LA-UR- 02-5949

Title: Possibility of a High-power, High-gain Amplifier FEL

Author(s): Dinh C. Nguyen, Henry Freund

Submitted to: 24th International Free-Electron Laser Conference
Argonne, Illinois
September 9-13, 2002

Los Alamos
NATIONAL LABORATORY

Form 836 (8/00)

Possibility of a High-power, High-gain Amplifier FEL

Dinh C. Nguyen[1,*] and Henry P. Freund[2]

[1]*Los Alamos National Laboratory*
[2]*Science Application International Corporation*

Abstract

High-gain amplifier FEL offer many unique advantages such as robust operation without a high-Q optical cavity and potentially high extraction efficiencies with the use of tapered wigglers. Although a high average power, cw amplifier FEL has not been demonstrated, many key physics issues such as electron beam brightness requirements, single-pass gains, saturation, etc. have been resolved. In this paper, we study the feasibility of a high-power FEL based on the high-gain amplifier concept. We show that with suitable electron beam parameters, i.e. high peak current, low emittance, low energy spread, and sufficient tapered wiggler length, peak output power of 1 GW and optical pulse energy of 8 mJ can be achieved. We also outline a possible configuration of a high-power, high-gain amplifier FEL with energy recovery.

PACS codes: [Click here and type the PACS codes]

Keywords: [Click here and type the Keywords]

1. Introduction

Amplifier FEL hold the promise of high output power, robust gains and good efficiencies. To operate an amplifier FEL at optical wavelengths, one needs a starting "seed" signal, a high peak current, low emittance electron beam and a long wiggler with two-plane focusing. The seed signal can be either an external laser beam or a low-power return of the FEL beam itself. Amplifier FEL benefit from recent advances in high-brightness electron beam generation and high-gain SASE wiggler development. RF photoinjectors routinely produce low-emittance, high-peak-current electron beams [1]. Large single-pass gains have also been observed at mm [2], IR [3], visible [4] and vacuum UV wavelengths [5]. More recently, SASE saturation has been demonstrated [6]. A concomitant effort to achieve high peak power, high gain FEL, albeit at low duty factors, has proven the concept of regenerative amplification [7]. In principle, high average power and efficiency can be achieved with a properly tapered wiggler and energy recovery of the spent electron beams. However,

practical considerations in transporting electron beams around bends for energy recovery preclude high-efficiency wigglers. This paper focuses on the possibility of a high-power, high-gain amplifier FEL with energy recovery and energy-spread compression to re-circulate electron beams exiting a high-efficiency tapered wiggler.

2. Amplifier FEL Basics

2.1 High power

The optical power of an amplifier FEL grows exponentially with distance z in the wiggler,

$$P(z) = \frac{1}{9} \frac{P_0 e^{z/L_G}}{\left[1 + \frac{1}{9}\frac{P_0}{P_{sat}}\left(e^{z/L_G} - 1\right)\right]}$$

(1)

and saturates at peak power P_{sat} as given by

$$P_{sat} \approx \rho P_{beam} \qquad \text{uniform wiggler} \quad (2a)$$

$$P_{sat} \approx \frac{\Delta\gamma}{\gamma_0} \cdot \eta_C P_{beam} \qquad \text{tapered wiggler} \quad (2b)$$

P_{beam} is the electron beam power and ρ is the FEL gain parameter, defined as

$$\rho = \left(\frac{a_w \lambda_w JJ}{4\pi\gamma}\right)^{2/3}\left(\frac{I}{2I_A\beta\varepsilon_n}\right)^{1/3} \quad (3)$$

The average power is the FEL duty factor, f, times the peak power P_{sat} as given in Eq. 2. High average power is achieved by operating the electron injector and linac at high duty factor. Compared to oscillator FEL, optical damage is a lesser concern in high-power amplifier FEL because there are no high-Q optical resonators.

