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Design and Establishment of an Implementation to Simulate and Analyse the Tertiary Undulator of the FEL

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ABSTRACT

This paper discusses how the power of the free electron laser (FEL) beam was increased without increasing the size of the laser device by using a new model with a different technique for the undulator; the purpose of this technique is to make full use of the undulator magnets in a three-row system instead of the two-magnet system. This technique reduces the size of the laser device by decreasing the undulator's length and controlling the path of electrons within the rows of the undulator magnets. From the analysis of the obtained simulation results, it can be concluded that it is possible to make the FEL device with double the power output without increasing the size of the device; this will increase future applications of the FEL in the civil and military fields.

KEYWORDS

Laser, coherent photons, wavelength, output power, magnets, SASE

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1. Introduction

The scientific and technological development witnessed in various fields of life is the result of many important scientific discoveries. One of the most crucial of these discoveries is the laser beam and its use as a tool with high accuracy in solving problems and reaching the best solutions. Therefore, it has become necessary for researchers and scientists to develop laser-generating devices to suit those applications.

Since the invention of the laser by Theodore Maiman in 1960, scientists and researchers have been racing to develop a device that generates a laser beam with distinctive specifications to suit all civil and military applications (Madey, 1971).

The most important specifications of the desired laser are the control of the wavelengths and power of the output laser beam. The best type of laser that produces a laser beam with these characteristics is the free-electron laser (FEL), which was invented 10 years later by John Madey in 1970. The FEL differs from other types of lasers in regard to its physical form. The most effective medium is emitting electrons from an electronic gun. These electrons can be accelerated to reach a certain energy (300–500 MeV) and then enter the undulator (two rows of magnets) to make these electrons move in a sinusoidal motion in order to release coherent photons, which then reach a certain threshold level in a resonator with suitable specifications and eventually leads to the formation of the required laser beam.

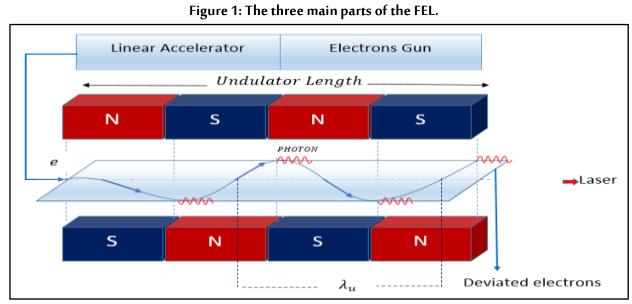
The control of the electrons' energy and the specifications of the undulator are the distinguishing features of the FEL, whereby the wavelength and the power of the output laser beam are controlled. However, the size of the FEL device is a problem in some of its applications; consequently, researchers are working on reducing the size of the device by developing some of its parts (Al-Aish and Jawad, 2017; Kamil and Al-Aish, 2022; Zhang *et al.*, 2013; Varro, 2012; Hannon, 2008).

This paper explores how the power of the FEL beam was increased without increasing the undulator length by using a new model with a different undulator technique; this technique's purpose is to make full use of the undulator magnets in a three-row system instead of the two-magnet system. This technique reduces the size of the laser device by shortening the undulator's length and controlling the path of electrons within the rows of the undulator magnets.

2. Technique and implementation of the work

The FEL self-amplified spontaneous emission(SASE) consists of three main parts (electrons gun, linear accelerator, and undulator) as shown in Figure 1. It illustrates that the original undulator consists of two rows of magnets and that the coherent photons can be increased by increasing the undulator length. This paper demonstrates that a rise in the number of coherent photons was achieved without changing the undulator length. Moreover, a new row of magnets was added, making a total of three rows, as shown in Figure 2 (Mahmood and Al-Aish, 2022; Al-Aish, 2017; Kamil *et al.*, 2019; Mansfield, 2005; Al-Aish and Kamil, 2022).

Figure 1: The three main parts of the FEL.



To calculate the effect of the additional new path on the output laser specification, an executable program called TUFEL was constructed using the Matlab 2019 software, as shown in Figure 3. It contains several parameters to simulate the change in the movement of the electrons, from accelerated linear motion to sinusoidal motion of the synchrotron beam formation.

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Figure 2: The triple undulator of the FEL.

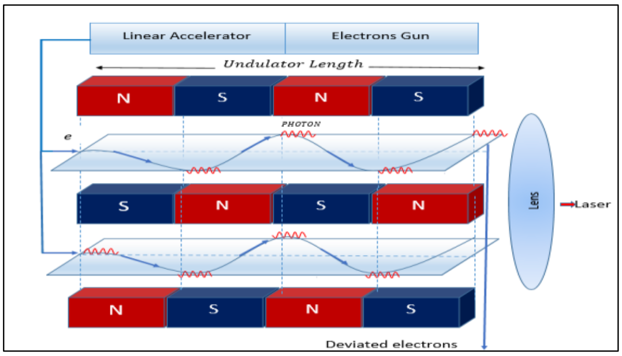
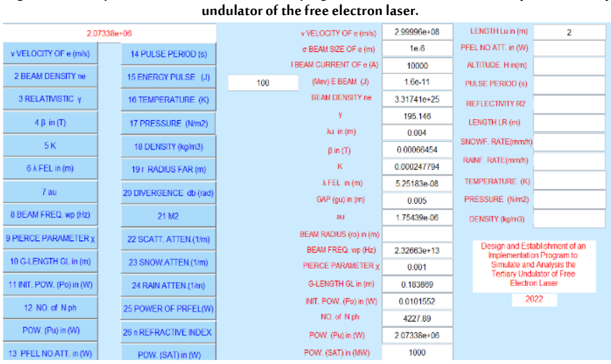


Figure 3: The implementation of the executable program TUFEL to simulate and analyse the tertiary undulator of the free electron laser.



