improved.

The main amplifier system had an end-pumped four pass arrangement as shown in Fig 4. A large-aperture active mirror is under preparation and a rod type was used. The 12 mm diameter, 6.6 mm length 5 at. %. Yb:YAG rod was sandwiched between two copper plates with its end faces and was conductively cooled with the plates which has a liquid nitrogen inside. To improve the thermal contact between the copper plates and the laser crystal 100µm indium foil was used. The end faces of the laser material were both AR coated and pumped by two 2.5kW fiber coupled laser diodes with pump duration of 700 µs. The emission outputs from both diodes were focused so that their waist over the length of the crystal was 4mm in diameter.

The amplified pulse energy was measured with respect to the diode current for a seed pulse input energy of 2.4 mJ as shown in fig.5. The saturation over a diode current of 20 Amperes was attributed to parasitic oscillation loss. The amplified energy increased again around a diode current of 30 Amperes, which was credited to an improvement to the spatial mode coupling between the pump area and the amplfied beam by a thermal lensing effect. At further diode input energies, the spatial coupling moved away from the optimum and the output energy decreased. The spatial beam quality was good due to axial thermal synmetry. The pulse duration decreased to 7 ns from 10 ns. Using several active mirrors arrangement, parasitic oscillation will be prevented, thermal lensing will reduce and the spatial mode coupling will be improved.

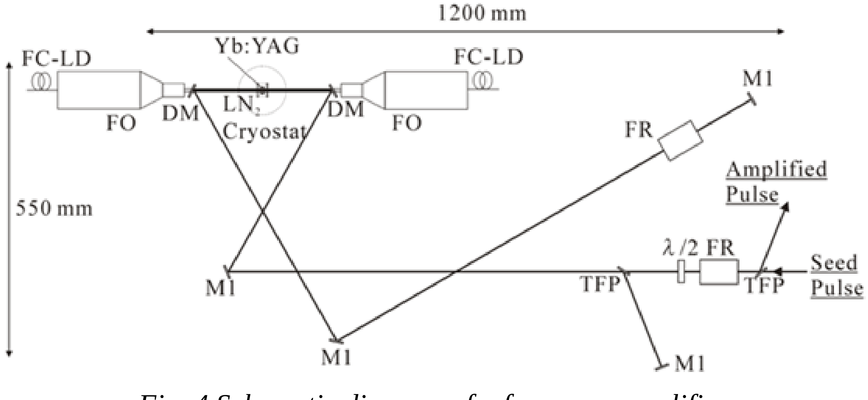

Fig. 4 Schematic diagram of a four-pass amplifier

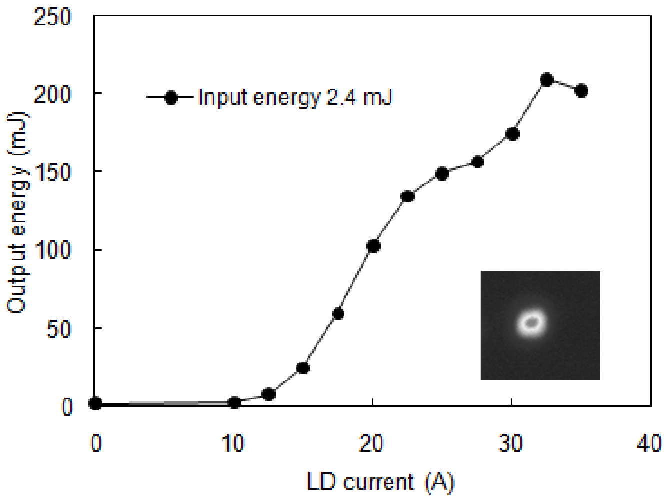

Fig. 5 Amplified pulse energy after four passed as diode current.

5. Conclusion

The “GENBU”-laser has been conceptually designed for not only a milestone of a new reactor laser driver but also the next high-power laser applications. The main laser and the OPCPA lasrer produce pico-seconds, kilo-joules and femto-seconds, peta-watts pulses at 100 Hz. Two new technologies of a cooled Yb:YAG ceramics and an large-aperture active-mirror arrangement has been adopted in the system to break through the limit of the existed laser power. 1 J, 100 Hz, 10 ns laser system of “GENBU-Kid” is under construction. 0.2 J pulse enegy was obtained at 100 Hz with a Yb:YAG rod. The active-mirror Yb:YAG is under preparation. Using it, “GENBU-Kid” will satisfy the specifications.

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