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Free-Electron Lasers as Pumps for High-Energy Solid-State Lasers

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Abstract

High average-power free-electron lasers may be useful for pumping high peak-power solid-state laser-amplifiers. At very high peak-powers, the pump source for solid-state lasers is non-trivial: flash lamps produce thermal problems and are unsuitable for materials with short florescence-times, while diodes can be expensive and are only available at select wavelengths. FELs can provide pulse trains of light tuned to a laser material's absorption peak, and florescence lifetime. An FEL pump can thus minimize thermal effects and potentially allow for new laser materials to be used. This paper examines the design of a high average-power, efficient high-gain FEL for use as pump source. Specifically, the cases of a 100 J class pump, and a 100 TW-class laser at a planned fourth-generation light-source are considered.

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1. Introduction

High energy and high-power lasers have found wide usage in research and application including material processing, solid-state research, particle physics, and as drivers for other radiation sources such as x-ray (K-alpha) production. From early proposals of laser driven accelerators [1] to recent applications such as high-field physics [2], nuclear physics, [3] fusion science [4], proton-beam generation [5], and radiography [6], the demand for high power and high-energy lasers has increased. Still, lasers in the greater than 100 TW or 10 J class are challenging to build, involve large investments, and can only be developed for a limited set of wavelengths. While thermal limits and optical-damage thresholds constraint the selection of gain media, the lack of viable pump-sources further restricts usable materials. Flashlamps produce large thermal-loads and are not suited to materials with

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short fluorescence-times (such as Ti:S). Diodes remain expensive, difficult to use on very large crystals, and are more practical at longer wavelengths.

Free-electron lasers (FELs) have long promised to provide high average optical-powers, and recent work indicates that this promise can be delivered upon by increasing the efficiency, duty factor and bunch repetition-rate of existing designs. FELs can provide pulse trains of light tuned to a laser material's absorption peak, and duration. An FEL pump would thus minimize thermal-effects and potentially allow for new laser-materials to be used. For instance, a high-power FEL could pump a high-energy Ti:S amplifier and produce PW-class pulses. Moreover, FEL light-source facilities are being designed and built already; a high-energy laser at such a fourth-generation light-source could be used for novel pump-probe experiments while taking advantage of existing infrastructure.

This paper proposes the use of a high average-power, efficient, high-gain FEL for use as a pump source. Specifically, two cases are considered: a 1 KJ-class pump for a 100 J high-energy laser; and, a 25 J pump for a 100 TW-class high peak-power laser.

2. The FEL as a Pump

Existing solid-state lasers are pumped by flash lamps, diodes or other lasers. A comparison of existing pump-sources with the type of FEL considered here is shown in Table 1 and reveals the regime of applicability for novel pumps: at high pump-energies and shorter wavelengths conventional pump-sources are inadequate or don't exist. While flashlamps produce unwanted heat due to their broadband spectrum, they are the most mature and most widely used type of pump — the world's most powerful laser, NIF, is flashlamp pumped [7]. Diodes are becoming widely used because they are reliable, stable, tuneable to match common laser-material absorption-bands and therefore are thermally favourable, and are becoming economically viable (est. at $5/Watt). However, diodes are still difficult to couple to large crystals, and are not practical (efficient) for wavelengths below about 800 nm.

Table 1: A comparison of existing laser pump sources with the FEL based pump. The FEL is suited to high energy and short wavelength applications.

	Pump Source			
	Flashlamp	**Diode**	**Laser**	**FEL**
Avg. Energy	Very high	High	Low	High
Peak Energy	Medium	Low	High	Very High
Heat Load	High	Low	Low	Very Low
Wavelength	VIS	IR - NIR	IR-UV	IR - UV

2.1 The Ideal Pump

An ideal laser-pump is matched to the gain medium in wavelength, bandwidth, time structure and size [8]. The wavelengths of available pumps have, in many ways, determined which materials are investigated for use in lasers. New pump sources especially in the UV would make possible the use of new materials offering new lasing-wavelengths and new operating-regimes (e.g. Ce3+:Li-CAF). The ideal pump source is also stable shot-to-shot; is electrically efficient and has a low cost per Watt. The optical properties of pump sources is also an issue for large amplifier crystals as they require many sources to cover the material.

