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A FREE ELECTRON LASER WEAPON FOR SEA ARCHER

by

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Sea Archer is a conceptual design for a 181 m long Surface Effect Ship, displacing 13,500 tons, that can achieve speeds up to 60 knots. It's main role is to act as a small aircraft carrier with an air wing of Unmanned Combat Air Vehicles, Unmanned Air Vehicles and helicopters. The proposed date for employment is 2020. To provide self defense, a layered defense concept was proposed and the FEL weapon is to be the inner layer defense.

It is shown that the requisite power would be a beam output of 1.5 MW operating in the 1μm wavelength. This minimizes the effect of atmospheric attenuation, thermal blooming and turbulence. The system proposed will be installed on the Sea Archer within a volume of 12 m by 4m by 2m with an expected weight of 55 tons. It will have two beam directors optimizing the coverage angle of the ship. The system will be drawing power from energy storage devices, which enables the weapon to fire up to a total of 10 targets or 60 seconds of engagement before recharging is required.

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A FREE ELECTRON LASER WEAPON FOR SEA ARCHER

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"*I can do all things in HIM who strengthens me"*

Philippians 4:13

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I. INTRODUCTION

Lasers have many industrial and scientific applications; low power uses include surgery and fiber optic networks, while high power lasers are employed in the manufacturing industry for welding and material processing. The military also has a vested interest in applying this technology as a directed energy weapon. For instance, a shipboard directed energy weapon system would provide many advantages for point defense; foremost will be the speed of light beam coupled with the high lethality it provides against an incoming Anti-Ship Cruise Missile (ASCM). The most promising type of laser weapon in a naval environment would be the Free Electron Laser (FEL).

FELs provide coherent, tunable, high power radiation, which spans wavelengths from millimeter to visible, with the potential of achieving ultraviolet to x-ray wavelengths. It is also capable of exhibiting similar optical properties characteristic of conventional lasers such as high spatial coherence and a near diffraction limited radiation beam. A difference from conventional lasers is the use of a relativistic electron beam as the FEL lasing medium, as opposed to electrons in bound atomic or molecular states. Hence, the term "free-electron laser". The main advantage of FELs compared to chemical or CO_2 lasers is the tunability of the laser beam. This allows users to change the wavelength of light to suit the application. At present, there has been no attempt to reach the power output required for missile engagements. To date, the most powerful FEL has 2 kW average power at the Thomas Jefferson National Accelerator Facility (TJNAF), though it may be modified to an increased power output of 10kW and even to 100kW in a few years. [1]

This thesis will study the effectiveness of a FEL as a weapon and propose a system that can be installed on the Sea Archer. The Sea Archer is a design project for a fast and lightweight aircraft carrier undertaken by the NPS Total Ship System Engineering (TSSE) curriculum. This concept was initiated by Admiral Cebrowski at the Naval War College during their annual war games. The ship design is part of a school wide project called Crossbow. It includes students from

System Engineering and Integration, which analyzed the requirements and are the overall systems integrators. The Aeronautics department was involved in designing an Unmanned Combat Air Vehicle (UCAV) for the aircraft carrier called Sea Arrow, while students in the Logistic curriculum provided the logistic analysis and support for the whole Crossbow Taskforce. The complete combat system suite for Sea Archer was assigned to the author for implementation and design.

Chapter II discusses the background concept for the Sea Archer carrier and proposes an original configuration of combat systems derived by the author for the platform.

Chapter III provides a comparative study between the FEL and the Rolling Airframe Missile (RAM). The author will prove the effectiveness of the FEL in terms of engagement time.

FEL theory and simulations will then be covered in Chapter IV. This will provide an overview of the physics pertaining to an FEL weapon. A discussion on the benefits of utilizing short Rayleigh lengths supported with simulation results of the power and gain output will be presented. This portion was a co-authored paper presented at the 23rd International Free Electron Laser Conference held in Darmstadt, Germany.

Target engagements issues will be discussed in Chapter V, with emphasis for a FEL as a combat system onboard a ship. Beam propagation issues in a naval environment were also analyzed by the author.

Chapter VI will propose the system architecture of a FEL weapon onboard onboard the Sea Archer. FEL parameters necessary for a shipboard weapon are also discussed.

