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Design and Simulate a New Defense System of Free Electron Laser DSFEL

Abstract*- As a result of rapid progress in the development of offensive weapons, it became necessary to build up an effective defense system against these technically advanced weapons. In this paper, it has been designed and simulates a new defense system of free-electron laser DSFEL with important advantages capable of destroying air targets (static or mobile) within a range of 70 km from the ground level. The proposed defense system consists of three main units a free electron Laser, optical lenses and control system. Numerous parameters were computed, beginning from the specification and quality of free electron Laser and atmosphere attenuation affecting on the laser beam, in addition to the quality of the target should be destroyed. The results of simulations show that the possibility of destroying any target with high precision despite the large attenuation that occurs to the laser beam such as absorption, scattering, turbulence, and reflection. It is clear through simulations that the original power of laser beam will be significantly reduced as a result of numerous and varied losses as they pass through the atmosphere. But as a final result, the laser can be used as an effective weapon to destroy long-range targets.*

Keywords*- Free electron laser, atmosphere attenuation, undulator, refractive index structure*C_n^2*, Beam divergence.*

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1. Introduction

Most air defense systems of the world's armies use conventional ammunition (bullet or rocket), but the defense system of free-electron laser DSFEL proposed in this work is employed the laser power to defeat a target by structurally destroying sections of its. Many benefits can be achieved by using a laser, such as almost zero time of flight, quick reaction, true line of sight weapon and low utilization cost [1].

As a result of the wide use of laser in our lives, many types of laser have been invented, which vary in power, operation, Wavelength, and complexity. Many significant benefits of a free electron laser FEL over other types of lasers [2], such as adjusted over a range of wavelengths and the efficiency of free electron lasers.

The FEL consists of three units an electron accelerator, a static periodic magnetic field “wiggler or undulator” and an optical resonator as shown in Fig 1. These units interact to produce stimulated emission which leads to coherent radiation in the optical resonator.

The proposed basic design of DSFEL is including simulation to destroy the target (aircraft or missile) within the range of 70 km from the ground level.

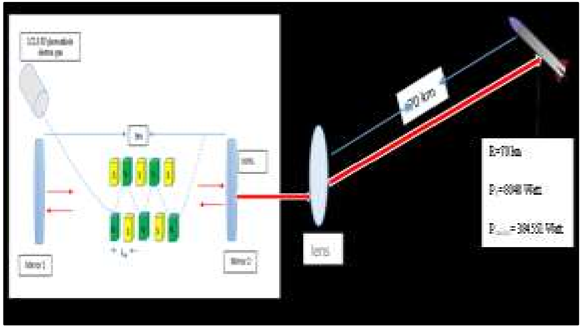

Figure 1: Shows the design of DSFEL.

2. General Design of DSFEL

To create a laser, beam of defense system DSFEL, it was used the linac coherent light source (LCLS) RF photocathode gun to generate electrons beam with energy (135 MeV) [3], which must be accelerated until it approaches the speed of light, and then enters to undulator. Due to the order and sequence of the magnetic poles, the electron beam accelerates in the transverse direction, causing them to emit radiation in the form of light. Finally, the light in the optical resonator is amplified to obtain wavelength λ in Infrared range (λ = 875.1 nm) Table 1 shows a basic parameters used to design DSFEL.

The specific wavelength of DSFE design can be determined from Eq. 1. [4,5]:

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$$\lambda = \frac{\lambda_m}{2\gamma^2}(1+\frac{K^2}{2}) \qquad (1)$$

Where λ_m a period of the undulator, K is the undulator parameter and $\gamma = E_{beam}/m_e c^2$, E_{beam} the electron beam energy.

The undulator parameter K is given by:

$$K = \frac{e\, B_m\, \lambda_m}{2\pi\, m_0 c} = 0.934\, B_m[T]\, \lambda_m[cm] \qquad (2)$$

Where B_m the magnetic field, e electron charge, m_0 invariant mass and c is the speed of light in vacuum.

