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Invited Paper

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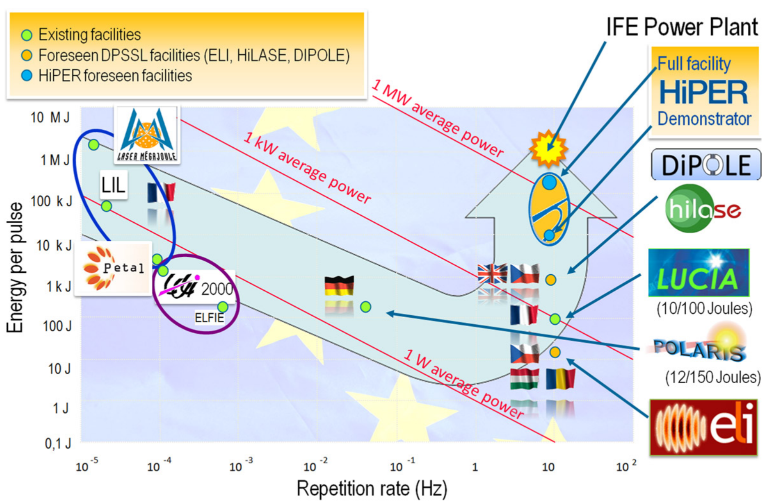

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Current Status on High Average Power and Energy Diode Pumped Solid State Lasers

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(Invited Paper)

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Abstract: With ongoing efforts in Europe, the United States, and Asia on power production through inertial fusion, intense work has been focused on proposing and studying Diode Pumped Solid State Lasers (DPSSLs). Such drivers should be able to deliver 1 to 10 kJ at a repetition rate in the 10-Hz range and a wall-plug efficient nearing 10%. Recent achievements will be presented with emphasis on 100 J-class prototypes, which are currently being built.

Index Terms: Solid lasers, power lasers.

High-Power laser Energy Research (HiPER) [1]–[5] in Europe, Laser Inertial Fusion Engine (LIFE) [6], [7] in the United States, and Generation of Energetic Beam Ultimate (GENBU) [8] in Japan are scientific programs that are dedicated to demonstrating the feasibility of laser driven fusion [1] as a future energy source. Fusion energy is an attractive, environmentally clean power source using sea water as its principal source of fuel. Demonstration of the scientific proof of principle is expected between 2011 and 2012 as part of the National Ignition Fusion (NIF) and Laser Méga Joule (LMJ). These programs rely on two main pillars, respectively, associated with fusion physics and laser engineering (through Diode Pumped Solid State Laser (DPSSL) studies).

LIFE laser system [9]–[11] is designed considering the 15 years of experience the Lawrence Livermore National Laboratory (LLNL), acquired on the Mercury laser Diode Pumped Solid State Laser (DPSSL), which demonstrated 61 J at 10 Hz in 2008 [12]. Aiming at delivering several kJ at a 10 to 20 Hz repetition rate with a $>$ 10% efficiency, the foreseen architecture would rely on a dual amplifier in cavity (NIF-like scheme). It relies on gas cooled Nd^{3+} doped phosphate glass, while Yb^{3+} or Tm^{3+} are still considered as alternate doping ions for ceramics or crystal host matrices like YAG, Y_2O_3, S-FAP, CaF_2 or SrF_2, whereas in 2010, assessment of basic properties of several new laser glasses was performed, and several subscale prototype experiments are foreseen for 2011, like new Pockels cell technology, near field spatial filtering, or advance laser diode pulser.

GENBU is a milestone in Institute for Laser Engineering (ILE, Osaka, Japan) laser development for fusion reactor drivers [8]. The main laser will deliver 1 kJ at a repetition rate ranging from 50 to 100 Hz in the picosecond regime. The two-stage amplifier relies on cryogenically cooled Yb^{3+}:YAG with the original Total Reflection Active Mirror (TRAM) architecture [13], [14]. ILE work relies on a decade long experience on DPSSL with the High Average-power Laser for Nuclear Fusion Application (HALNA) program, which demonstrated 21 J at 10 Hz in 2008 [15].