The FEL is able to provide most of the above characteristics with a few possible exceptions: the stability, efficiency, and cost of the FEL warrant discussion. A seeded high-gain FEL driven to saturation is stable to the extent that the electron-beam parameters do not fluctuate significantly. Operating as a pump source, the integrated energy delivered to the laser crystal is more significant than shot-shot fluctuations; thus, a feedback system could be used to assure that the integrated energy is indeed stable. The efficiency of conventional high-gain FELs is low (varying as the FEL parameter ρ; approximately 0.1% - 1% in typical systems). Tapering of the undulator, along with bunch compression, has been shown to produce efficiencies approaching 10% in already-achieved undulator lengths. Finally, the cost of free-electron lasers is inherently high due to the attendant infrastructure. At lower pump energies (< 10 J), the costs of building an FEL seems unlikely to compete with conventional lasers or diodes. However, at pump energies around 100 J, the cost analysis is vague. Moreover, large diode-arrays costing millions of dollars can only operate at one wavelength (or at best, over a narrow wavelength-range), and have a limited lifetime: an

FEL can be tuned and thus pump multiple types of laser amplifiers. (of course, time structure is constrained to what the RF system can deliver).

2.2 Description of a Pump FEL

The components of an (high gain) FEL acting as a pump are a high average-power accelerator with a high-brightness injector; a long tapered-undulator; and, a high repetition-rate seed-laser. (Alternative configurations such as FEL oscillators or regenerative amplifiers — RAFEL — are not considered here.) The "gain medium" in an FEL is the electron beam. Because the electron beam is continuously refreshed, there are no thermal-load problems in an FEL, and hence, a high average-power device has long been promised [9]. Still, production of high average-power, high-brightness electron-beams has been a challenge and a number of approaches have been considered including energy-recovery linacs, and superconducting systems. In addition, conventional accelerating systems can be and have been used at high duty-cycles. The salient point here is that the electron beam needs to provide a high integrated-energy only over the fluorescence time of the crystal to be pumped.

3. Challenges & Opportunities

The production of a high-brightness high average-power beam presents significant technical challenges including thermal management, efficient production of high-power RF, and development of a suitable drive-laser (assuming a photoinjector is used). In the accelerator, correction for beam loading and mitigation of wakefields are issues. The design of a high-efficiency FEL is straightforward if a tapered undulator is employed; however, such an undulator would introduce a large energy-spread on the beam making recirculation or energy-recovery schemes difficult. Finally, tailoring the repetition rate, microbunch current (charge), and macropulse duration to deliver the desired pump-energy during the gain crystal's fluorescence time may be difficult. The above significant challenges face most high average-power devices in some form.

4. Example Systems

We consider two examples of an FEL pumped solid-state laser. In the first example, we attempt to match the performance of the state-of-the-art MERCURY diode-pumped laser system while the second example is based on a system operating parasitically at the LCLS.

4.1 A MERCURY-like pump

The MERCURY laser utilizes arrays of diodes (over 6000 in total) to drive a 4-pass gas-cooled amplifier system using ytterbium-doped strontium fluorapatite crystals [10]. The project goals include 10% electrical efficiency at 10 Hz and 100 J with a 5-ns pulse length, and represents the state-of-the-art in diode pumped solid-state lasers (DPSSL). The peak power of the diode arrays is 640 kW. Yb:S-FAP has a fluorescence time of about 1.1 ms with an absorption peak of 905 nm. The light from the complex diode-arrays is funnelled into the disk amplifier through multiple reflections in a polished chamber (non-imaging optic).

