Laser-diode and Flash Lamp Pumped Solid-State Lasers

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Abstract. Since the early 80's, most authors are considering that to enable high-average-power operation at the highest laser efficiency, it is necessary to replace flash lamp pumped solid-state lasers with laser-diode pumped solid-state lasers. This assumption is based on the fact that diode pumping has many advantages compared to flash lamp pumping that is seen as an old technology. Although it is very difficult to get true numbers, we shall show that Diode Pumped Solid State Lasers nearby the kW level have a moderate efficiency (<<10 %), lower than expected. Flash lamp pumped fusion lasers are still in the run with a low efficiency but can access high beam quality and high harmonic generation efficiency. For the ELI project, we believe that considering a flash lamp pumped laser makes sense when the amplifier can run at 1 shot/mn to delivering 200J of green light. We shall show that it is an engineering problem to be solved with the help of: adaptive optic and large non linear crystals.

Keywords: Solid-state lasers, diode-pumped lasers, flash lamp pumped lasers.
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INTRODUCTION

Neodymium doped glass lasers (Nd: glass) are by far the most widely used type of drivers in Inertial Confinement Fusion both in existing facilities and in the largest being built : the National Ignition Facility (NIF) in the USA and the Laser Megajoule (LMJ) in France. There are several good reasons for the preponderance of this type of laser material but the most important is its availability at large size. Laser design is a compromise solution somewhere between good beam quality, high electrical to optical efficiency and low cost of operation. Most of the time, repetition rate and wall-plug efficiency are discussed but the main issue to deal with is thermal loading in the laser amplifiers because the amplified beam quality is related to the laser material ability to dissipate heat.

If we discuss the possibility of extending solid-state laser technology to high-average-power and of improving the efficiency of such lasers, the critical elements of the laser design are [1]:

1. the thermal management (removing heat from the center of the solid with a cooling system at the end surfaces),
2. the thermal gradient control (minimizing optical wave front distortions),
3. the pump energy utilization (overall efficiency including absorption, stored energy, gain etc),

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4. the efficient extraction (filling most of the pumped volume with extracting radiation and matching pump duration to the excited-state lifetime).

Does it make sense to optimize all these parameters? We can win a world record in laser extraction efficiency but can we achieve efficient second-harmonic-generation or how many times diffraction limited is the laser beam?

LASER EFFICIENCY

Laser drivers for fusion energy must be highly efficient lasers because a simple rule of thumb tells us that: (Laser wall-plug efficiency) x (target gain) > 10 otherwise most of the power produced will be used by the driver [2] (this means that the recirculating power fraction must be less than 20%). Both laser wall-plug efficiency = 10% and target gain = 100 are cited as goals for Inertial Fusion Energy (IFE). Looking at the Cost of Electricity (COE), it is possible to show that the cost of the laser driver scales strongly with laser energy, but weakly with pulse rep-rate [3].

Flash lamp pumped lasers have been widely studied in the past. Although lamp efficiencies are between 0.45 for Krypton arc lamp and 0.54 for Xenon arc lamp [4], the overall laser efficiency can hardly exceed 1 %. An example is given figure 1.