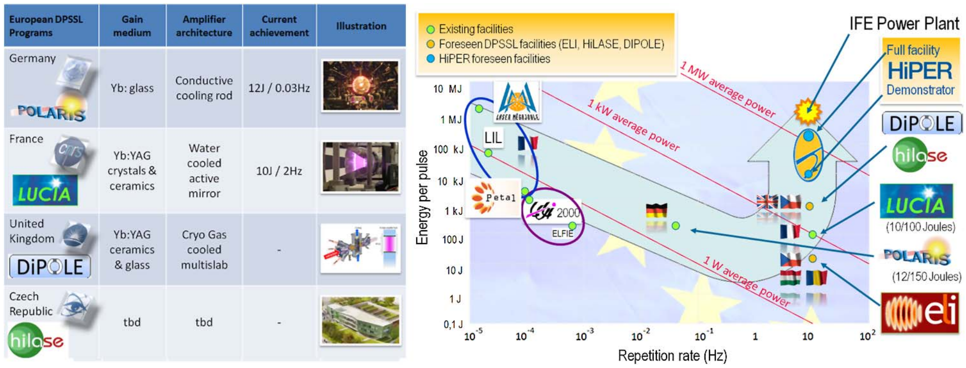

Fig. 1. (Right) Existing and foreseen European high energy DPSSL facilities distribution over a log–log energy versus repetition rate map. (Left) Summary of ongoing and foreseen high energy DPSSL programs in Europe in 2010.

Considering recent shut down (Mercury, USA) and reconversion (HALNA, Japan) of experimental high energy DPSSL programs for IFE, the momentum is now pointing toward Europe in the beginning of this new decade. Let us therefore concentrate now on European efforts largely linked to the HiPER program (ns and ps regime) and to Extreme Light Infrastructure (ELI; http://www.extreme-light-infrastructure.eu/), which is a consortium of European laboratories where, although at a lower energy level than HiPER, DPSSL activities are going on as well. Fig. 1 gives an overview of European landscape on high-energy DPSSL physics.

The HiPER program, which is part of European Authorities roadmap since 2006, is currently in its preparatory phase (2008–2011). Twenty six European partners share expertise to study ignition scheme and laser driver design. The power-to-grid demonstration is expected at the horizon of 2035–2040 after testing the key reactor components. Three DPSSL schemes are explored in conjunction with 100 J test bed prototypes [2], [3], [16]:

- The Science and Technology Facilities Council Rutherford Appleton Laboratory (STFC-RAL), United Kingdom, proposes a kJ scheme based on high pressure Helium cooled slab amplifiers at cryogenic temperature [17]. The proposed architecture is similar to the LLNL Mercury program with a noticeable difference in terms of gain medium: ceramic Yb^{3+}:YAG in place of a S-FAP crystal. In order to experimentally explore that option, STFC-RAL started, in 2009, the DIPOLE program. A 10-J prototype was commissioned in 2010 with a He cryo-cooled gas amplifier hosting four 55-mm diameter co-sintered ceramics YAG slabs (Yb^{3+} as lasing ion and Cr^{4+} in periphery for cladding).
- The Institut für Optik und Quantenelektronik at the Friedrich Schiller Universität (IOQ-FSU) Jena, Germany, proposes a HiPER scheme based on angular and spectral multiplexing extraction through $Yb^{3+}:CaF_2$ slabs. The gain medium is cryo-cooled using a Helium gas high pressure flow in a quite similar way to the STFC-RAL proposed HiPER amplifier scheme. IOQ-FSU operates the DPSSL Petawatt Optical Laser Amplifier for Radiation Intensive experimentS (POLARIS) laser system for several years and is deeply involved into $Yb:CaF_2$ growth. POLARIS current energy achievement is 8 J on a daily basis.
- The Centre National de la Recherche Scientifique (CNRS) Laboratoire pour l'Utilisation des Lasers Intenses at the Ecole Polytechnique, Palaiseau, France (LULI-CNRS) proposes a HiPER scheme based on cryo-cooled active mirror amplifiers with a static Helium cell at low (10 to 100 mbar) pressure. Six amplifiers in a double pass configuration would be required to reach the 10 kJ unit beam requirement for HiPER. This innovative cooling scheme will be explored in the LULI DPSSL program Lucia. In 2010, after activation of its first water-cooled active mirror amplifier head, this laser was able to deliver around 7 J at 2 Hz [18].