As the electrons and the radiation propagate through the undulator, the radiation power P_0 grows exponentially as:

$$P_0 = P_r\, e^{d/L_G} \qquad (3)$$

Where P_r the initial power, d is the undulator length. The initial power is the integrated shot noise incoherently radiated into the dominant growing mode by the electrons passing through the first gain length the noise power [4,5]:

$$P_r = \frac{1}{9}\frac{\varphi^2 c\, E_{beam}}{\lambda} \qquad (4)$$

Where$\varphi = (\frac{K\, w_p}{4\gamma\, w_0}\, F_{(k)})^{2/3}$,$w_p = \sqrt{\frac{4\pi\, n_e\, r_e\, c^2}{\gamma}}$, $w_0 = 2\pi c/\lambda_m$, φ is the FEL scaling parameter, w_p is the beam plasma frequency , $F_{(k)}$ is a Bessel function ~1, w_0 is a frequency of oscillation, r_e is a radius of the electron and n_e is the density of electron beam [4,5].

The FEL gain length L_G is inversely proportional with φ , the gain length is given by [5]:

$$L_G = \lambda_m/4\,\pi\,\sqrt{3\,\rho} \qquad (5)$$

Table 1: The basic parameters used to design DSFEL.

Parameters	Amount	Unit
Electron beam energy E_{beam}	135	Mev
Radiation wavelength λ	875.1	nm
Undulator period λ_m	2.5	Cm
Undulator field B_m	1.194	T
Undulator gap g	6	Mm
Undulator parameter K	2.78	
FEL parameter $\boldsymbol{\varphi}$	$1.6x10^{-3}$	
Power gain length L_G	1.24	m
Out power from DSFEL P_0	1130	MW
Undulator Length d	4.5	m
Number of Undulator period N	180	
The length of the cavity resonator L_c	9	m

There are many parameters must be calculated to destroy any target, such pulse duration, wavelength, air pressure, a material of surface target, target velocity and the thickness of the target's surface. Therefore, the power of DSFEL is exposed to a series of attenuation resulting from those parameters. Initially, the laser power P_d (in watt) to defeat a target can be calculated through the amount of energy needed Q_d (in Joules) to heat a certain section from target up to the melting(or vaporizing) point [6].

$$P_d = \frac{Q_d}{t} = \frac{\rho\,(l\,wd_t)}{t}[C(T_m - T_R) + L_m + C(T_m - T_v) + L_v] \qquad (6)$$

Where ρ is a density of surface material, $(l, w\ and\ d_t)$ represent the dimensions for a small section of the target surface (length =2.5 cm , width = 2.5 cm and thickness = 0.3 cm), C the-specific heat capacity of the target, T_m melting point of target material, T_R the target temperature at altitude R , L_m is latent heat of melting of target surface , T_v vaporizing point of target material, L_v Latent Heat of vaporizing of target surface.

Suppose that time t equal to 3 seconds depending on the target speed and the range. The power from DSFEL must be focused on the target long enough for the surface material to absorb the radiation. Table 2 presents a list of different targets with their velocity, burn time, surface material (often steel or aluminum), surface thickness and the Power that required destroying its target.

The greatest losses that reduce the impact of DSFELs' power are reflectivity of the target surface, where the polished surface will reflect more energy than a roughened surface. The reflectivity of polished of steel and aluminum around 90% (losses in the power), therefore the power needed becomes[6]:

$$P_{needed} = \frac{P_d}{1-0.90} = 10\, P_d \qquad (7)$$

In this paper, the amount of power needed to destroy a target was calculated at a distance of 70 km, and it was about 384551 watts. When a laser beam of DSFEL propagates through the atmosphere, other losses will be attenuate the beam such as turbulence, scattering, absorption and thermal blooming.

Table 2: Thermal Properties of Common Metals [1].