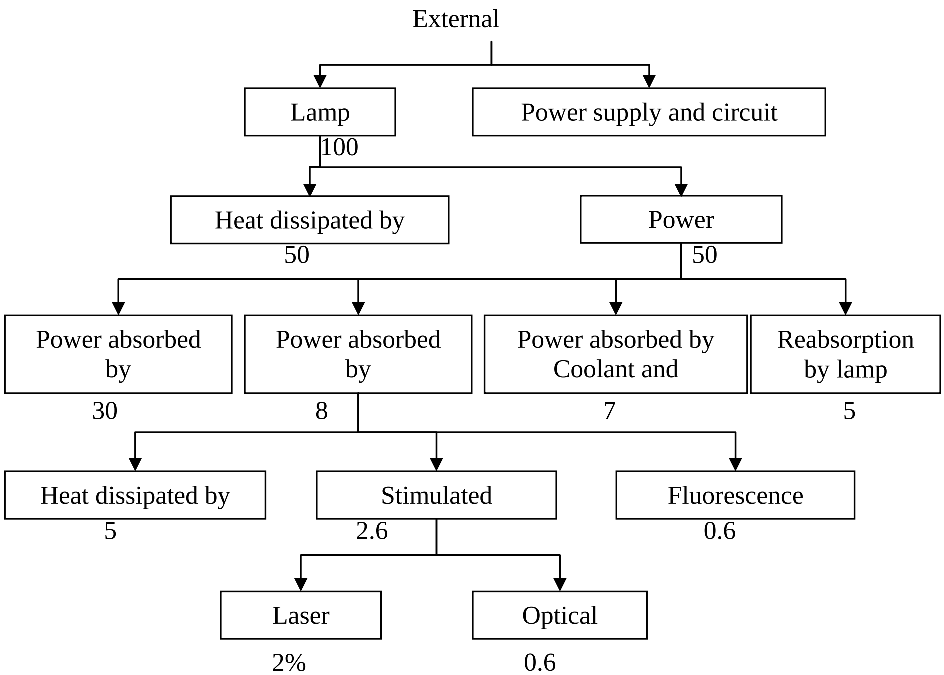

FIGURE 1. Percentage values measured on an Nd: YAG laser pumped by two krypton arc lamps from [5]. 1% total laser efficiency assuming 50% lamp efficiency.

According to this percentage balance, NIF/LMJ total efficiency can be assessed in the range 0.5 to 1 %. 0.66% efficiency has been published for NIF [6].

Diode-pumped lasers can be very efficient. Examples can be found in [7] where power exceeds 100 W and optical to electrical efficiency can reach 23-24% (cooling is not taken into account). Most of these examples concerns CW lasers. One example [8] is a high rep-rate QCW lasers (rep-rate = 1 kHz) with good efficiency (18%). Unfortunately, none of these highly efficient lasers are suitable for frequency conversion or beam propagation because M^2 > 10. Most of the time, efficiency is measured as the ratio of the laser output to the absorbed pump power or energy. It is much better to take into account the input pump power like [8] and the best would be to have access to the electrical power including the power consumption of auxiliary equipments (cooling equipments). Figure 2 shows the data from [7] where M^2 values and wall-plug efficiencies are plot.

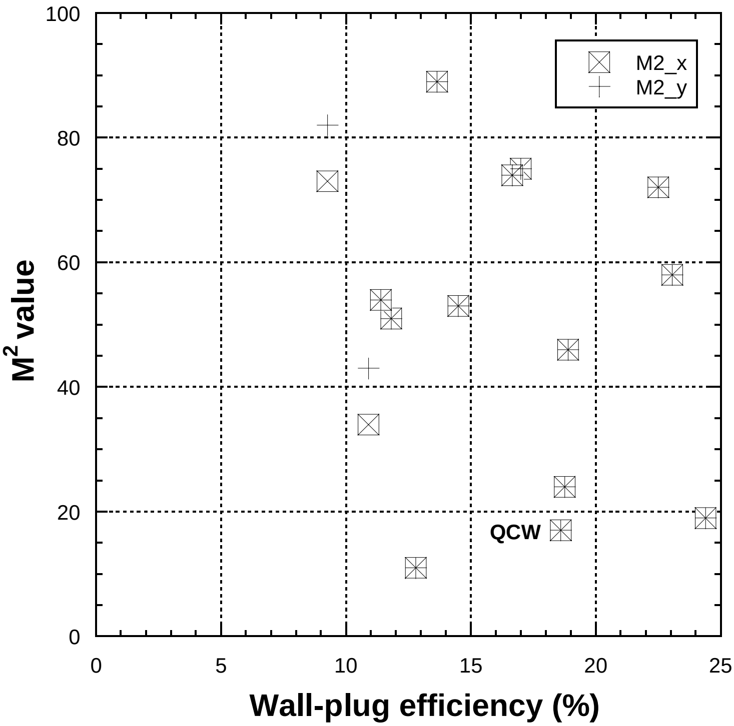

FIGURE 2. M^2 values and wall-plug efficiencies of diode pumped solid state lasers from [7]. All data are related to CW powers between 100 W and 800 W, except one indicated as QCW (rep-rate = 1 kHz) from [8]. Wall-plug efficiencies are calculated assuming 50% diode efficiency.

