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Simulation of a Regenerative MW FEL Amplifier

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Abstract

Both oscillator and regenerative amplifier configurations are being studied to optimize the design of a MW-class FEL. The regenerative amplifier uses a longer undulator and relies on higher extraction efficiency to achieve high average power, whereas the oscillator is a more compact overall design requiring the transport of the high energy electron beam around bends for energy recovery. Using parameters extrapolated from the 1 kW LANL regenerative amplifier, simulations study the feasibility of achieving 1 MW average power.

The US Navy is investigating the possibility of using a MW-class Free Electron Laser (FEL) for ship self-defense against anti-ship missiles (ASM). A design workshop resulted in two possible MW FELs, the oscillator and the regenerative amplifier. The MW oscillator design, although it is a more compact overall design, presents a challenge in understanding the electron beam transport phenomena known as coherent synchrotron radiation (CSR) feedback. The regenerative amplifier design uses a longer undulator and relies on higher extraction efficiency to achieve high average power. In studying the LANL proposed parameters for the regenerative amplifier FEL (RAFEL) design [1], this paper explores the analysis of the regenerative amplifier design and optimizes its efficiency.

The amplifier design does not use energy recovery so there is no requirement to bend the high energy beam which can cause deterioration of the electron beam quality; however, without energy recovery, higher extraction efficiency is required. One-dimensional computer simulations are used to describe a single pass of the optical wave and to optimize the efficiency using a tapered undulator. The tapered undulator represents an advantage when the electron phase acceleration δ exceeds the deceleration that can be obtained without taper in strong fields. The single-pass FEL efficiency η of a tapered undulator is the fraction of the electron beam energy converted to laser light. The limit on η is determined by the maximum taper rate δ that can maintain trapped electrons over the number of periods N in the undulator [2]. Gain G is the fractional change in power of the optical power in a single pass through the undulator. In weak fields, the FEL amplifier has high gain described by $G(\tau) \approx exp[(j/2)^{1/3}\sqrt{3}\,\tau]/9$ [2]. The gain is exponential in τ along the undulator with growth rate proportional to $j^{1/3}$, where $j = 8N(e\pi KL)^2 \rho F / \gamma^3 mc^2$ is the dimensionless current density, $\rho = 3 \times 10^9 I(A) / ec\pi r_b^2$ is the electron beam density, and F = "area of electron beam"/"area of light beam" is the filling factor.

Table 1 shows the proposed parameters of the MW regenerative amplifier developed at LANL. The 1 MW RAFEL uses a beam of 100 MeV electrons with a peak current of 400A, yielding a peak electron beam power of 40 GW. The average current of the RAFEL is 0.2 A, so that the average electron beam power is 20 MW. The single-pass FEL efficiency η is the fraction of power extracted from electron beam in one pass through the

Table 1. Parameters for the MW regenerative amplifier designs developed at LANL

Parameters	Proposed Value
Beam energy E	100 MeV
Beam radius r_b (rms)	0.17 mm
Energy spread $\Delta\gamma / \gamma$	0.02%
Pulse duration (FWHM)	20 ps
Peak current $\hat{I}$	400 A
Average current I	0.2 A
Undulator parameter K	1.71
Undulator period λ_0	2 cm
Optical wavelength λ	1 μm

undulator. The RAFEL will feed back on the order of 0.01% to 1% of the optical power and require an extraction efficiency of approximately 10% to 15% in order to provide 2 MW to 3 MW of optical power in the infrared (IR). In an attempt to achieve the desired efficiency, the initial undulator length is $L = 4$ m corresponding to $N = 200$ periods. The dimensionless initial optical field a_0 [2] and tapered undulator of strength δ are varied to find the optimum efficiency. The maximum extraction efficiency found was 8% which is less than the desired efficiency. In an effort to improve the design efficiency, the length of the undulator is increased from 4 m to 6 m. The change in undulator length corresponds to a change in the dimensionless current density to $j \sim 12{,}000$ with $N = 300$ undulator periods. The values of a_o and δ are varied to find the optimum efficiency using numerical simulations. The contour plot of efficiency versus a_o and δ is shown in figure 1.

The maximum efficiency is 13% with gain $G = 556$, a_0 =150, and taper rate $\delta = 260\pi$ starting at time $\tau_S \sim 0.2$ along the undulator. Increasing δ beyond the optimum value, the efficiency drops due to fewer electrons being trapped. For δ below the optimum value, the efficiency drops due to insufficient taper. The effect of changing a_0 away from its optimum value is less sensitive than changing δ. Starting with high a_0, the separatrix does not grow rapidly and trap electrons, resulted in a lower efficiency; whereas with low a_0, more electrons leak out from the separatrix, resulting in a lower efficiency. The above result for efficiency is an over-estimated since it does not include the effect of diffraction of the optical beam, longitudinal pulse effects, or beam quality.

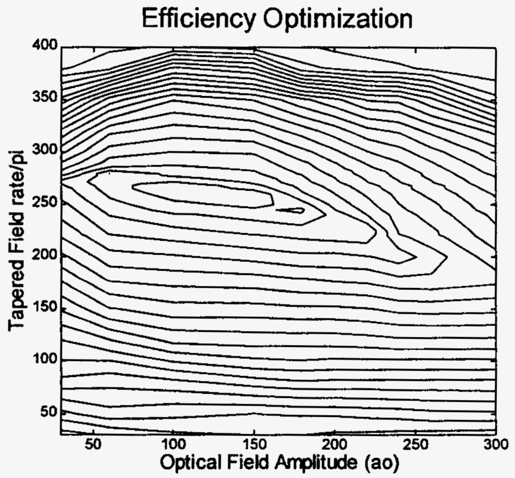

Fig 1. Contour plot of Efficiency vs. Optical Field Amplitude and Tapered Field Strength.

Acknowledgments

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