The electrons will move to the first (original) path and the second (new) path through bending magnets. Thus, the number of coherent photons N_{PH} will double as a result of the electrons passing through two paths instead of one path.

The number of coherent photons N_{PH} generated as one electron passes through the original path depends on the number N_u of electron wavelengths λ_u resulting from the oscillation of the electron during its passage through the length of the undulator L_u. The number N_u is calculated by the following equation (Al-Aish and Kamil, 2022; Bergman *et al.*, 2017; Steiniger *et al.*, 2014; Dhedan *et al.*, 2022; Ali *et al.*, a2022):

$$N_u = \frac{L_u}{\lambda_u} \tag{1}$$

Each λ_u generates two coherent photons. Therefore, the N_{PH} for one electron in the first path is given by the equation:

$$N_{PH} = \rho\, E_e\, \lambda / h\, c \tag{2}$$

Where: ρ represents the Pierce parameter, E_e represents the energy of the electrons' beam, c represents the velocity of light, h represents Planck's constant, and λ represents the wavelength of the output laser. λ is calculated using the equation below:

$$\lambda = 4.095 \times 10^{-14} \times \left(\frac{\lambda_u}{{E_e}^2}\right)\left(1 + \left(4354.77 \times {\lambda_u}^2\, B^2\right)\right) \tag{3}$$

Where: B is the intensity of the magnetic field.

Thus, due to the passage of electrons through two paths instead of one path, the number of coherent photons N_{PH} will double.

$$N_{PH} = 2\, \rho\, E_e\, \lambda / h\, c \tag{4}$$

The transmission of an electron beam through the undulator will lead to the generation of a coherent photon beam to form the output laser, which has power formed by the following equation (Ali *et al.*, b2022; Pflueger, 2018; Colson, 1976; Romaniuk, 2009; Al-Aish *et al.*, 2019):

$$P_u = \left(\frac{c\, E_e\, \rho^2\, N_{PH}}{9\, \lambda}\right) e^{(21.57\, \rho\, L_u/\lambda_u)} \tag{5}$$

The saturation power P_{sat} is given by the equation:

$$P_{sat} = \frac{\rho\, I_{beam}\, E_e}{e} \tag{6}$$

Where I_{beam} is the current of the electron beam.

3. Results and discussion of simulation

The main goal of this paper is to reduce the undulator length in order to reduce the size of the FEL device while maintaining or increasing the power of the output laser.

Therefore, the results shown in this paper are concentrated in support of this goal, as shown in Table 1. The standard values of the other parameters of the FEL are shown in Table 2.

Table 1: The results of simulation for (N_{PH}, P_u, and λ).

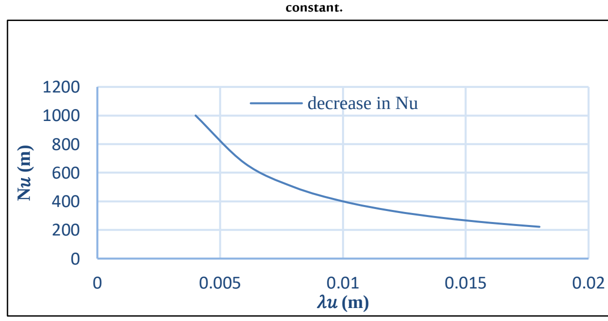
λ_u(m)	N_u(m)	λ (nm)	N_{PH} (one path)	N_{PH} (two path)	P_u(W) (one path)	P_u(W) (two path)
0.004	1000	52.51	4227.89	8455.78	2073380	4146760
0.006	666.6	78.78	6342.27	12684.54	56936.3	113872.6
0.008	500	105.30	8477.71	16955.42	9435.06	18870.12
0.010	400	134.22	10805.3	21610.6	3208.92	6417.84
0.012	333.3	172.47	13884.5	27769	1563.51	3127.2
0.014	285.7	233.79	18820.8	37641.6	935.531	1871.026
0.016	250	338.81	27275.5	54551	636.469	1272.938
0.018	222.2	514.17	41392.4	82784.8	471.706	943.412
0.02	200	791.33	63705	127410	371.18	742.36

Table 2: The standard values of the other parameters of the free-electron laser.