As an example, reference [8] gives 6% electrical efficiency and M^2=15. In reference [9], it is possible to find the M^2 as a function of the laser output power (M^2 varies from 13 and 18.7 when output power is increased from 100 to 434 W).

Another example is given in [10] where one can find a detailed calculation of expected performances, including the laser efficiency (optical to optical) and the overall efficiency (optical to electrical) that is expected to be in the range 7.3 to 9.6 %.

As soon as $M^2 > 4$, it is quite impossible to have high frequency conversion efficiency unless having intra-cavity frequency conversion [8]. It is quite difficult to scale frequency conversion efficiency as a function of the beam quality parameter M^2, but an attempt was made in [11] to compare different lasers on a long-range efficiency: a 1kW laser whose $M^2 = 5$ is 25 times less efficient than a 40 W $M^2 = 1$ laser. This means that the useful power at long range P_{LR} is equal to the power at short range P_{SR} divided by M^4. In the same reference [11], it was said that "once the beam propagation is solved, the currently available technology is capable of producing 100 kW to 1MW of average output power at 6 to 12% wall plug efficiency". Power scaling as a function of beam quality is given in [12] where the beam quality factor scales as the square root of the incident diode power. If one assumes that the laser output power is proportional to the diode power, then the laser output power is scaling as M^4.

There are several programmes involving diode-pumped Ytterbium lasers at the kW level: MERCURY [13] (LLNL, Livermore, USA), HALNA [14] (ILE, Osaka, Japan) and LUCIA [15] (LULI, Ecole polytechnique, France), but none of them have been able to reach that kilowatt level (100 J @ 10 Hz). Mercury has had the best results: 55 J at 10 Hz rep-rate at 1047 nm during 8.5 hours (peak at 62 J); 32 J at 10 Hz rep-rate at 523 nm in YCOB with a 5.5-cm aperture. The laser efficiency can be estimated assuming a 50% diode efficiency and a total pumping peak power of 640 kW (8 panels of diode stacks) during 750 µs. The total diode energy is equal to 480 J and the laser total efficiency is 5.7% in the infra-red and 3.3% in the green. At 1047 nm, the enclosed energy at 80% is 4 times diffraction limited.

Another example of expected high efficiency diode pumped solid state laser is the Solid State Heat Capacity Laser: 67 kW have been obtained in 2006 using 5 ceramic 10-cm aperture Nd:YAG slabs [16]. This average output power is obtained in a ½ second burst mode, 500 microsecond pulse width, at 200 Hz rep-rate. Neither efficiency nor beam quality known, but 2 x Diffraction Limit has been measured at 10 kW. How much at 67 kW? The main trouble comes from the pump uniformity of the diode arrays. One more example is the Disk Laser Face-pumped by 2D-stack Diode Arrays [17]: 1 to 5 40-mm Nd:YAG disks. With 27 kW pump power per disk (6.75 J) at 400 Hz (10% duty cycle) and 50% diode efficiency at 120 A, typical 26% optical efficiency has been measured at 3.24 kW output with 8 x Diffraction Limit leading to 13 % wall-plug efficiency.

TRENDS TO IMPROVE LASER EFFICIENCY

What are the drawbacks of diode pumping? Gain (highly doped materials) and energy storage (high intensity pumping) are increased to achieve the highest efficiency, but this leads to many thermal problems and transverse gain (and consequently the use of cladding parts to stop Amplified Spontaneous Emission).

What can we do to increase the laser efficiency?

1. Use adaptive optics to decrease the beam quality factor.
2. Cool the amplifier medium to cryogenic temperature to increase optical efficiency and thermo-mechanical properties.