Parameters	Missile	Aircraft
Velocity $\boldsymbol{v_t}$ (m/s)	800-5250	50-350
Surface Material	Steel	Aluminum
Surface Thickness d (cm)	0.1-0.3	0.1-0.3
The-specific heat capacity C (J/gm.C^0)	0.452	0.91
Melting point $\boldsymbol{T_m}$ (C^0)	1425	660
Vaporizing point $\boldsymbol{T_v}$ (C^0)	2971	2467
Latent Heat of Melting $\boldsymbol{L_m}$ (J/gm)	250	321
Latent Heat of Vaporizing $\boldsymbol{L_v}$ (J/gm)	6200	10500
Density $\boldsymbol{\rho}$ (gm/cm^3)	7.87	2.70
Mass m (gm)	14.75	5.06
Total Energy $\boldsymbol{Q_d}$ (J/cm^2)	1153653	664029
Total Power $\boldsymbol{P_d}$ (Watt)	384551	221343

I. Standard Atmosphere modeling

The Standard model of Atmosphere is used to determine the amount of temperature (T) pressure (P) and density (ρ) as a function of the altitude. Temperature decreases with altitude at a constant rate of -6.5 K /km up to the troops (Borderline between the troposphere and the stratosphere) from 0 to 11 km where this layer contains 78.09 % Nitrogen gas, The change in temperature rate from 11 to 20 km is 0 K/km where T in this altitude is constant 216.650 K , and from 20 to 32 km the change is 1 K/km where T increased with altitude because in this layer (Stratosphere) it contains Ozone gas and this gas absorbs short wavelengths thus the heat rises, from 32 to 47 km T increasing with altitude (rate 2.8 K/km). While from 47 to 51 km the change is 0 K/km (T become a constant at 270.650 K). Finally, from 51 to 71 km the T decreasing with altitude at a rate -2.8 K/km. To calculate the temperature degree at any altitude by [7,8]:

$$T = T_L + L_{rate}(R - R_{\ L}) \qquad (8)$$

Where T_L is the temperature at the base of the layer, L_{rate} is the change in temperature rate, R the Altitude in meters, $R_{\ L}$ is the altitude at the base of the layer in meters.

The Pressure variations with altitude can be calculated by using the [8]:

$$P = P_L \ exp\left[\frac{-g(R-R_L)}{r_g\, T_L}\right] \qquad (9)$$

Where the P_L is the pressure at the base of the layer, r_g real gas constant for air = 287.04 $m^2/K.sec^2$, g the acceleration of gravity = $9.80665\ m/sec^2$.

The density in the altitude R given by [7]:

$$\rho = \frac{P_L\ exp\left[\frac{-g(R-R_L)}{r_g\, T_L}\right]}{r_g(T_L+L_{rate}(R-R_{\ L}))} \qquad (10)$$

II. Loss of turbulence

The turbulence is generating as result to the change of air density and thermal gradients in the atmosphere layers. That's lead to changing the refractive index of those layers; consequently, refract the path of the laser beam. The refractive-index in Earth's atmosphere is a function of pressure, temperature, and wavelength, and wavelength of laser weapon (in this work (λ = 875.1 nm)). The refraction-index neglecting water vapor pressure is given by [8]:

$$n = 1 + \frac{77.6\ P}{T} \times\ 10^{-6}\ \left[1 + \frac{7.53x10^5}{\lambda^2}\right] \qquad (11)$$

It's essential to analysis the propagation of laser weapon energy through atmospheric layers so that they constructively interfere to form a high irradiance spot size on target. In addition, constructive interference will not be induced due to changes in the refractive index.

Another important parameter is the refractive-index structure parameter for characterizing the amount of refractive index fluctuation and it's descript by the value of C_n^2 Table 3 show the Refractive index structure parameter influence on the atmosphere, The amount of given by [9]:

$$C_n^2 = \frac{[(n_2-n_1)^2]}{r^{2/3}} \qquad (12)$$

Where r represents a scalar distance.

Table 3: Refractive index structure parameter influence on the atmosphere [6].