II. BACKGROUND

The Sea Archer will be a 13,500 Ton aircraft carrier, employing a surface effect concept to achieve a top speed of 60 knots. There will be a total of 8 embarked Unmanned Air Combat Vehicles (UCAVs) performing strike and combat air patrol roles, while Helicopters will be utilized for mine detection and clearance roles. Torpedoes and missiles will allow it to also attack submarines and surface crafts respectively. Other Unmanned Air Vehicles (UAVs) will perform air surveillance and reconnaissance tasks.

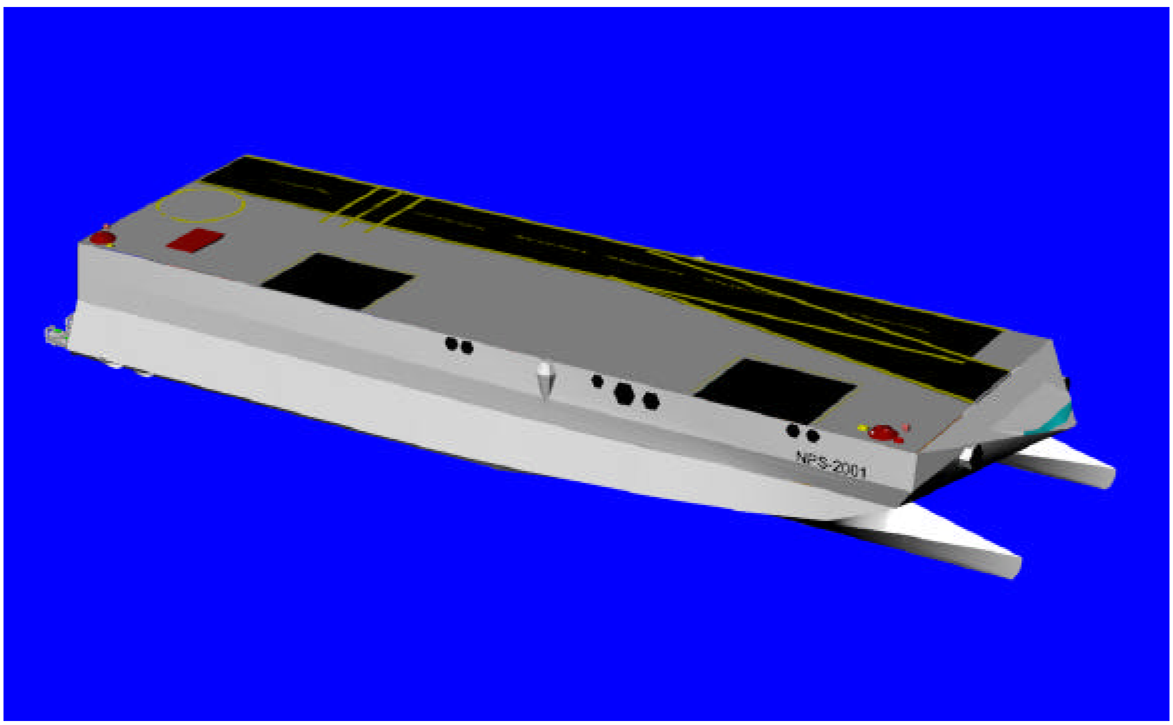

Figure 1 – Sea Archer

To enhance its effectiveness it is expected that Sea Archer will travel as part of a Crossbow taskforce that will include 7 other Sea Archers, Sea Lance IIs' and Sea Quivers. Sea Lance IIs' will be a platform that provides superior long range defense capability for the taskforce matching the speed and performance of Sea Archer. Sea Quiver will be a replenishment vessel that has the ability to match the endurance and speed of the Sea Archer. The paradigm of this taskforce is to exploit the advantages of distributed platforms which is contrary to current deployment concepts of a Carrier Taskforce Group.

One of the tasks in designing the ship is to provide a comprehensive combat suite to ensure the survival of the vessel in a combat scenario. To fulfill this requirement, a layered defense was implemented for the combat system suite. Layered defense provides “Rings of Fire” against enemy targets at different ranges. The notion is that each layer will take out any missiles that had leaked from a previous layer and as such provide adequate overlapping protection to the vessel in an event of a missile saturation attack. Table 1 and Table 2 provides an overview of this concept for surface and air defense.

