Journal of Physics: Conference Series **244** (2010) 012010 doi:10.1088/1742-6596/244/1/012010

Multi kJ level Laser Concepts for HiPER Facility

J.-C. Chanteloup[1], D. Albach[1], A. Lucianetti[1], K. Ertel[2], S. Banerjee[2], P. D. Mason[2], C. Hernandez-Gomez[2], J. L. Collier[2], J.Hein[3], M. Wolf[3], J. Körner[3], B. J. Le Garrec[4]

[1]Laboratoire LULI, Ecole Polytechnique, 91120 Palaiseau, France, [2]Central Laser Facility, STFC Rutherford Appleton Laboratory, Chilton, Didcot, OX11 0QX, United-Kingdom, [3]Institute for Optics and Quantum Electronics, Max-Wien-Platz 1, 07743 Jena, Germany, [4]CEA-CESTA, 15 avenue des Sablières, BP2, 33114 Le Barp, France.

jean-christophe.chanteloup@polytechnique.fr

Abstract One of the biggest challenges the HiPER project is facing is to identify a laser architecture that meets all the demanding requirements. Among those are high wall-plug efficiency (15 to 20%) and repetition rate (5 to 10 Hz). In order to perform this task, four teams from the co-authors' institutions are working together and exploring several approaches described here.

1. Introduction

Two options rely on Yb:YAG gain medium as it can be manufactured in large sizes (ceramics), provides good thermo-mechanical properties and a reasonably long fluorescence lifetime. Active Mirror (AM) (section 2) and He-gas cooled Stack of Thin Slabs (SLS) [1] are the two amplifier architectures explored. In both cases, cryogenic temperature will improve thermal management (better thermal conductivity) but will affect Amplified Spontaneous Emission (ASE) management due to higher gain. ASE issues are addressed differently leading to an AM concept relying on multiple ~kJ beams to be ultimately phased when required whereas the SLS concept allows to reach ~10 kJ in a single aperture (a 1 kJ demonstrator is described in section 3). A third option based on fluoride laser materials with and without cryo-cooling together with pulse stacking techniques is investigated (section 4). Indeed a key factor for HiPER is the reduction of manufacturing/ownership costs: a long fluorescence life time laser material is then a solution to reduce the diode quantity. Yb doped fluorides exhibit exceptional parameters but required advanced extraction schemes due to their low emission cross sections. This third option features a very broad band amplification capability allowing a highly flexible short pulse generation (required for HiPER fast ignition scheme). Finally our fourth option (section 5) relies on the use of coherent/incoherent addition of a few million fibres as proposed in 2007 at the IFSA conference [2]. Such a design is attractive in terms of laser safety, operation and maintenance. This concept will required a large number of fibres since one single fibre can only handle a limited power [3]. Amplification relies on diode pumped fibre amplifiers, a technology known to carry limited wall-plug efficiency. Main questions to be answered are: how much power can we manage per fibre (for both ns and ps pulses), how many fibres shall we need to scale to a typical 10 kW level output at 1µm wavelength (1 kJ at 10 Hz rep-rate) and how much thermal power has to be removed at that level.

2. Yb:YAG active mirror amplifier concept

The Laboratoire pour l'Utilisation des Lasers Intenses (LULI) explores an IFE driver concept based on parallel amplification of nine ~120cm² aperture beams carrying each about one kiloJoule of laser light. The chosen host matrix is the YAG garnet whereas Yb^{3+} is selected as a doping ion. Aperture requirement will not exceed 160 mm in diagonal. Amplifiers concept is based on the so called "active mirror" architecture. This approach allows a re-circulation of the pump light improving efficiency. The thermal management approach relies on single side cooling.