$\boldsymbol{C_n^2\ (m^{-\frac{2}{3}})}$	**Atmospheric turbulences**
10^{-16}	Weak
10^{-15}	Mean
10^{-14}	strong
10^{-12}	Very strong

Fried parameter r_0 is used to describe the turbulence of the beam propagation, which represents an atmospheric coherence diameter. The r_0 parameter is a circular diameter of the laser beam which maintains coherence in the propagation distance. A lower r_0 value implies stronger turbulence. If the r_0 value is significantly smaller than the laser beam director size, the laser beam will break up into much smaller, incoherently radiating beam. The relation between r_0, C_n^2, λ, and the distance to target d can be given by [10]:

$$r_0 = \frac{0.33\,\lambda^{6/5}}{[R^{\frac{3}{5}}\left(\frac{[(n_2-n_1)^2]}{r^{\frac{2}{3}}}\right)]^{3/5}} \qquad (13)$$

III. Loss of Scattering

The scattering coefficient model under the influence of haze (μ) is:

$$\mu = \frac{3.912}{R}\left(\frac{55x10^2}{\lambda}\right)^q \qquad (14)$$

Where λ is wavelength in angstrom (in this work λ = 8751 A^0), μ scattering coefficient in haze weather (Km^{-1}), R is the range in Km and The value of q depends on the range of laser weapon, when $R \leq 6\,km$ q is given by $0.585\ (R)^{1/3}$ and when $6km < R < 50\ km$ q is equal to 1.3 and for $R > 50\ km$ q is equal to 1.6 [11].

When the laser beam travels from the DSFEL toward the target during the atmosphere, there will be a loss of power due to atmospheric attenuation (mainly due to gas absorption). From the law of Beers-Lambert, the attenuation of laser power through the atmosphere is[10]:

$$P_R = P_0\, e^{-\mu R} \qquad (15)$$

Also, the time needed to deliver the power between the DSFEL and the target is calculated

Also, the distance (D_t) will travel to reach the target during the time for the laser beam to arrive at needed target it can be calculated by:

$$D_t = v_t\left(\frac{R}{3x10^8}\right) \qquad (16)$$

Where v_t the speed of the target in m/s, R the altitude in mater and the D_t distance [2].

The laser beam of DSFEL can be accurately modeled as a Gaussian beam. The expansion of spot size e called Beam divergence $\emptyset_d$ which can be calculated by the following equation [10]:

$$\emptyset_d = \frac{\lambda\, R}{\pi} \Bigg/ \frac{0.33\,\lambda^{6/5}}{\left[R^{\frac{3}{5}}\left(\frac{[(n_2-n_1)^2]}{r^{\frac{2}{3}}}\right)\right]^{3/5}} \qquad (17)$$

3. Results and Discussion

In this work, the results were obtained by simulation using the Visual Basic software, where many parameters were calculated, which attenuated the DSFEL's power. Table ٤ shows the data of the attenuation of DSFEL power. . It can be seen from Fig (2) the power of DSFEL depended on undulator length d, that means a power generation of 1130 MW needs a length of undulator equal to 4.5m. Fig 3. shows accurately that moving away from the earth's surface causes a significant change in temperature, as a result to different composition of the atmosphere depending on Eq.8. Also the pressure P (mbar) and density ρ (kg/m^3) Varies with altitude R (km) depending on Eqs.9, 10 as shown in Figs. 4&5. It can be shown the P and ρ drops exponentially with increasing altitude above mean sea level because most of the atmospheric mass is concentrated in a troposphere layer. Subsequently, this has significant effects on the DSFEL's power depending on the amount of change in T, P and ρ.

The change of values T and P causes variation in the refractive index n, Where the refractive index decrease continuously until it reaches ~1 at 70 km. Fig 6 shows the change in refractive index n as function Pressure P (mbar).