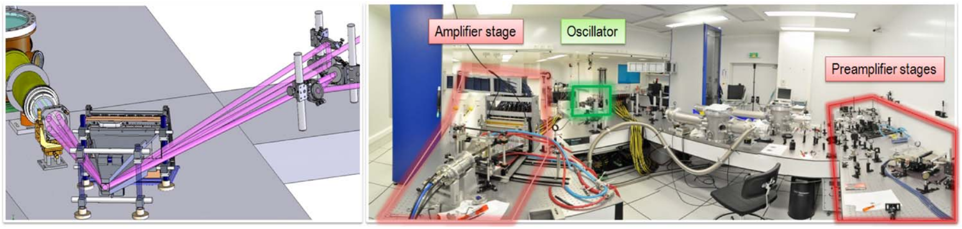

Fig. 2. (Right) Lucia laser layout pictured with oscillator and amplifying stages. (Left) Four pass extraction scheme illustration at the amplifier level.

To complete the overview of European efforts toward high energy DPSSLs, let us mention other important projects currently under development:

- The Institute of Physics of the Academy of Science (Prague, Czech Republic) launched the High-average power pulsed lasers (HiLASE) project in January 2011, which aims to deliver 100 J at 10-Hz laser pulse trains by 2015. Two amplifier architectures will be simultaneously explored in the first phase: thin disk with back conductive cooling and cryo-cooled slab disks with Helium at high pressure.
- The Helmholtz-Zentrum Dresden-Rossendorf (HZDR, Dresden, Germany) is also exploring DPSSL systems, although at a smaller scale. Recent developments have shown a 1.5-J diode-pumped laser using an Yb^{3+}:YAG slab at room temperature [19], with the option for Yb^{3+} doped CaF_2.

Lucia, which is the LULI DPSSL program, relies on active mirrors cooled from the HR coated back surface of Yb^{3+}:YAG crystals (see Fig. 2). All crystals are large enough (60 mm diameter for the main amplifier for a 24 mm extraction beam) to help circumvent transverse oscillations due to ASE. Over the past two years, most of the efforts were dedicated to ASE [20] and thermal [21] management. 300-μJ $-$ 7 ns pulses produced by the oscillator are amplified in two active mirror multipass preamplifers to reach around 100 mJ before entering the main amplifying stage for a four-pass extraction layout, leading to a 7-J pulse train [18]. Recent improvements in injected beam quality allowed us to overcome the 10-J threshold level in 2011.

Lucia is used as a test bed for further development related to the HiPER or ELI programs. Gain medium engineering is among the key aspects currently explored by the Lucia team [22]; gradient doped (several at% per cm) and large (10-cm-diameter range) Yb^{3+}:YAG crystals have been successfully grown in collaboration with Laserayin Tekhnika csc (www.laser.am) [23].

Another promising axis of research is dedicated to the design of an efficient, tunable, and long-term reliable cooling architecture for a large-disk laser amplifier at cryogenic temperature. The Lucia second amplifier head will indeed rely on cryogenic cooling with a thin, low-pressure gas cell located at the HR side of the active mirror gain medium. This innovative cooling concept is relevant for HiPER/ELI as well.

Finally, let us mention the very active field of DPSSLs relying on chirp pulse amplification. Recent energetic achievement [24]–[26] has indeed demonstrated that 100 mJ to J level short pulses can be produced in the 10–100-Hz repetition rate range, opening the way to 1-to-10-W average power applications requiring ps and fs pulse durations.

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