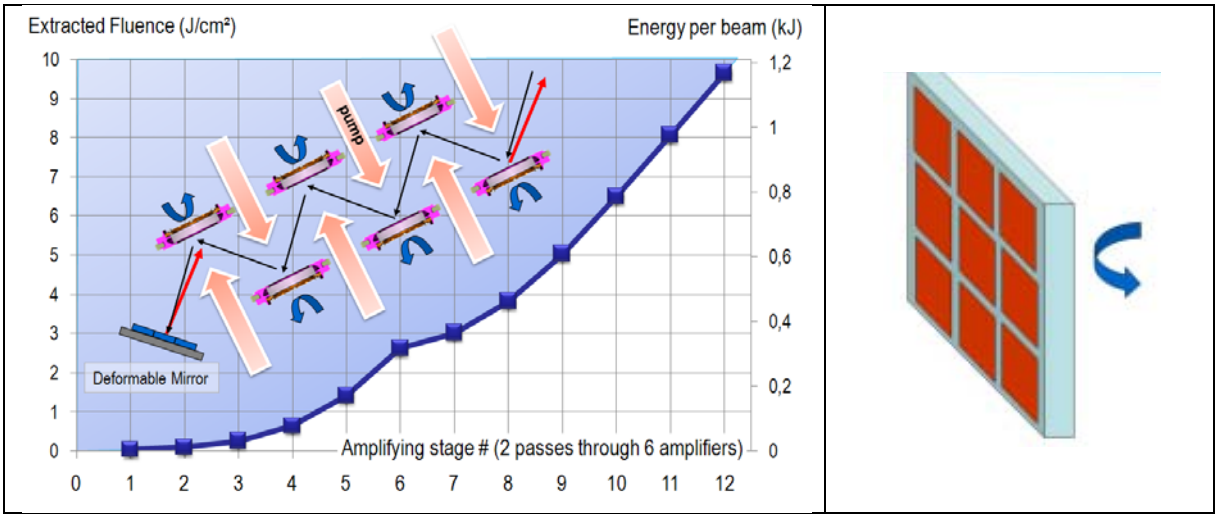

Fig. 1: Left: Single beam extracted fluence evolution through amplification process. Between amplifying stage 6 and 7, the beam is hitting a deformable mirror and is send back for a second pass through the amplification chain. Right: Mosaic active mirror amplifier distribution with single side cooling (blue arrow).

Amplifier chain design is based on parallel extraction of nine (3x3) beams propagating back and forth through a set of six active mirrors. A set of nine deformable mirrors will allow wave front correction for beam quality management. ASE, B Integral and thermal managements, together with global efficiency, will lead to the optimum set of values for doping concentration, thickness and pump brightness. A 1D numerical model was developed in order to identify the optimum set. It shows that doping level will be below 1 at%, thickness will vary between 1 and 3 cm and pump brightness will vary between 4 and 8 kW/cm².

3. Yb:YAG gas cooled amplifier concept

The Central Laser Facility develops a Yb:YAG ceramic based concept for a kJ-class DPSSL amplifier that could potentially be scaled to multi-kJ energies. Numerical modeling has shown that the required pump and extraction fluence levels for efficient operation are prohibitively high at room temperature, due to the thermal population of the lower laser level and the still rather low gain cross section. This can be overcome by cooling the medium to cryogenic temperatures. Fig. 1 shows gain and maximum achievable optical-to-optical efficiency for a Yb:YAG amplifier that is end-pumped at 940 nm from both sides with 1 ms long pulses of 5 nm FWHM spectral width. At 175 K operating temperature, the efficiency reaches > 50 % (the limit being 58%) at the moderate total pump fluence of 10 J/cm^2. The small signal gain is at this point 3.8 and the optimum optical depth (doping x thickness) is 3.15 % cm. To avoid excessive ASE losses, the maximum transverse gain-length product needs to stay below 3 at any point. Hence, regardless of amplifier size, the doping level needs to be chosen such that the thickness is 1.3 times the width.