Table 4: show the data of the attenuation of DSFEL weapon

R (Km)	**T (K)**	**P (mbar)**	$\rho\ \left(\frac{kg}{m^3}\right)$	**n**	$C_n^2\ (m)^{-2/3}$	$\mu_{total}\ (Km)^{-1}$	**r_0 (m)**	**$\emptyset_d$ (m)**	**P(W)**
0	288.15	1013.25	1.225	١.٠٠٠٢٧٢٨	$6.37x10^{-12}$	٠	٠.٠٠٧٧	٠	$1130x10^6$
5	255.65	540.18	0.736	1.0001639	$2.89x10^{-12}$	٠.٤٩١٦	٠.٠٠٦٩	٠.٥٩٧	$1.90x10^6$
10	223.15	264.34	0.4127	1.0000919	$1.18x10^{-12}$	٠.٢١٧٨	٠.٠٠٩٢	١.٩٦٠	$0.43x10^6$
15	216.65	120.44	0.1936	1.0000431	$3.96x10^{-13}$	٠.١٤٢٥	٠.٠١٥٤	٣.٥٣٨	$0.18x10^6$
20	216.65	54.74	0.0880	1.0000190	$8.18x10^{-14}$	٠.١٠٦٩	٠.٠٣٥٧	٤.٥٣٢	$0.10x10^6$
25	221.65	26.154	0.0411	1.0000091	$1.71x10^{-14}$	٠.٠٨٥٥	٠.٠٨٤٣	٥.٠٧٥	64669.4
30	226.65	12.909	0.01984	1.0000044	$3.82x10^{-15}$	٠.٠٧١٢	٠.١٩٤١	٥.٣٥٩	٤٤٠٧٩.٨
35	237.05	7.120	0.0104	1.0000023	$9.78x10^{-16}$	٠.٠٦١١	٠.٤١٥٨	٥.٥٠٩	٣١٨٤٦.٢٥
40	251.05	4.372	0.0060	1.0000013	$2.95x10^{-16}$	٠.٠٥٣٤	٠.٨١٣٥	٥.٥٩٥	٢٤٠١٨.٢٦
45	265.05	2.827	0.0037	1.00000082	$1.00x10^{-16}$	٠.٠٤٧٥	١.٤٩٢٢	٥.٦٤٦	١٨٧١٩.٥١
50	270.65	1.646	0.0021	1.00000047	$3.13x10^{-17}$	٠.٠٤٢٧	٢.٨٨٤٢	٥.٦٧٧	١٤٩٧٦.٢

55	259.45	0.689	0.00092	1.000000200	$6.47x10^{-18}$	٠.٠٣٣٨	٧.١٧٦٤	٥.٦٩٣	٦ ١٢٥٦٢.٣
60	245.45	0.246	0.00035	1.000000078	$1.02x10^{-18}$	٠.٠٣١٠	٢١.٠٧٠	٥.٦٩٩	١ ١٠٦٩٨.١
65	231.45	0.078	0.00011	1.000000026	$1.29x10^{-19}$	٠.٠٢٨٦	٧٠.٧٩٠	٥.٧٠١	٤ ٩٢٢٧.٢٩
70	217.45	0.021	0.000034	1.000000007	$1.22x10^{-20}$	٠.٠٢٦٥	٢٨٣.٧٤	٥.٧٠٢	٨٠٤٧.٦٨

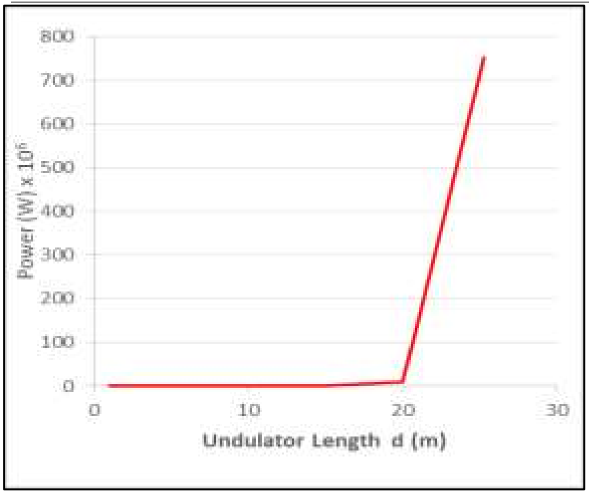

Figure 2: Shows the Power of DSFEL depend on Undulator length d (m).

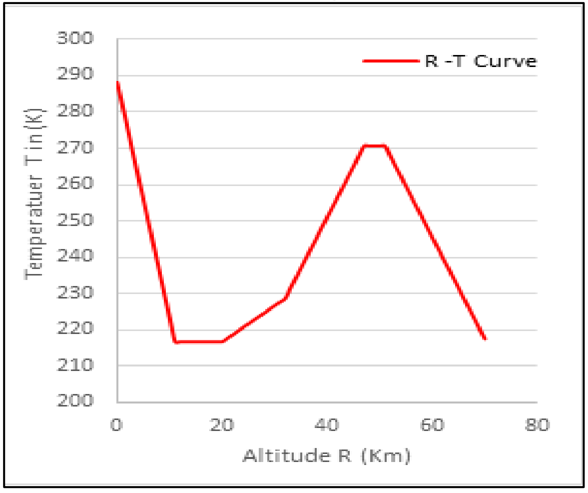

Figure 3: shows the change in temperature degree with altitude R (km).

