CRYOGENICALLY COOLED 1J, PS YB:YAG SLAB LASER FOR HIGH-BRIGHTNESS LASER-COMPTON X- RAY SOURCE*

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Abstract

A prototype solid state picosecond laser is reported for single shot laser-Compton bio-imaging applications. The target specification is 1J, 1ps at 120Hz with good beam quality for precise pointing to 10 µm focused 43MeV electron beam with 1nC charge. 0.1J stretched pulse is obtained from a thin disc Yb:YAG laser, and amplified through a cryogenically cooled Slab Yb:YAG module in a multipass configuration. Temperature dependent gain characteristics is analysed and concluded as the designed optimization is sufficient for long time stable operation for the laser-Compton imaging.

INTRODUCTION

Single shot X-ray imaging is critical for many practical applications, and the required specification for the laser-Compton source is explained as the X-ray photon must exceed some threshold parameters. It was already well studied on the optimization of the laser-Compton hard X-ray source by single shot base [1, 2] and the experimental results agreed well with theoretical predictions. Highest photon number is obtained in the case of counter propagation of laser pulse and electron bunch with minimum focusing area before nonlinear threshold.

The number of obtainable X-ray photon flux N_0 is calculated in the normal incidence collision, lineally as Ne Np / r^2 where Ne is the total electron number, Np is the total laser photon number, and r is the interaction area radius. Longer wavelength laser like ps CO_2 laser is advantageous to generate higher brightness X-rays at a fixed wavelength due to higher gamma factor of employed electron beam, namely higher beam energy [3]. And the same energy laser pulse contains 10 times photons compared to solid state laser ones. Disadvantage is the total system size, which is larger compared to the case of solid state laser. The approach to increase the photon flux is equivalent to increase Ne, Np and decrease r, but there are instrumental limitations to realize these simultaneously. The practical limitation is the maximum electron number Ne and minimum interaction area diameter r. These are determined by the emittance of the accelerated electron bunch and Coulomb repulsion. It is reasonable to assume it as 1nC, 3ps and focusable down to 10µm diameter at 43MeV acceleration energy. The suitable peak X-ray energy is 33keV for bio imaging application. Another limitation is the onset of the nonlinear threshold of the higher harmonics generation, which is characterized by the laser field strength

a_0=eE/m f_L c

where E is the amplitude of laser electric field, f_L is the laser frequency and c is the velocity of light. The laser energy for the nonlinear threshold of a_0~0.6 corresponds to 1J with 1ps at 10 µm focusing in case of Yb:YAG laser. It is thus reasonable to make a design of a Yb:YAG laser of 1J pulse energy with 1ps pulse length, and a high beam quality to be focused down to 10 µm diameter in the interaction region. The required beam quality parameter M^2 is less than 1.5 in a standard normal incidence configuration. The pointing stability should be also less than a few µm. The generated X-ray total photon number is ~10^9 for each shot.

Conventional rod type solid state laser is suffered by the thermal distortion in a high repetition rate operation, and achievement of the required M^2 and the pointing stability is impossible. Enhancement cavity is recently favoured to realize effective high pulse energy in a cumulative mode, but the focus region parameter r becomes larger to avoid optics damage.

HiLASE project is committed to make a progress in the field of new generation solid state laser, and we are developing a laser system based on Yb-doped materials, to deliver output energy of 1J with the repetition rate of 120Hz and the pulse duration of 1-2ps with M2<1.5. The laser system consists of a seed mode-locked fiber laser and two amplifier stages, namely, an Yb:YAG thin disk regenerative amplifier, and a cryogenically cooled single slab as the booster amplifier (Figure 1).

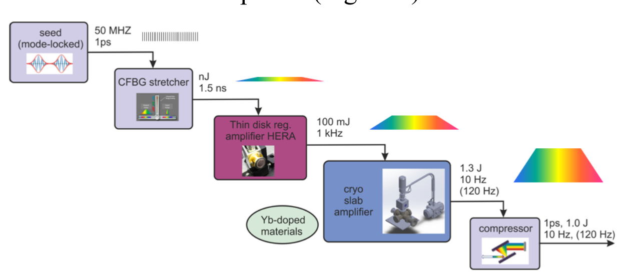

Figure 1: Schematic layout of 1J, 120Hz, ps laser system. The system consists of a fibre oscillator, regenerative thin disk amplifier, and a cryogenically cooled multi pass booster amplifier.