With this very low aspect ratio, distributed cooling is required. The cooling approach demonstrated on the Mercury laser [1] was thus chosen for our concept. Here, the gain medium is divided into a number of thin slabs with He-gas as coolant flowing between them (see Fig. 3). Also, slabs with different doping concentrations can be employed. The concentrations can be chosen such that the

overall thickness is reduced and the heat load in the individual slabs equalized. If the amplifier is sized for a 1 kJ output energy at a fluence of 5 J/cm^2, the aperture size will be 14 x14 cm^2. For a constant doping level, the required thickness would then be 18 cm, with the doping concentration being 0.18%. If ten slabs with optimized different doping levels are used, the material thickness can be reduced to 10 cm, with the doping then ranging from 0.18% in the outer slabs to 0.5 % in the two central slabs.

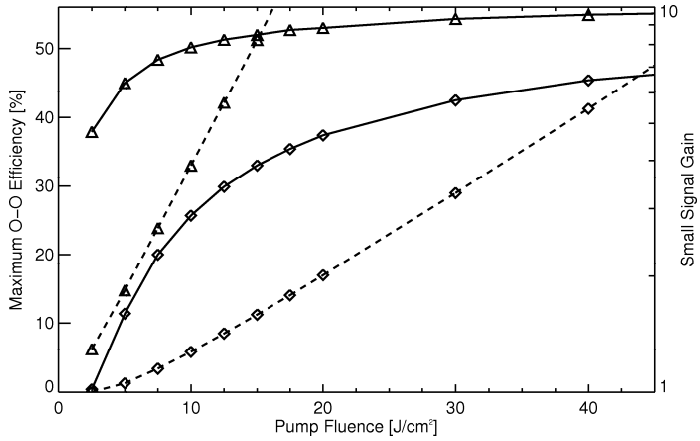

Fig. 2: Efficiency (solid lines) and gain (dashed lines) as a function of total pump fluence, calculated at room temperature (diamonds) and at 175 K (triangles).

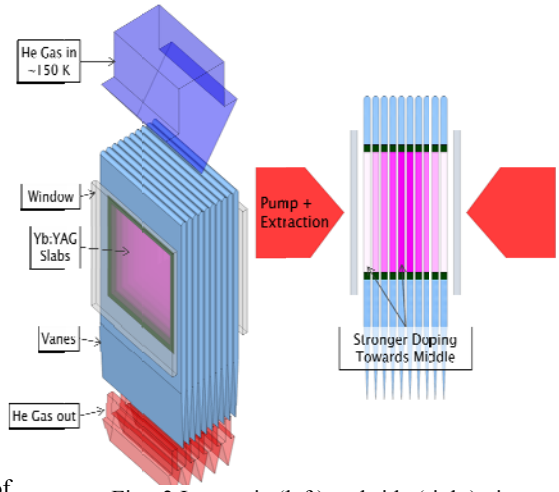

Fig.: 3 Isometric (left) and side (right) view of amplifier geometry

4. Yb:CaF2 gas cooled amplifier concept

The driving laser source for a fusion facility has to fulfil certain criteria, where of main interest are the total power consumption and the facility costs needed to provide the requested pulse parameters. The following proposal from The Institute for Optics and Quantum Electronics, addresses these constraints in the direction of minimizing the peak power requirement for the pumping diode lasers. Combined with that optimisation, the laser fluence in a beam line has to be maximized in order to reduce the required facility space consumption. Nevertheless, this approach is connected with the drawback of the higher amount of heat per volume that needs to be dissipated by the cooling system.

This proposal is based on a laser material with a long fluorescence life time, a good thermal conductivity, broad bandwidths for absorption as well as for emission, and most of all a high probability of large scale production. According to the high fluence in the laser beam line an appropriate extraction scheme is proposed together with a gas-cooled thin-disk stack as the amplifying medium.