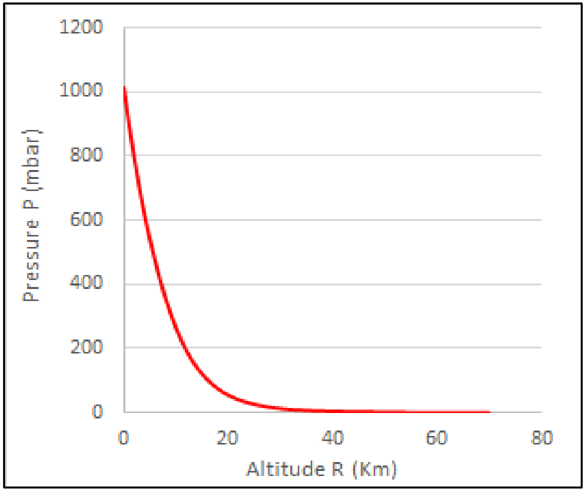

Figure 4: Shows the change in Pressure P (mbar) with altitude R (km).

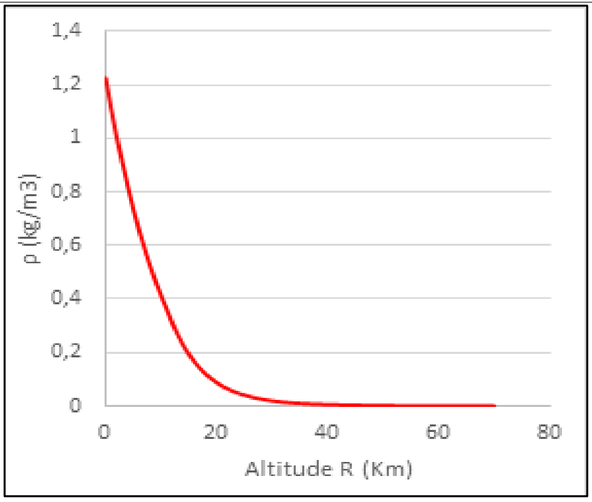

Figure 5: Shows the change in the density ρ (kg/m3) with altitude R (km).

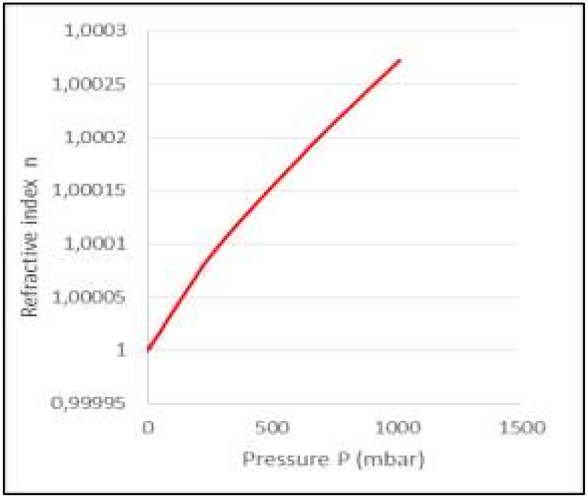

Figure 6: shows the change in refractive index n as function Pressure P (mbar).

The refractive index structure constant C_n^2 use to measure the strength of atmospheric turbulence and it decrease with altitude and when C_n^2 increases cause increases in atmospheric turbulence Fig 7. Shows the change in the index of refraction structure parameter $\boldsymbol{C_n}^2(\mathrm{m})^{-2/3}$ with altitude R (Km), The scattering and absorption coefficient $\boldsymbol{\mu}$ $(\mathrm{Km})^{-1}$ an exponential function of altitude R (km) as shown in Fig 8. The acute disturbances occur in the first layer of the atmosphere (0 to 11 km) which are caused by the gases and soils that are abundant in this layer.