	Range	***Sea Lance***	***Sea Archer***
Outer Layer Defense	200 km		Sea Arrow
Middle-Layer Defense	50 km	Medium Range Missiles	
Inner-Layer Defense	30km	Super Sea Sparrow Missile	Super Sea Sparrow Missile / USC Missiles
Point Defense	5 km	RAM	FEL

Table 1 - Layered Air Defense for Sea Archer

	Range	***Sea Lance***	***Sea Archer***
Outer Layer Defense	>200 km		Sea Arrow
Middle-Layer Defense	>50 km	Harpoon / Medium Range Missiles	
Inner-Layer Defense	30km	Super Sea Sparrow Missile	Super Sea Sparrow Missile / USC Missiles / Helo Missiles
Point Defense	5 km	SCGS	FEL/SCGS

Table 2 - Layered Surface Defense for Sea Archer

It can be seen that Sea Archer is heavily dependant on other assets for long range defense and as such its point defense system has to be highly effective in the event of saturation attack by Anti-Ship Cruise Missiles (ASCM). This system must be able to engage targets at longer ranges and allow quick reengagements of multiple targets. For Sea Archer, the FEL system has been suggested as the weapon of choice for the final layer.

Other systems included in the Sea Archer combat system suite are shown in Figure 2. To complement the FEL system, there are a total of 64 Sea Sparrow type of missiles that are to engage air and surface targets up to 30 km. It is also supported by an Unmanned Surface Craft (USC) that carries short range missiles for surface to air and surface to surface engagements. Four Small Caliber Stabilized Gun Systems (SCGS) will provide protection from surface targets with the ability to engage up to 5km.

Sensor suites include a Multi-Function Radar, Volume Search Radar, Infra-Red Search and Track and Electro-Optical Systems. This would all be integrated with a Cooperative Engagement Capability, where information would be shared seamlessly across the entire Crossbow taskforce.

