Current status of the LUCIA laser system

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The current status of the LUCIA laser program is discussed. While aiming at 100J, 10Hz, 10ns, a first milestone is set at 10 Joules with a repetition rate of 1-3 Hz. 7ns long, sub-mJ pulses generated by a cavity-dumped oscillator are first preamplified at the sub-J level. Thermal effects limit amplification and repetition rate at this stage. These pulses will be injected into the main amplifier, where amplification is limited by amplified spontaneous emission. It is expected that these pulses reach energy level of ~10J.

1. Introduction

The LUCIA laser system [1] is designed to deliver pulses with energies in the order of 100J with a pulse duration of 10 ns combined with a repetition rate of 10 Hz in its final configuration. The first milestone for the project is set at 10 J with a repetition rate of 1-3 Hz. Main issues to be addressed are Amplified Spontaneous Emission (ASE) and thermal effects management. The impact on the successive stages is somewhat different. Early amplification stages are limited by thermal effects whereas the main amplifier section is limited by ASE [2]. Experimental feedback collected from this program are of great interest for further scaling requirements imposed by the next generation of kJ DPSSL laser beam lines, e.g. for the HiPER project [3,4].

2. System status

Currently, the LUCIA beam line consists of a cavity dumped oscillator, a PreAmplifying Stage (PAS), followed by a beam shaping section and completed by a Main Power Amplifier (MPA).

The oscillator uses Yb\textsuperscript{3+}:YAG as active medium and delivers 7 ns long pulses at 1030 nm with 350 µJ at repetition rates up to 10 Hz. The amplifying medium is not actively cooled and therefore we experience a ~10 % drop in output energy at a repetition rate of 10 Hz compared to the single-shot operation of the oscillator.

These pulses are successively amplified in a pre-amplifier system to the 100 mJ level. A first pre-amplification stage (PAS) section relies on a crystal pumped by one laser diode stack whose emission is concentrated on a 3.5 x 4.8 mm\textsuperscript{2} large surface. The intensity reaches 17kW/cm\textsuperscript{2} in average. The average gain per pass is ~4.5 at the maximum driving current for the laser diode stack of 150A and a pump duration of 1 ms. Amplification is performed through four passes using angular multiplexing and relay imaging. The gain medium is a 30 mm diameter Yb\textsuperscript{3+}:YAG crystal doped at 5 at.% with a
thickness of 3.2 mm. As the pump surface is relatively small, we see no evidence of transverse ASE or parasitic oscillations (the large un-pumped periphery acting like an absorbing cladding for 1030 nm radiation). The injected beam has a Gaussian shape with a 1/e² diameter of 3 mm, therefore one can expect a strong impact of the thermal behavior of the active medium on the phase, through focalization and aberrations like astigmatism and coma. As already mentioned, beam propagation is performed using image relay, conserving the intensity distribution in the relay planes. Nevertheless, phase distortions accumulate, increasing the intensity on the imaging lenses. Figure 1a shows the result of a phase measurement at the exit of the PAS for the static phase. A polynomial decomposition on the Zernike basis reveals that the main distortion is due to defocus. 0° astigmatism is important too, as the pumped zone is rectangular. The necessity of a compensation of the phase distortion is currently under observation. Energy limitations are, so far, set by the Laser Induced Damage Threshold (LIDT) of the transport optics used after the PAS. (figure 1b). Lenses designed for a higher LIDT have recently been installed.

After pre-amplification, the beam is transported to the main power amplifier (MPA) using relay imaging combined with a magnifying telescope assembly. The last imaging telescope also filters the high spatial frequencies introduced by a serrated aperture [5] placed in its object plane. The serration pattern is a circular distribution of linear teeth of 1 mm height and a width of 300 µm. The inner diameter of the circular serration pattern is 20 mm.