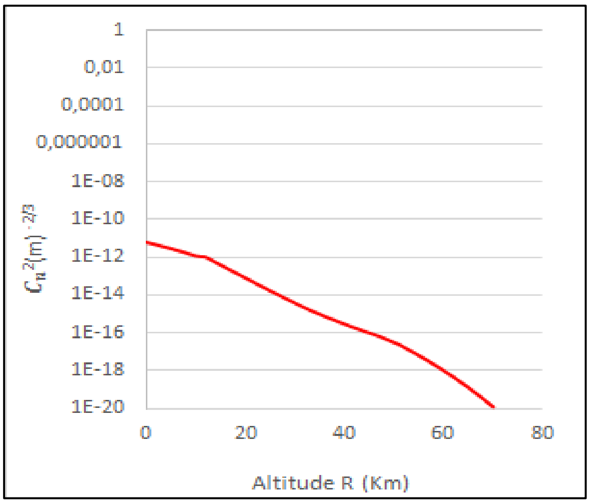

Figure 7: Shows the change in the index of refraction structure parameter $C_n^2 (m)^{-2/3}$

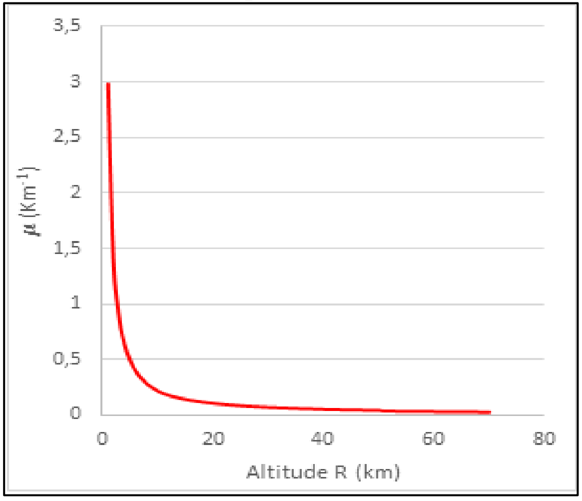

Figure 8: Shows the scattering and absorption and fog coefficient as an exponential function of altitude R (km).

The Fried parameter r_0 parameter defines a circular diameter over which the laser beam maintains coherence Fig 9. Shows change in the Fried parameter r_o (m) with Altitude R (Km). The laser weapon power P_R (watts) that arrives in the target decrease with altitude Fig 10. show the effect of altitude R (km) on laser power P_R (W) we can see the power exposed to high losses in the first five-kilometer because the concentration molecular of gasses and dust be higher than the layers above it. Fig 11 Show the change in the distance D_t target will travel before Power reach it with altitude R for the Aircraft and Missile, that means an increase in the time needed to deliver the power between the DSFEL and the target, where D_t depend on the speed of the target. Finally, Fig 12 Shows the Divergence of beam spot size of laser $\emptyset_d$ (m) with Altitude R (Km). It can be seen the high divergence of beam spot size occurs in troposphere layer. Therefore, a lens should be used to reduce the laser beam divergence.

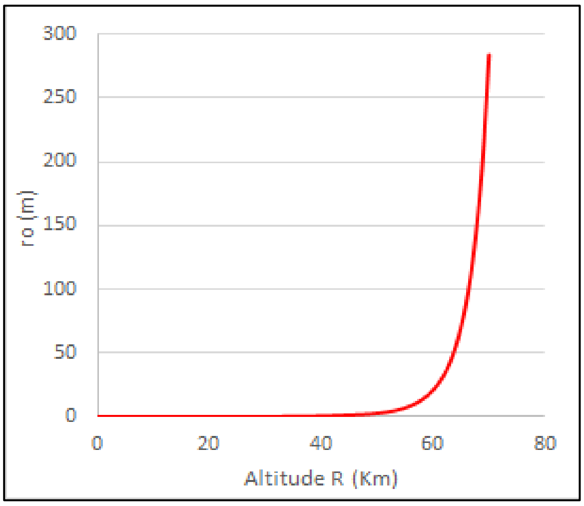

Figure 9: Shows change in the Fried parameter r_o (m) with Altitude R (Km)

