FREE ELECTRON LASERS 1996
G. Dattoli, A. Renieri (eds.)
1997 Elsevier Science B.V.



# Ultra-compact, High-gain, High-power Free-electron Lasers Pumped by Future Laser-driven Accelerators

Y.C. Huang[1], R.L. Byer

*Edward L. Ginzton Laboratory, Stanford University, CA 94305-4085, USA*

**Abstract**

The electron bunch length and emittance from a ~ GeV/m laser-driven accelerator are significantly smaller than those from a conventional RF accelerator. We show that in the future a λ = 1.5 Å single-pass free-electron laser with peak and average power comparable to the Linac Coherent Light Source could be constructed within a 25 meter distance, including a 20-meter, 15-GeV accelerator and a ~ 5-meter wiggler.

## 1. Introduction

With the rapid advance of the laser technology, laser-driven accelerators have made significant progress in the last few years. The physics experiment for a dielectric-based crossed-laser-beam accelerator [1], shown schematically in Fig. 1, is being carried out at Stanford University. In Fig. 1 a linearly polarized, 1-D focused $TEM_{00}$ laser beam is spatially split into two beams by a wedge beam splitter cut at the Brewster angle. The two laser beams are focused and recombined at the center of the ~ 400 μm long accelerator stage. The PZT phase controller and the two half-wave plates ensure that on the electron axis the transverse fields cancel and the axial fields add. The analysis in Ref. [1] indicates an average acceleration gradient of 0.7 GeV/m without damaging the optical components.

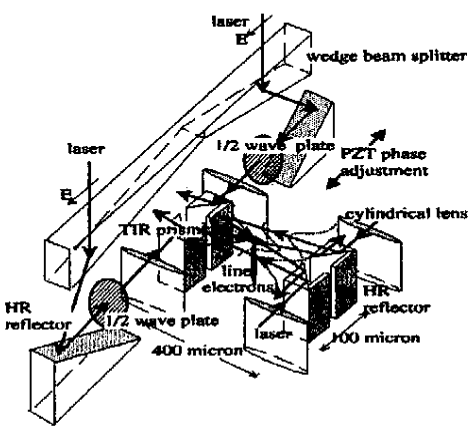


Fig. 1. The Stanford laser-driven accelerator

In a laser accelerator, the electron bunches, separated by a ~ 1 μm laser wavelength distance, are within a 0.1 psec ~ 10 psec mode-locked laser pulse duration. The mode-locked laser pulses, repeating at ~ 100 MHz, are in turn modulated by 10 ~ 20 nsec Q-switch laser pulses. The Q-switch laser pulse repetition rate can be of a few tens of kHz.

Since the acceleration gradient of a laser-driven injector can be of several GeV per meter [2], electron emittance presumably can be improved by orders of magnitude. Moreover, given a constant current, the number of electrons in each optical cycle is about four orders of magnitude less than that in each RF cycle. Therefore normalized emittance in a laser accelerator pumped by a 1 μm laser wavelength could be in the range of $10^{-3} \sim 10^{-5}$ mm-mrad in each optical cycle. The low emittance and the prebunched electron beam from a laser accelerator suggest the possibility of driving an ultra-compact, high-gain, high-peak-power, single-pass

## 2. Laser Accelerator Pumped SASE FEL

The design parameters for the Linac Coherent Light Source (LCLS) using a linear wiggler are listed in the second column of Table 1 [3, 4], and those for the laser accelerator pumped FEL (LA-FEL) are listed in the third column.

The laser power $P$ from the SASE FEL [5] grows exponentially along the wiggler axis $z$, scaled approximately as $P = P_n e^{z/L_{g0}}$ [3], where $P_n$ is the noise power coupled into the synchronism wavelength, $L_{g0} = \lambda_w / 4\pi\rho\sqrt{3}$ is the gain length for a given wiggler period $\lambda_w$, and $\rho$ is the fundamental FEL parameter. Since the fundamental FEL parameter is proportional to the one-third power of the charge density and the charge density is inversely proportional to emittance, the gain length $L_{g0}$ is thus proportional to the one-third power of emittance. In addition, emittance introduces electron longitudinal energy

[1] Department of Nuclear Science, National Tsing-Hua University, Hsinchu, Taiwan 30043

spread, which, along with the intrinsic energy spread and FEL diffraction, increases the gain length according to [3]

$$L_g = L_{g0}\left[1 + F(\eta_d, \eta_\varepsilon, \eta_\gamma)\right], \quad (1)$$

where $F(\eta_d, \eta_\varepsilon, \eta_\gamma)$ is a third degree polynomial of $\eta_d$, $\eta_\varepsilon$, $\eta_\gamma$. The three variables, $\eta_d$, $\eta_\varepsilon$, $\eta_\gamma$, account for the gain reduction due to diffraction, emittance, and energy spread, respectively. The gain reduction due to diffraction is assumed to be negligible, because our parameter range satisfies the optical guiding condition defined in Ref. [6]. free-electron laser (FEL) in the short wavelength regime.