The MPA is pumped by a partially filled laser diode array, delivering ≈120 J within 1 ms over a ~10 cm² area, resulting in an intensity of up to 12 kW/cm². The active medium is a 60 mm diameter circular Yb³⁺:YAG crystal doped at 2 at.% with a thickness of 7 mm. Without the negative impact of transverse ASE, considerably high values for the small signal gain (up to 3 cm⁻¹) are theoretically possible. But gain measurements on the MPA show a strong limitation introduced by ASE (see figure 2), as the transverse gain is significantly larger than the gain in extraction direction. The MPA was designed to amplify a rectangular beam. Its pumped area is with its 26 x 38 mm², large enough favouring ASE and parasitic oscillations. Reducing the pumped area to a 30 mm diameter circular aperture by introducing a simple mask, the gain in the amplifier increases significantly from a maximum of ~2 per pass to ~2.8 (green curve). Reflecting the wasted pump energy, with Fast-Axis (FA) concentration mirrors, into the effectively useful pump area, the intensity increases from
~12 kW/cm² to ~16 kW/cm², raising the gain again to ~3.2 per pass in the MPA (blue curve). Gain being still limited by the parasitic oscillations within the active medium itself, an index matching liquid was injected in a peripheral cavity located at the outer border of the crystal. A gain of ~3.4 per pass was achieved (pink curve), limited by a back reflection from the crystal mount leading to the parasitic oscillations. Pump durations longer than ~700 µs are not reasonable as they will lead to pure heating and not show any positive contribution to the achievable gain.

Besides the ASE limitations due to the transverse oscillations, accumulated phase resulting in focal changes on the one hand and depolarization on the other. These were monitored and used as a criterion to qualify the laser head. We studied two different designs for the main amplifier gain medium geometry. The first relied on a 2 at.% doped rectangular crystal with a size of 40 x 36 mm² and a thickness of 8.4 mm. Both crystal faces were AR coated at 940 nm, whereas only one face was also AR coated at 633 nm, with the other one HR coated at 633 nm. This offers the possibility to measure both surfaces deformation independently by flipping the crystal in its mount. The second crystal is a cylinder (60 mm diameter, 7 mm thick, 2 at.%) AR coated for both pump and probe (at 1064 nm in this case) on one side and HR for both on the other. This second design demonstrates a significant improvement compared to the rectangular one - almost one order of magnitude in the introduced static thermal lens, as shown in figure 3a.

The stress induced birefringence of the 60 mm diameter crystal was measured using a set of crossed polarizers as described in [6]. Minimizing the birefringence is achieved by orienting the crystallographic [111]-axis perpendicular to the pumped surface and parallel to the extraction [7]. As the gain medium exhibits a natural birefringence, the average depolarization (square dots) within a 25 mm diameter beam shows a minimum at about 200 W of injected average power on a 30 mm diameter surface. The depolarization in the centre (circle dots) however rises almost linearly with the injected average power. This can be understood, as the intrinsic birefringence depends on the growth, orientation, mounting and coating of the crystal, whereas the introduced birefringence is linked to the added thermal stress, exhibiting a classical four-foil shape with a local maximum in the centre. The overall average depolarization observed never exceeds 1°.

The working point (for 10 J extraction level) for the MPA is in the order of ~100-300 W average pump power in the current pumping configuration. We therefore expect a single pass gain of approximately 3 (including transport losses) and negligible defocusing as well as a minor depolarization in the 4-pass design for the MPA.

![Figure 2: single pass gain evolution with time (ms) during and after a 1 ms pump pulse](image)

Figure 2: single pass gain evolution with time (ms) during and after a 1 ms pump pulse (see exponential decays starting at the end of the pump pulse for all curves). Each curve is associated to a different transverse ASE control strategy put in place according to inserted legend and full body text explanation.
3. Conclusion

The influences of thermal effects as well as ASE are studied in the context of the experimental realization of the first energy milestone (10J) for the LUCIA laser project. While ASE plays no important role for the oscillator as well as for the PreAmplifying Stage (PAS), it is important for the Main Power Amplifier stage (MPA). Thermally introduced static deformation is measured for the PAS as well as for the MPA and an evaluation for the introduced birefringence was performed for the MPA as well.

4. References

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