We consider a MERCURY-class pump that can deliver 1 KJ of 905 nm light in 1.1 ms. A superconducting linac is selected to take advantage of the long fluorescence-time. For simplicity, we assume a TTF-based linac capable of generating about $3x10^5$ bunches of 1 nC each — filling 1 in 5 RF buckets — at about 60 MeV [11]. Production of the beam may be challenging due to the long RF-pulse and the long drive-laser train: an RF thermionic-gun with a compression alpha-magnet could be considered [12] due to the long FEL wavelength. The resulting beam is sent though an undulator (≈10 m) with a period of 2 cm and a K=1 to produce a 5%-efficient FEL. Each electron bunch would produce some 3 mJ of optical energy, yielding 1 KJ of optical power for the train. Of course, this is an un-optimized design; one could, for instance, consider filling every RF bucket, and shortening the train to 200 μs.

4.2 A 100 TW-Class Laser for LCLS

The Linac Coherent Light Source is one of a few fourth-generation light-sources being constructed [13]. Such a facility will provide x-ray pulses with unprecedented brightness and brilliance. The intensity of the x-ray pulses is sufficient that single-shot measurements are possible and necessary – the target is vaporized. Pump-probe experiments have long been a standard at existing light-sources, and will likely continue at fourth-generation sources. The destruction of the target after a single "probe" pulse implies that new methods must be used to obtain time-delay probe information (i.e. chirped pulses, multiple samples, etc.). The need for multiple laser-sources synchronized to the x-ray pulse seems clear from the user demands [14]. The availability of a 100 TW-class laser may allow for novel experiments (i.e. pumping of high density materials and non-linear techniques) using the intense x-ray pulse as a probe of sufficient intensity to image the target.

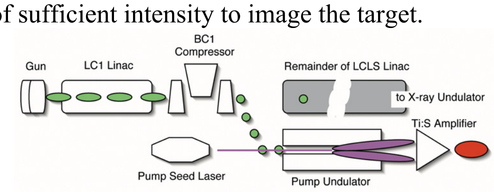

Figure 1: A schematic of the front end of the LCLS with a multibunch beam diverted into a seeded FEL acting as a pump for a Ti:S amplifier.

We envision an FEL driven by the front end of the LCLS including the photoinjector, low-energy linac and bunch compressor. The photoinjector is assumed to have a high quantum-efficiency cathode and be driven by a multi-pulse laser (e.g. LANL AFEL or the DESY TTF). The resultant beam parameters are assumed to be 2000 bunches (filling every 5^{th} RF bucket) each of 1 nC. At the end of the first bunch compressor (BC-1), the beam is 250 MeV with a peak current of 500 A. Such a beam, sent into an FEL with 5% efficiency can deliver 25 J of pump light (at 490 nm) over the fluorescence time of Ti:S (about 3.5 μs). While these parameters appear ambitious, and the beam-loading compensation may require additional linac-sections downstream (running all sections at a lower gradient); the necessary beam-brightness is considerably lower than that required for the LCLS, and the undulator is a long but straightforward design (e.g. 5 cm period, K≈2.5, 10-20 m un-optimized) — such undulators have already been built and used in FELs [15]. A final-amplifier driven by this pump could produce over 10 J of 800 nm light, and could easily be compressed below 100 fs, yielding over 100 TW peak power at the experimental hall.

5. Future Work

The use of an high energy, high-efficiency FEL as a pump for a solid-state lasers may find application in existing facilities as well as purpose-built machines.. Ultimately, the practicality of such a system may be an economic decision as diodes become more affordable. However, the flexibility of the FEL to pump at multiple wavelengths and to act as a useful source in its own right may prevail over a simple cost-analysis. Work remains to find laser-materials better suited to the FEL-based pump-source, optimize the FEL design, and consider a realistic accelerator. Finally, accelerator-based alternatives to FEL pumping need to be considered such as direct electron-beam excitation of a gain material, optical pumping of laser diodes, and FEL-assisted mixing using an optical parametric amplifier (OPA).

6. References

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