We have obtained the output energy of 45mJ (further work to 100mJ is progressing with twin head configuration), from the regenerative amplifier at the repetition rate of 1 kHz with M2 <1.2 In case of the booster amplifier, to make the system compact, efficient

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and cost-effective [4] with joul-level pulses at repetition rate of 120 Hz, we decided to adopt a conduction-cooled laser architecture based on pulsetube cryocooler (see Figure 2). We believe that an acoustic-Stirling coolhead without moving parts will significantly reduce vibrations of the gain medium and thus improve the pointing stability of the laser system. To properly design the high energy amplifiers, which suffers from ASE or parasitic oscillations that deplete the inversion population and so limits the gain and stored energy, preparation of precise gain measurement technology is essential. The extraction efficiency η_E for the amplifier is defined as [5]:

$$\eta_E = \eta_{overlap} \frac{F_{out} - F_{in}}{F_{sat} g_0 l_{eff}}$$

where $\eta_{overlap}$ is the spatial mode-overlap efficiency factor, g_0 is the small signal gain coefficient, l_{eff} is the signal optical path length, F_{sat} is the saturation fluence of the gain medium, F_{out} and F_{in} is the output and input fluence respectively. Hence to maximize the energy extraction, the mode overlapping needs to be as high as possible. In this paper we present a precise gain distribution measurement technology that allows one to find the real small signal gain value and optimize the size and profile of the input seed beam. We have evaluated the temperature dependence of gain bandwidth of the Yb:YAG crystal. The experimental result is analyzed and confirmed for long time operation at 120Hz.

EXPERIMENTAL SETUP

A novel method is introduced for a spatial evaluation of the single pass gain (Figure 2). This method allows to avoid the unfavourable effect of mode mismatching, by providing precise 2D gain profiles with plain scale. The new approach makes use of a tunable narrow band home-made source as a probe beam and of a CCD camera as a detector. The tunable laser was built in Littman configuration and comprises of a single emitter laser diode and a transparent grating with groove density of 300mm^{-1}. The tuning range of the probe beam extends from 1011nm up to 1041nm with a linewidth approximately of 1nm.

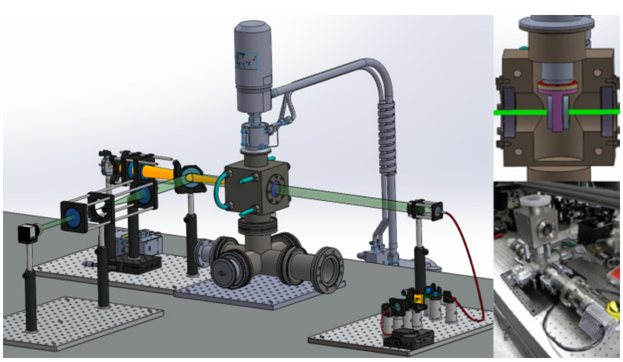
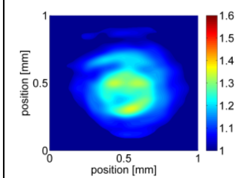
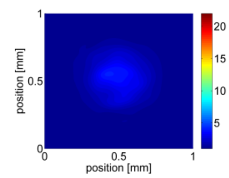
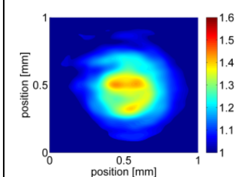
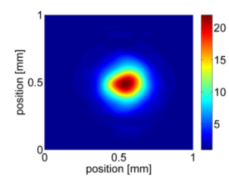
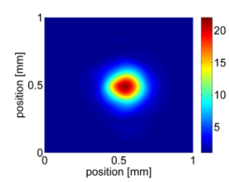
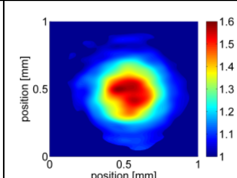
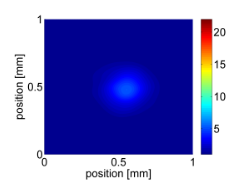
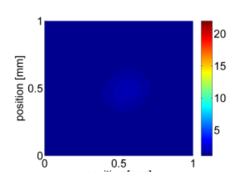
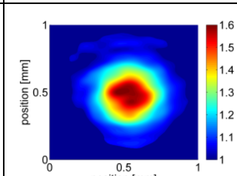
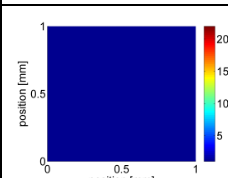
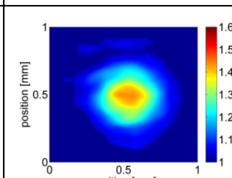