Table 1. Parameters used for the LCLS and the LA-FEL.

| parameters | LCLS | LA-FEL |
|---|---|---|
| wavelength (Å) | 1.5 | 1.5 |
| normalized emittance (m) | $10^{-6}$ | $10^{-9}$ |
| peak current (A) | 5000 | 5000 |
| energy spread (%) | 0.02 | 0.02 |
| rms pulse length $l_b$ | 50 μm | 0.5 Å |
| macro repetition rate | 120 Hz | 50 kHz |
| wiggler period $\lambda_w$ | 3 | 3 |
| wiggler parameter $a_w$ | 2.6 | 2.6 |
| beta function β (m) | 10 | 10 |
| gain length | 3.1 m | 0.2 m |
| saturation length (m) | 58 | 1 ~ 5 m |
| peak photon power | 40 GW | 300 GW |
| average photon power | 0.6 W | 0.8 W |

It can be shown from Eq. (1) that with normalized emittance of $10^{-3}$ mm-mrad the gain length for the LA-FEL is ~ 15 fold shorter compared to that for the LCLS.

Since the rms electron bunch length in a RF accelerator, $l_b \approx 50$ μm, is about 0.05% of the wavelength, $l_b$ in a laser accelerator can be therefore ~ 0.5 nm or 1.7 atosecond for a $\lambda_l = 1$ μm pump laser wavelength. Even though strong slippage due to the short pulse length forces the saturation power in the LA-FEL to scale as $P_{sat.} \approx \rho P_{beam}\sqrt{l_b/l_c}$ [5], where $l_c$ is the coherent length in a SASE FEL, the saturation power in the LA-FEL is about 7 times of that in the LCLS, if emittance of $10^{-3}$ mm-mrad can be achieved in the LA-FEL.

### 3. Coherent Spontaneous Radiation

When the electron bunch length is comparable to or smaller than the radiation wavelength, electrons radiate coherently with a radiation power proportional to $N^2$, the square of the number of electrons. Assuming $a_w = 2.6$ and $\lambda_w = 3$ cm, we calculate in the following the coherent spontaneous radiation power without considering additional bunching or FEL amplification.

With the help in Ref. [7], we show in Fig 2 the average radiation power per unit wiggler length in a 1% spectral width versus the synchronism wavelength. A 1.5 MHz effective μ-pulse repetition rate (30 optical cycle in 50 kHz laser pulses) is assumed. Because the coherent spontaneous radiation energy is proportional to $N^2$, we calculate for $N = 10^5$, $N = 10^6$, and $N = 10^7$ or I = 1 kA, 10 kA, and 100 kA with an uncompressed pulse length of $\sigma_z = 5$ nm. As expected, the coherent radiation power increases dramatically when the radiation wavelength is only a few times longer than the electron bunch length.

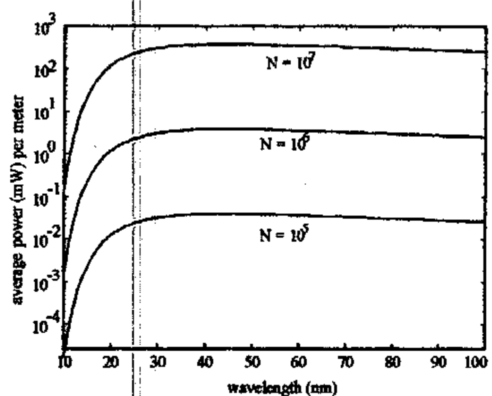


Fig. 2 The coherent spontaneous radiation power from a laser accelerator pumped wiggler.

### IV. Summary

We show in this paper, by employing the laser-driven accelerator, the single-pass SASE FEL wiggler, compared to the LCLS, is reduced in length by ~ 10 fold while reaching a higher or a comparable peak and average power. In the future, the total length of a $\lambda_s = 1.5$ Å FEL pumped by the 0.7 GeV/m gradient laser accelerator [1] could be constructed within a 25 meter distance, including a 20 meter distance for the accelerator. In the soft x-ray and UV spectrum, the powerful coherent spontaneous emission generates milliwatt or a few tens of milliwatt average power from a meter long wiggler pumped by a laser-driven accelerator.

### References


[1] Y.C. Huang, and R.L. Byer, accepted for publication in *Appl. Phys. Lett.* Oct. 7, 1996.
[2] Nakajima *et al.*, *Phys. Rev. Lett.* 74, 4288 (1995).
[3] Ming Xie, Proceedings Particle Accelerator Conference, Dallas, Texas (1995) 183-5.
[4] Arthur, D. Materlik, R. Tatchyn, and H. Winick, *Rev. Sci. Inst.* 66 (2) (1995) 1987.
[5] R. Bonifacio, N. Piovella, and B.W.J. McNeil, *Phy. Rev.* A 44, No. 6 (1994) R3441.
[6] E.T. Scharlemann, A.M. Sessler, and J.S. Wurtele, *Phy. Rev. Lett.* vol. 54 no. 17 (1985) 1925.
[7] S. Krinsky, *Nucl. Inst. Meth.* 172 (1980) 73-6.