2.2 Exponential gain

In a sufficiently long uniform wiggler, the FEL power grows exponentially versus distance with a characteristic gain length L_G given by

$$L_G = \frac{\lambda_w}{4\pi\sqrt{3}\rho}(1 + \eta_{3D}) \quad (4)$$

To achieve high gains in a reasonable wiggler length, one minimizes the gain length by employing high peak current (increasing ρ), low emittance, low energy spread electron beams and a Rayleigh range long compared to the gain length (minimizing 3D gain reduction effects) [8].

2.3 High efficiency

The saturated efficiency of an amplifier FEL with a uniform wiggler is poor because of the typically small ρ parameters and slippage in the long wiggler. Using a tapered wiggler and a seed optical signal can provide a significantly higher efficiency. The tapered wiggler efficiency is given by the wiggler's energy taper and the trapping fraction, which is a function of the FEL intensity and the taper rate.

$$\eta_{taper} = \frac{\Delta\gamma}{\gamma_0} \cdot \eta_C\left(I, \frac{\Delta\gamma}{\gamma_0}, L_{taper}\right) \quad (5)$$

With a properly tapered wiggler, the capture efficiency is about 50% and, depending on the energy taper, the FEL efficiency can be as high as 10-20% at optical wavelengths. The difficulty is how to control the large energy spreads in the electron beams exiting the tapered wiggler.

2.4 Optical guiding

The optical beam of an amplifier FEL is not defined by an optical resonator, but by the electron beam emittance and the electron focusing β function. The FEL beam is guided inside the uniform wiggler by the large gain (gain guiding) and by the refractive index of the electron beam (refractive guiding). The rms radius of the FEL beam is determined by the electron beam emittance and focusing optics

$$w_{FEL} = \sqrt{\frac{4\varepsilon_n\beta}{\gamma}} \quad (6)$$

Inside the tapered wiggler, optical guiding decreases sharply and the FEL beam expands at a rate

$$\theta_{FEL} = \frac{\lambda}{4\pi}\sqrt{\frac{\gamma}{\varepsilon_n\beta}} \quad (7)$$

This expansion inside the tapered wiggler can be used to decrease the FEL optical intensity below the damage threshold of any optics that are downstream of the wiggler and thus reduces the risk of optical damage in these optical elements.

3. Amplifier FEL with Energy Recovery

A possible configuration of the high-power, high-gain amplifier FEL with energy recovery is shown in Figure 1. The electron beam travels counter-clockwise, starting from the injector at the top, going around the ring one and a half times and terminates at the beam dump.
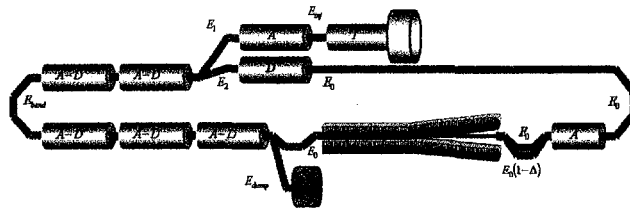

Figure 1. Schematic of the high-power, high-gain amplifier FEL with energy recovery. I: Injector; A: Accelerator; D: Decelerator; A-D: Accelerator-Decelerator (same linac).

The electron beam generated by the injector is boosted to beam energy sufficiently high to overcome space-charge emittance growth in the dogleg bend.

After the dogleg, the beam is accelerated in two linac modules to E_{bend}, and then turns around in an achromatic and isochronous 180° bend. After three additional linac modules, the beam reaches energy E_0, the FEL resonant energy. A chirp is imposed upon the electron beam, either by accelerating the beam off-crest in the linac modules or by adding a phasing cavity, followed by bunch compression in a chicane. The high-peak-current, low-emittance beam is injected into a wiggler with two-plane focusing. In a straight amplifier configuration, an external optical beam is also injected into the wiggler with the electron beam. FEL interaction bunches the electrons and rotates them in longitudinal phase space. The uniform wiggler length is chosen so that the electrons rotate one-quarter of the synchrotron period before the taper section begins.

