

Design of a free-electron laser driven by the LBNL laser-plasma-accelerator [★]

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Abstract

We discuss the design and current status of a compact free-electron laser (FEL), generating ultra-fast, high-peak flux, VUV pulses driven by a high-current, GeV electron beam from the existing Lawrence Berkeley National Laboratory (LBNL) laser-plasma accelerator, whose active acceleration length is only a few cm. The proposed ultra-fast source would be intrinsically temporally synchronized to the drive laser pulse, enabling pump-probe studies in ultra-fast science with pulse lengths of tens of fs. Owing to the high current ($\gtrsim 10$ kA) of the laser-plasma-accelerated electron beams, saturated output fluxes are potentially greater than 10^{13} photons/pulse. Devices based both on SASE and high-harmonic generated input seeds, to reduce undulator length and fluctuations, are considered.

Key words: free-electron laser, laser-plasma accelerator

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Recent advances in laser-plasma accelerators have demonstrated generation of low energy spread, GeV beams [1]. These experiments used an intense ($>10^{18}$ W/cm²) laser pulse focused into a plasma channel ($\sim 10^{18}$ cm⁻³), created using a gas-filled capillary with length of a few centimeters, to generate plasma waves with accelerating fields on the order of 100 GV/m. The bunches emerging from a laser-plasma accelerator have naturally short durations (tens of fs, on the order of the plasma period), and are intrinsically synchronized to the laser driver, making such a source ideal for ultra-fast

pump-probe applications. These laser-plasma accelerator experimental results [1] open the possibility of a new class of compact, high-peak flux, free-electron lasers in which the conventional accelerator is replaced by a GeV-class laser-plasma accelerator (several cm in length), in principle greatly reducing the size and cost of such light sources [2–4].

In this paper we discuss recent design work for a proposed FEL driven by the existing laser-plasma accelerator at LBNL. The base machine and FEL parameters are given in Ref. [3]. They include e-beam characteristics of 500 MeV, 0.2 nC, 20-fs FWHM duration (*i.e.*, 10-kA peak current), $\varepsilon_N = 1$ mm-mrad normalized transverse emittance, and an uncorrelated energy spread of 0.25%. Recently the THUNDER undulator [5] has been transported to LBNL from Boeing and, after magnetic measurements are concluded, is scheduled for installation

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Table 1

FEL Parameters and Numerical Simulation Results	
Radiation wavelength, λ	31 nm
Resonant photon energy	40 eV
FEL parameter, ρ	0.007
3D Gain length	0.2 m
Slippage length	7 μ m
Spontaneous radiation power	8 kW
Steady-state saturation power	29 GW
Energy/pulse (at 5 m)	0.2 mJ
Peak brightness ^a (at 5 m)	2×10^{16}
Saturation length (SASE, 10 kA)	5 m

^a photons/pulse/mm²/mrad²/0.1%BW

into a new experimental area in early 2008. Its characteristics include a 21.8-mm period, linear polarization, and a minimum gap of 4.8 mm producing a peak B of 1.02 T ($K = 1.85$); the field may be tapered linearly in each 50-cm section. Wiggler-plane focusing is provided by a canted-pole topology, leading to a β -function of 3.6 m at 500-MeV energy.

Presently, we are considering two modes of FEL operation: (1) self-amplified spontaneous emission (SASE) and (2) external seeding by a high-harmonic generation (HHG) source at 31-nm wavelength. Existing laboratory HHG sources have demonstrated production of ultra-short (tens of fs) coherent pulses (31 nm) 0.3 μ J of energy (see, Ref. [6]), and we have adopted nominal seed parameters of a Gaussian pulse with 15 MW peak intensity and a duration of 20 fs. HHG seeding has significant advantages over the simpler SASE mode of operation as it will provide improved temporal coherence, reduced fluctuations, and a much reduced power saturation length. On the other hand, SASE operation avoids possible difficulties with mode overlap and shot-to-shot accelerator energy jitter and, moreover, allows simple wavelength tuning by varying the undulator gap.

Table 1 lists the expected FEL performance for the 10-kA beam SASE case. These results were obtained with the GINGER simulation code and presumed a normalized, uncorrelated energy spread σ_E of 0.25% with no temporal energy centroid chirp. At saturation (5 m), the proposed FEL would be capable of producing $>10^{13}$ photons/pulse. Using a 5-kA beam with HHG-seeding, the saturation length is 2.4 m, and the third harmonic power would be $\approx 5\%$ that of the fundamental (12 GW).

Inasmuch as many of the plasma-accelerator e-beam parameters are presently not well determined in terms of shot-to-shot jitter (*e.g.*, beam duration τ_b) or some average values (*e.g.*, ε_N , instantaneous energy spread, and chirp), we have performed a number of FEL output sensitivity studies. For the

HHG-seeded cases, we find that the saturated power drops by a factor of two when σ_E exceeds 0.5% whereas the emittance may be as large as 4 mm-mrad (presuming a matched beam). On the other hand, the third harmonic power is far more sensitive to ε_N than σ_E . For SASE cases, increasing σ_E beyond the nominal value quickly prevents power saturation in the 5-m length of the THUNDER undulator. Simultaneously varying the charge Q and τ_b shows large sensitivity to Q but relatively little to τ_b over a range of 5 to 30 fs. Even in the absence of any accelerator jitter, the RMS shot-to-shot SASE output jitter is about $\pm 25\%$ in photon number at the fundamental and $\pm 50\%$ at the third harmonic.

Even for the small undulator gap, we do not expect resistive wall wakefields to significantly degrade the performance of the FEL for peak currents ≤ 30 kA. Also the induced energy chirp $\delta E/E$ over a coherence length $4\pi\lambda/\rho$ created by the longitudinal Coulomb self-fields should be small compared to the FEL parameter ρ for the parameters considered.

In this paper we have described the design and present status of a proposed FEL driven by the laser-plasma accelerator at LBNL. Further characterization of the electron beam properties are currently underway, as well as continued laser-plasma accelerator development, including triggered injection to further reduce the electron beam energy spread.

We would like to express our appreciation to Boeing Phantom Works for making the THUNDER undulator available through an extended loan for these experiments. We are also grateful for Boeing's assistance in preparing shipping THUNDER to LBNL.

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