3. Use wide angular acceptance crystals to access high frequency conversion with moderate M^2 factors.

There are engineering solutions to correct the wave front with deformable mirrors, pinholes and optical image relays. This configuration has been successfully tested in the last fusion lasers to correcting the wave front. Both NIF and LMJ prototype (LIL facility) have achieved more than 85% THG efficiency. Both NIF and LMJ prototype (LIL facility) can fire every 2 hours (amplifier slabs are not cooled). LLE (OMEGA EP) while using this type of amplifier with water cooled lamps (but still un-cooled slabs) can fire every hour [18]. If cooling the slab surface is possible, the repetition rate can increase up to 1 shot per minute. This is because the heat flux or heat transfer (***h*** in W/cm^2.K) is increased and the temperature drop across the cooling boundary is decreased. Typical ***h*** values are from 1 to 10 W/cm^2.K. This can be achieved with flow-cooled plates. This principle has been successfully tested on the Mercury laser with Helium gas [13].

Many improvements have been made while using Ytterbium instead of Neodymium [19], considering cryogenic cooling [20] and the use of ceramic gain media instead of single crystals [21]. It is known that operating the laser medium at low temperature should lead to higher thermal conductivity. At 77 K, the thermal conductivity of un-doped YAG is greater than 70 W/m.K; between 300 K and 77 K, the value of the thermo-optic coefficient decreases by about a factor twelve while the value of the thermal expansion coefficient decreases by four [20]. Between 330 K and 77K, both emission and absorption cross sections increase respectively by 4 and 2 while the absorption line width decreases by 2. According to D. Brown [20], the extractable power can be increased by a factor 4 to 5 between 300 and 77 K but if the typical heat flux coefficient ***h*** fall in the range 1-10 W/cm2.K for water cooling at room temperature, it is a little bit less for liquid N_2 at 77K.

The highest beam quality is obtained with CW lasers at cryogenic temperature. From [22], one gets 2.3 kW CW at 120 K and M^2 between 1.6 and 1.9 (at 800 W output power). 80 % diode efficiency is expected at 940 nm, but it is not clear what the diode efficiency for the master amplifier was. Nevertheless a 30% total efficiency is reported although the excellent beam quality is reported at 800 W, not at 2.3 kW. Other authors have published high output CW powers with Yb:YAG at cryogenic temperature, 165 W, M^2=1.02 [23]; 273 W [24]; 340 W, M^2<17 [25] and wall-plug efficiencies between 20 and 40% (assuming 50% diode efficiency).

Moderate M^2 factors require wide angular acceptance crystals to access high frequency conversion [26]. Type II LBO crystals cut in YZ principal plane exhibit high angular acceptance ~8.7 mrad.cm at 1053 nm. Large LBO crystal boules are available to manufacture up to 12-mm thick and 50-mm diameter crystals [27] and within a few years it we be possible to get up to 100-mm free aperture LBO crystals.

CONCLUSION

Although there are very efficient diode-pumped solid state lasers, it turns out that when looking through the beam quality (or M^2) point of view, only few systems can be considered as really efficient. The only highly efficient with the highest beam quality (i.e. M^2 close to 1) are CW lasers at cryogenic temperature.

Apart from multi kW-level lasers for military applications, Mercury is the only QCW laser that has been operated $3x10^5$ shots but with a moderate efficiency (<<10 %), lower than expected. This is because QCW diode bars have a typical 1% duty cycle that makes them suitable for pumping ytterbium at 10 Hz (excited state lifetime is typically 1 ms in garnets). Using CW diodes means either CW operation or a few kHz repetition rates (this is true for both neodymium and ytterbium doped solid state hosts).

Moreover, learning curves [28] are telling us that diode bar prices are dropping with growing market but who knows how long we are going to wait for the market? The conclusion is that QCW diode bars are too expensive to be used in low rep-rate lasers (i.e. less than 10 Hz).

For the purpose of pumping large Ti:Sapphire crystals for the ELI project [29], we believe that considering a flash lamp pumped laser to delivering 200J of green light makes sense as soon as the main amplifiers repetition rate does not exceed 1 shot per minute. Flash lamp pumped lasers are still in the run with a low efficiency but can access high beam quality and high harmonic generation.

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