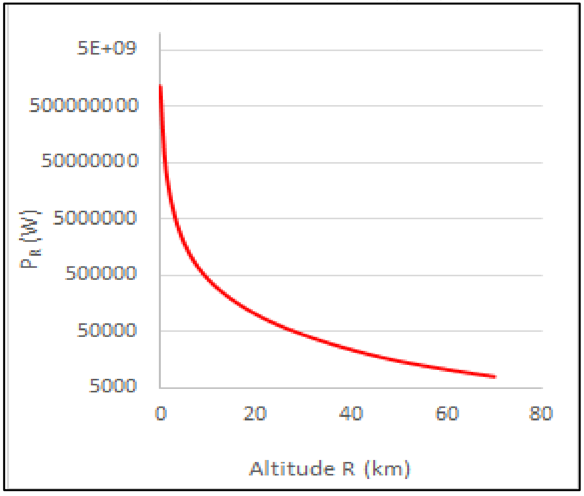

Figure 10: Shows the effect of altitude R (km) on laser power P_R (W).

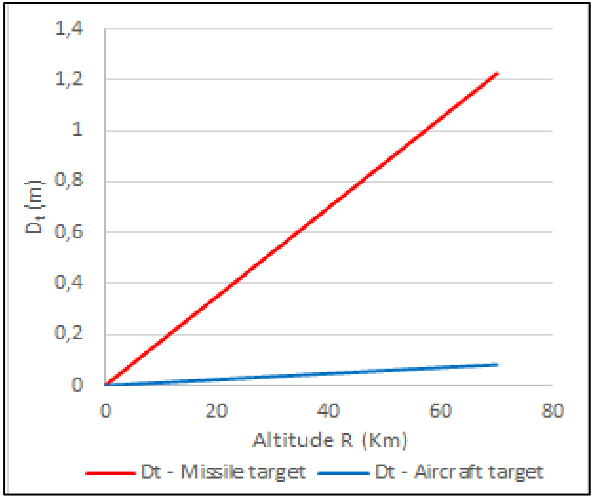

Figure 12: Shows the change in the distance D_t target will travel before Power reach it with altitude R (km).

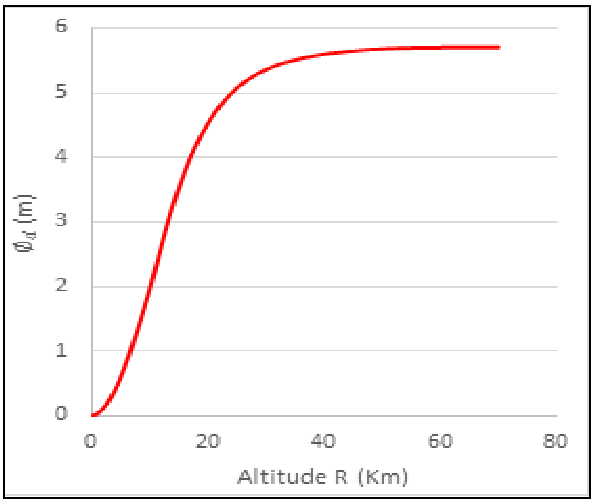

Figure 32: Shows the Divergence of beam spot size of laser $\emptyset_d$ (m) with Altitude R (Km).

4. Conclusion

- The effectiveness of DSFEL depends on the energy of electron beam and the Undulator length, where the output power of DSFEL can be controlled by increasing the undulator length.
- The wavelength of DSFEL weapon depended on the undulator period, undulator field and energy of electron beam.
- The turbulence effect significantly on the effectiveness of DSFEL, which is produced from temperature fluctuations, construction of the gas and dust atoms.
- The high attenuation be in the troposphere layer (0-11 km) and decreased by increasing the Altitude.

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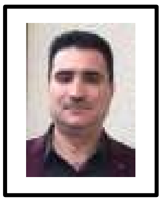

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