L_u	2 m		σ	1e-6 m		ρ	0.001
I_{beam}	10000 Amp		E_e	100 Mev		Mass of e	9.1e-31 kg
n_e	3.3 e+19		c	3e+8 m/s		P_{sat}	1000 MW

According to Equation (1), the number of electron wavelengths N_u is inversely proportional to the wavelength of the electron λ_u, as shown in Table 1. Figure 4 shows the decrease in N_u against the increase of λ_u while the length of undulator L_u remains a constant.

Figure 4: The decrease in N_u due to the increase of λ_u while the length of undulator L_u remains a constant.



The number of coherent photons N_{PH} in the original first path represents the original photons, which will then increase by forming a new second path parallel to the first one; thus, the coherent photons will double due to their passage through the second path. According to Equation (2), the number of coherent photons N_{PH} is directly proportional to the wavelength λ of the output laser, as shown in Table 1. Figure 5a shows this increase in N_{PH} due to the increase of λ as a result of an increase in λ_u according to Equation (3). Figure 5b shows the relation between λ and λ_u.

Figure 5a: The increase in N_{PH} due to the increase of λ as a result of an increase in λ_u.

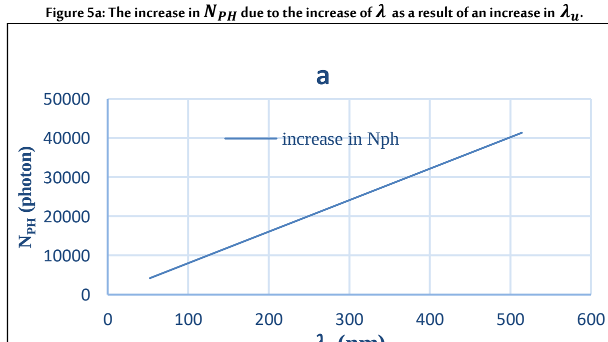
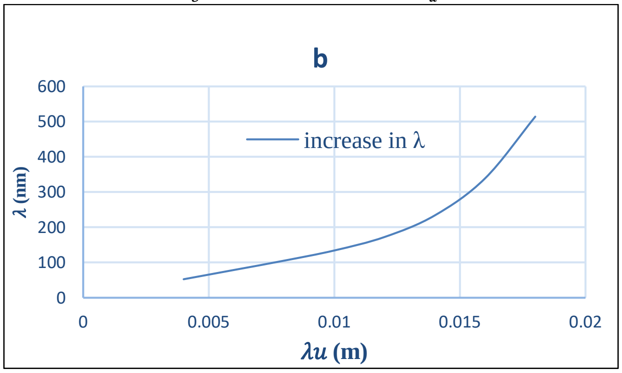


Figure 5b: The relation between λ and λ_u.



The undulator length L_u represents a group of wavelengths λ_u. By increasing the wavelengths λ_u (represented by the second path), the number of coherent photons N_{PH} will be increased according to Equation (4). Figure 6a shows the increase in N_{PH} as a result of an increase in λ_u.

The power of the output laser from undulator P_u will decrease as a result of the increase of λ according to Equation (5). Figure 6b shows the decrease in (P_u). On the other hand, the increase in laser power P_u can be observed in the case of two paths.

Figure 6a: The increase in N_{PH} due to the increase in λ_u.

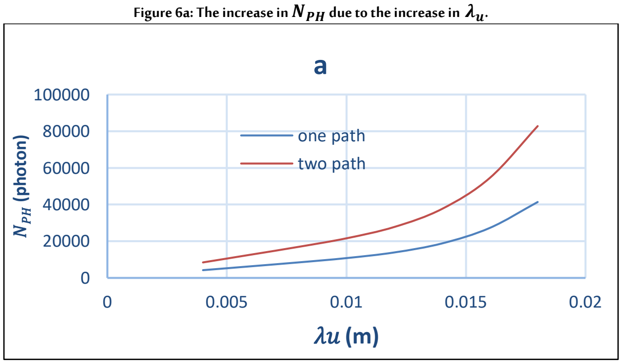
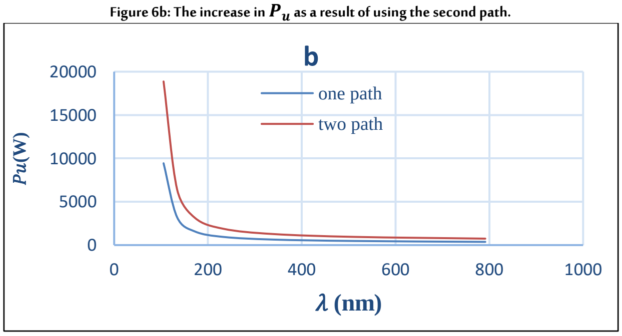


Figure 6b: The increase in P_u as a result of using the second path.



Finally, it is important to clarify that all results of the laser beam power P_u for the first and second paths had the least saturation power P_{sat}, which is 1000 MW according to Equation (6).

4. Conclusions

From the analysis of the obtained simulation results, it can be concluded that the increase in the number of photons as a result of adding the second path led to an increase in the output power of the laser beam without changing the undulator length.

Accordingly, it is possible to make the FEL device with a doubled output power without increasing the size of the device. This will help improve the future applications of the FEL in the civil and military fields.

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