Laser active media that fulfil the criteria above typically show a low emission cross section. The use of a low gain material has the advantage of reduced probability of transverse lasing affects, what allow an easier scale of the lasers aperture at relatively high doping concentrations. Such a scheme helps to keep the B-integral, i.e. the accumulated non-linear phase shift, on a low level if the non-linear refractive index is low for this material. CaF_2 seems to be a promising host for the laser active ions to fulfil these criteria. It is interesting to note that the first diode pumped laser incorporated a doped CaF_2 [4] and the first ceramic laser also used that type of material [5]. Pure single crystalline CaF_2 nowadays are produced for applications in lithographic systems on a tone scale. The growth of crystals with diameters of 380 mm is typical. Additionally, it was shown that highly doping with Ytterbium ions can be managed in order to ensure the required oxidation level Yb^{3+}.

Absorption and emission spectra of Yb:CaF_2 reveal a broad absorption ranging from 910 nm to 960 nm, wavelengths allowing convenient pumping with high power diode lasers [6].

Fluorides typically have low absorption in the UV. The result is a low refractive index at the emission wavelength in the near infrared. This broad transparency range results in a less likely multi-photon absorption and combined with the low refractive index the damage threshold can be assumed

to be higher compared to other Yb-doped laser materials. First measurements support this assumption but further investigation is required to see how surface treatment and anti-reflective coatings influences this behaviour.

The operation of Yb^{3+}-lasers at low temperatures is favourable because of the much higher gain and extraction efficiency [7]. The reason for this behaviour is the reduced population of the lower laser level in this quasi three level system which turns into a four level system with cryogenic cooling. Both the thermal expansion coefficient, and the thermal conductivity of $Yb:CaF_2$ behave in a positive way at temperatures around 100K, a temperature where liquid nitrogen can be used as the coolant. Additionally, the spectral properties change in a positive direction at lower temperatures and the amplification band width will be preserved.

The advantages of using $Yb:CaF_2$ as the laser active material for a fusion facility can be summarized as follows: This material has a low refractive, and non-linear refractive index at the emission wavelength, therefore a low B-integral in the amplifier chain can be managed. The low refractive index allows simpler anti-reflection coatings with high performance. CaF_2 is actually produced at a large scale for lithography and doped crystal production is likely. $Yb:CaF_2$ shows broad absorption and emission bands offering an advantage for pumping with unstabilized high power diode lasers. The broad emission allow wavelength multiplexing (the proposed scheme for energy extraction) as well as amplification of very short pulses and therefore provide a high versatility for the fast/shock ignition laser chains of the HiPER facility. Even short pulses in the picosecond range can be wavelength multiplexed because of the femtosecond pulse length capability of this laser material. The low emission cross section prevents the amplifier from transverse lasing and the long fluorescence life time reduces the amount of required diode laser pump power, i.e. the number of diodes and the costs of the system. The broad transmission range of $Yb:CaF_2$ indicates a potentially high damage threshold, what allows higher fluences of the extracting laser pulse and a high extraction efficiency at cryogenic temperatures. The thermal conductivity of $Yb:CaF_2$ is comparable to Yb:YAG and therefore a high repetition rate operation is supported. Amplifiers will be cooled with a similar technology as the one described in section 3.

It must be noted that in order to use the advantages of $Yb:CaF_2$ as the laser material a more complex extraction scheme for the amplifier design has to be chosen. The low single pass gain should be compensated by high laser beam fluences. To avoid laser induced damage of optical elements including the laser material itself it is proposed to amplify a couple of pulses in one amplifier head. To keep the effort of laser beam steering and relay imaging on an acceptable level a combination of angular and wavelength multiplexing is proposed. If, for instance, four pulses with different wavelengths are sent in four beams through the amplifying head, a total of sixteen pulses can contribute to the extraction fluence, where the peak intensity is not affected if all pulses are delayed by their pulse length. After amplification pulses can be rearranged to form very powerful beams by incoherent beam combination. Because the large band width of $Yb:CaF_2$ this scheme is also applicable for the amplification of chirped pulses if this is necessary for fast/shock ignition laser fusion facilities.