For improved efficiency, amplifier FEL should employ both high-extraction-efficiency wiggler and energy recovery. This combination however presents difficulties in transporting the electron beams with large energy spreads that result from the strong FEL interaction. To transport the electron beam around bends for energy recovery, one need to compress the electron beam energy spreads [9]. This is accomplished by rotating the electron beam's longitudinal phase space first with a chicane.
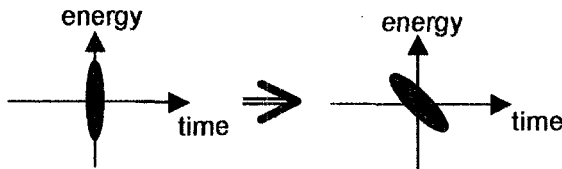

Fig. 2. Action of the chicane stretcher on longitudinal phase space.

The electron beam's longitudinal phase space is then rotated further in a linac operating near zero crossing such that those electrons at the initial energy are unchanged but the electrons at the decelerated energies are accelerated back to the initial energy.
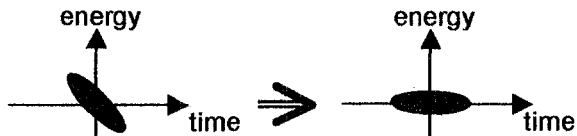

Fig. 3. Action of the accelerating linac operating near zero crossing to compress the electron beam's energy spread.

In effect, the linac provides the necessary power to the FEL and simultaneously compresses the electron beam's energy spread at the expense of a longer electron pulse length.

4. Simulations

Simulations were performed to test the feasibility of the high-gain amplifier FEL operating at 1.06 μ. The low electron beam energy of 76 MeV is chosen because this saves the length of linac modules and RF power and because of concerns for CSR transporting emittance growth in bending a high-energy electron beam. If the beam's normalized emittance at the wiggler entrance is not sufficiently low, it is then necessary to increase the beam energy further. Table I lists the relevant beam and FEL parameters for the MEDUSA and PARMELA simulations.

E_{inj}	10 MeV	λ	1.06 μ
E_1	21 MeV	λ_w	2.18 cm
E_{bend}	43 MeV	K_{ini}	1.085
E_0	76 MeV	ρ	.005
I_{peak}	400 A	L_G	37 cm
Q	3 nC	L_{taper}	6 m
$\varepsilon_{x, rms}$	15 μm	K_{fin}	.929
$\varepsilon_{y, rms}$	7 μm	P_{FEL}	1.05 GW
$\Delta\gamma/\gamma_{rms}$	0.5%	η_{FEL}	3.5%

Table I. Parameters for the amplifier FEL and beam simulations.

4.1 MEDUSA FEL simulations

We use the 3-D, polychromatic FEL simulation code MEDUSA [10] to simulate the interaction in a tapered wiggler. MEDUSA can model both planar and helical wiggler geometry and treats the electromagnetic field as a superposition of either Gauss-Hermite or Gauss-Laguerre modes. The field equations are integrated simultaneously with the three-dimensional Lorentz force equations for an ensemble of electrons. No wiggler-average orbit approximation is used, and MEDUSA can propagate the electron beam through a complex wiggler/transport line including multiple wiggler sections, tapered wigglers, quadrupole and dipole corrector magnets, FODO lattices, and magnetic chicanes. Since it is polychromatic, MEDUSA can treat both sidebands and harmonic radiation.