Figure 2: A test-bench of a spectrally resolved spatial gain measurement utilizing a narrow band tunable laser as a probe beam and a CCD camera as a detector.

Table 1: Single Pass Gain Profiles versus Probe Wavelength at 100 K and 300 K. Pump power = 11.24 W. To Prevent the Spatial Distortion of the Probe Beam Caused by Thermal Effects, the 4f Imaging System was Adopted

λ [nm]	crystal temperature: 100K	crystal temperature: 300K
1027.0	N/A	
1028.0		
1028.5		N/A
1029.0		
1029.5		N/A
1030.0		
1031.0		

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RESULTS

The spectrally resolved spatial gain measurement is shown which was conducted at cryo and room temperatures. The 3 at.% Yb:YAG crystal with the diameter of 5 mm and the thickness of 3 mm was mounted on a copper heat sink in a closed loop Gifford-McMahon cryostat. The cooling capacity of the cooler was 2 W at 30 K. The gain medium was pumped by a fiber-coupled laser diode (core diameter =105 μm, NA = 0.15) at 936 nm imaged, by two lenses with 75 mm and 150 mm focal length, to a pump spot diameter ($1/e^2$) of 210 μm.

To calculate the spatial gain distribution, the probe beam with and without pump beam, as well as, the luminescence was captured by the CCD camera. Then the spatial gain profile was calculated by dividing the amplified probe profile by the non-amplified probe profile after the subtraction of luminescence profile which was considered as a background. The gain profiles (see Figure 3) show that the single pass gain at 100 K was much stronger and narrower compared to the gain at 300 K which was distributed over 5 nm.

To evaluate the spectral bandwidths at cryo and room temperatures, we have replaced the tunable narrowband laser and the CCD camera with a superluminescence diode (SLD) and spectrometer, respectively. The spectral bandwidth of the SLD was 50 nm at central wavelength of 1035 nm. The measurements were conducted for three crystal temperatures, i.e. 120 K, 200 K and 300 K. It was noted that peak wavelength was shifting towards shorter wavelengths and gain bandwidth became narrower as the crystal temperatures decreased. Table 2 summarizes the gain bandwidth, peak wavelength and expected pulse duration of Fourier-transform-limited pulse (TLP).

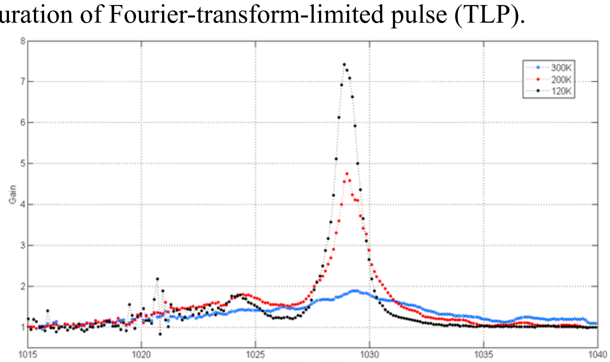

Figure 3: Gain as a function of wavelength for three temperatures: 120, 200 and 300 K.

Table 2: Summary of Gain Bandwidth, TLP and Peak Wavelength for 120 K, 200 K and 300 K

Temp [K]	Gain bandwidth [nm]	TLP [ps]	Peak wavelength [nm]
120	1.22	1.28	1028.9
200	1.57	0.99	1029.0
300	6.41	0.24	1029.4

CONCLUSIONS

An overview was presented on the picosecond cryogenically cooled booster amplifier that is going to generate joul-level pulses at repletion rate of 10 Hz, with prospect to 120 Hz. We introduced a novel method of spectral resolved spatial gain measurement which allows us to avoid adverse effect of mode mismatching and permits estimation of best spatial input beam profile to maximize the mode matching as well as the energy extraction from the gain medium.

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