5. Fiber approach

A new amplifying concept designed to produce high energy in either short or long pulses using coherent or incoherent addition of few millions fibres has been proposed in 2007 at the IFSA conference [2] and is currently explored by the Commissariat à l'Energie Atomique (CEA). It is clear that the fibre design looks really attractive from many different points of view: laser safety, operation and maintenance. The system will need a large number of fibres because one single fibre can handle a limited power. The system is based on diode pumped fibre lasers and this type of device has limited wall-plug efficiency: all that is not "light" will be removed as "heat". So far there are three questions to be answered: how much power can we manage per fibre, how many fibres we shall need, how much thermal power has to be removed?

5.1 Assess maximum energy per fibre.

For most high-output-power applications, several unique advantages have made ytterbium (Yb) the doping ion of choice. More specifically, ytterbium-doped fibres offer high output powers tuneable over a broad range of wavelengths, from around 975 to 1200 nanometres (typically around 1060 nanometres).

One of the most significant keys to ensuring broad marketability of fibres lasers is the development of a technique for producing ever-increasing output powers without sacrificing beam quality. Whatever the fibre design, it must not limit the total achievable output power and in pulsed laser devices the average power, peak power, and pulse energy.

One of the major advances in fibres technology in recent years has been the advent of large-mode-area (LMA) fibres, and the potential for these fibres to deliver diffraction-limited beam quality with mode-field areas greater than 10 times that for standard telecom type fibres. Companies without access to LMA fibre technology are essentially limited by nonlinear phenomenon such as stimulated Raman scattering (SRS) to the near-100-watt CW power regime. Single-fibre lasers have delivered output powers approaching 1.5 kilowatts and theoretical modelling suggests 10 kilowatts may be possible with the current fibre technology.

The key limits to power scaling [3] are: thermal rupture, melting of the core, thermal lensing, non linear effects, SBS and SRS, optical damage [8] (and how it is related to non linear effects), X-ray, γ-ray and neutron induced damages. For ns pulses, the range is 1 to 27 mJ. The typical output fluence range is 30 to 86 J/cm^2, depending on the core diameter. The damage scaling law is 475 J/cm^2 per ns (for 10 ns F_{damage}= 475 J/cm^2, etc.). Even at high repetition rates (tens of kHz), the average power does not exceed 50W, far from the CW limits indicated in figure 4. It seems obvious that multimode fibres will deliver much more energy, but the numerical aperture has to fit the overall laser design requirements, otherwise the energy will be lost.

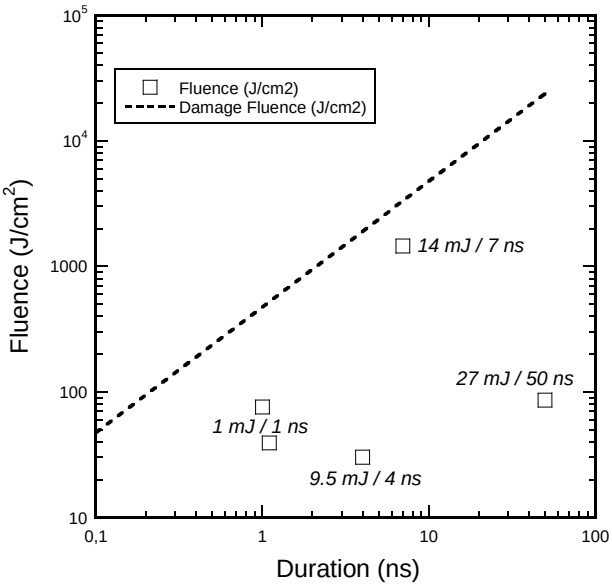

Fig. 4: Plot of the maximum fluence in fibre as a function of pulse (from ref.8). For pulses longer than 50 ps, damage occurs in single silica fibre at 475 GW/cm^2. Peak power does not exceed ≈ 2.5 MW.