Figure 4 shows the peak FEL power growth curve for a uniform (z < 9 m) and a tapered wiggler (z > 9 m). Whereas the uniform wiggler saturates at 54 MW, the tapered wiggler continues to amplify the FEL light above 1 GW. The rms optical beam radius also increases at a rate that agrees with Eq. 7.
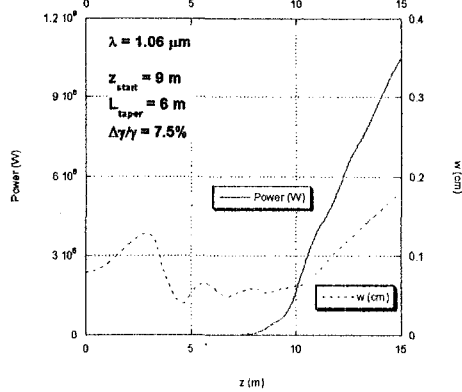

Fig. 4. MEDUSA simulation of power growth in a tapered wiggler.

4.2 PARMELA electron beam simulations

We use PARMELA to simulate the space-charge emittance growth in the electron beam transport from the injector to the wiggler. The electron beams are generated in a 700 MHz photoinjector [11] that produces beam emittance of 6.3 μm in both x and y. After the chicane, emittance in the x (bend) plane increases this number to 13.8 μm (See Fig. 5) whereas the y emittance increases slightly to 7.3 μm. Both of these numbers are less than the 15 μm emittance that was used by MEDUSA to simulate the FEL performance.
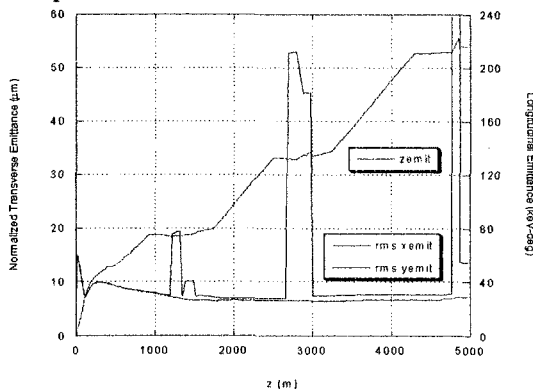

Fig. 5. Normalized transverse emittance and longitudinal emittance of the electron beam from the injector to the chicane.

We have not considered CSR effects in the chicane [12] that can significantly increase emittance in the bend plane. While this could present a problem, it is instructive to note that the wiggling plane can be chosen to be perpendicular to the bend plane, and CSR and other deleterious effects can also be mitigated.

5. Conclusions

We have outlined a possible approach to high-power FEL using recent advances in high-brightness electron beam generation and high-gain amplifier FEL. Using a conservative 3.5% efficiency, such an amplifier FEL can produce 1 GW peak power external to the FEL. We expect with optimisation the tapered wiggler extraction efficiency could be increased to the 10% level. The optical pulses can also be chirped and then compressed to achieve even higher peak power. High average power can be achieved by operating the amplifier FEL at high duty factor. The amplifier FEL can potentially produce high power without the problem of optical damage to the mirrors of the high-Q optical resonator.

6. References

[1] S. Russell, these Proceedings.
[2] T. J. Orzechowski et al., Phys. Rev. Lett. 54, 889 (1985).
[3] D.C. Nguyen et al., Phys. Rev. Lett. 81, 810 (1998); M. Hogan et al., Phys. Rev. Lett. 81, 4867 (1998).
[4] M. Babzien et al., Phys. Rev. E 57, 6093 (1998).
[5] J. Andruszkow et al., Phys. Rev. Lett. 85, 3825 (2000).
[6] S.V. Milton et al., Science 292, 2037, 2001.
[7] D.C. Nguyen et al., Nucl. Instr. Meth. Phys. Res. A, 429, 125 (1999).
[8] M. Xie, in Proceedings of the IEEE 1995 Particle Accelerator Conference (IEEE Cat. No. 95CH35843), p.183 (1995).
[9] C. Pagani et al., Nucl. Instr. Meth. Phys. Res. A 455, 733 (2000).
[10] H.P. Freund, S.G. Biedron, and S.V. Milton, IEEE J. Quantum Electron. 36, 275 (2000).
[11] S. Kurrenoy et al., these Proceedings.
[12] H. Braun et al., Phys. Rev. Lett. 84, 658 (2000).