5.2 Assess scalability to typical 10 kW level outputs

Both NIF and LMJ have included fibre lasers in their front-end design, with at least three purposes:
1/ Split a given function arising from the oscillator into 192 or 240 "arms" to feed the different laser beam lines; 2/Amplify the oscillator signal with high gain (10^6) and 3/ Delay the laser pulse to let fast electronic devices to implement closed-loop error signals to drive "safely" the laser system.

The system design must assess pulse shaping capability for ns and ps pulses. This principle is based on an Average Waveform Generator that is computer controlled. The input pulse shape is being

computed in order to compensate for saturation in the multi stage amplifier and to compensate for non linear effects in the frequency conversion crystals.

The ability to power scale fibre devices depends on two key criteria: pump power can be efficiently and cost effectively coupled into the fibre, and the fibre core parameters are such that it can convert this pump power into bright lasing or amplification without saturation or nonlinear processes that limit the performance.

It is common for companies to power scale laser output further by incoherently combining the outputs from several fibre lasers, sacrificing beam quality as the power increases. Of course and depending on the system requirements, both coherent and incoherent additions have to be made to ensure enabling pulse synchronisation, smoothing and coherent propagation of ps ignition beams down to the target in the cone-core design.

5.3 Assess thermal management

From a 1mJ fibre laser to a 1 kJ system, at least 1 million fibre lasers would be required, certainly more. Whatever the system design, fibre lasers will be stacked and thermal management has to be assessed to decide what type of cooling is required (if any).

Because a single fibre laser is a diode pumped laser, it is easy to calculate the heat deposited in the fibre that will escape to the outside through the cladding. This calculation is made according to the distribution of the signal and pump powers along the fibre. For simplicity and without loss of accuracy, the cylindrical approximation will lead to the well-known thermal loading expressed in W/m [9]. Thermal management includes thermal, stress and thermo-optic effects in the fibre [10].

6. Acknowledgements

The authors gratefully acknowledge the support of the Funding Agencies in undertaking this work (EC FP7 project number 211737): EC, European Commission, MŠMT, Ministry of Education, Youth and Sports of the Czech Republic and STFC, Science and Technology Facility Council of the United Kingdom.

7. Conclusion

Four currently explored options for kJ level diode pumped amplifiers have been presented in the framework of the HiPER program. Down selection will be performed in HiPER program next phase.

8. References

[1] A.Bayramian et al., “The mercury project: A high average power gas-cooled laser for inertial fusion energy development”, Fusion Science Technology, Vol. 52, Oct. 2007
[2] G.Mourou et al., “New amplifying concept for inertial fusion driver”, J. of Physics: Conference Series 112 (2008) 032052
[3] J.Dawson et al., “Scaling limits of high average power fibre lasers”, IEEE LEOS annual meeting,ThE1, nov.2008
[4] R. Keyes et al., “Injection Luminescent pumping of CaF_2:U^{3+} with GaAs diode lasers”, Appl. Phys. Lett., Vol.4, pp50-51 (1964).
[5] S.Hatch et al., “Hot-pressed polycrystalline CaF_2:Dy^{2+} laser”, Appl. Phys. Lett., Vol.5, pp153-154 (1964)
[6] M. Siebold et al., “Terawatt diode-pumped Yb: CaF_2 laser”, Opt. Lett., Vol.33, No.23, pp2770-2772 (2008)
[7] A. Pugžlys et al., “Spectroscopic and Lasing Properties of Cryogenically Cooled Yb,Na:CaF_2”, CLEO, paper MF4 (2008)
[8] A.Smith et al., IEEE J. of Selected Topics in Quantum Electronics, Vol.15, No.1, pp153-158 (2009)
[9] Y.Lee et al., IEEE J. of Selected Topics in Quantum Electronics, Vol.15, No.1, pp93-102 (2009)
[10] D. Brown et al., IEEE J. of Selected Topics in Quantum Electronics, Vol.2, pp207-217 (2001)