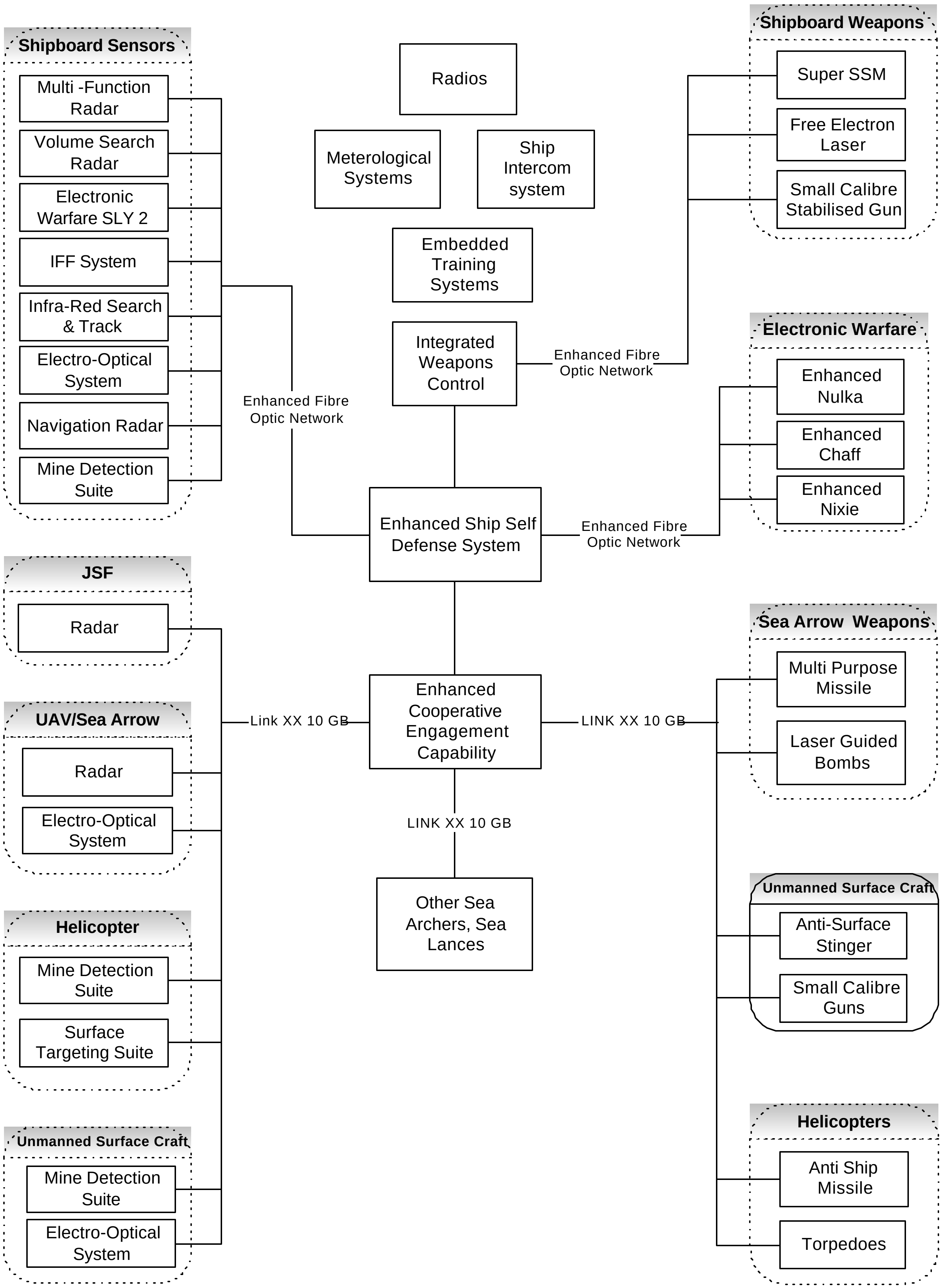

Figure 2 – Sea Archer Combat System Layout

III. RAM AND FEL COMPARISON

Current US Navy warships have the Phalanx Close in Weapon System (CIWS) as the final layer of defense against incoming ASCMs. The problem associated with this type of protection is the extremely short engagement range, typically at 1000m. At these distances, even if the incoming missile has been hit by several 20-millimeter rounds from Phalanx, the danger still exists that the missile has sufficient inertia and remaining components to damage the ship. This has been recognized and as such, all current and future USN ships will be upgraded to fire the RAM system to extend the engagement range.

A. RAM CHARACTERISTICS

The Rolling Airframe Missile (RAM) will be the weapon system that faces threat scenarios similar to a FEL Weapon System. Used as point defense for current and future US Naval Platforms, it exists in three possible configurations, the most prolific of which is the Mk 49 21 cell launcher system. The missile itself is based on the Sidewinder missile; having a nosecone with two 8 to 10 GHz Band Radio Frequency antennas and a rosette scan infrared seeker for terminal guidance. Behind this is a new dual-mode passive radio frequency seeker for mid-course guidance. The blast fragmentation warhead is the 9.09 kg WDU-17B. The missile has a stated maximum range of 9.6km, beyond which the rocket motor will have burnt out. The maximum speed attained is Mach 2 (686 m/s at sea level). It must be noted that the effective range will be lower. This is dictated by the effectiveness of sensor systems [2] (both on the vessel and the missile) to detect and acquire an incoming stealthy sea skimming ASCM and the requisite reaction for the RAM to reach the target.

To engage an incoming ASCM, the RAM must obtain a designation from other shipboard systems, either electronic or electro-optical sensors. Once given a target, the launcher will turn to the target's direction and elevation for efficient interception. Upon missile firing, the RF seeker will be activated. When it acquires the target, it will guide itself towards the missile with appropriate course alterations. During this process the IR seeker is also activated, once a sufficient signal-to-noise ratio is achieved, the seeker takes over guidance control for the terminal phase using proportional navigation. Once within the range of the laser proximity fuse, the system will initiate detonation of the warhead. Any time during the engagement process when the RF acquisition is lost the missile will go to the IR mode and seek the target. The missile is also capable of maneuvers up to 20 *g* in any direction. [5]

The table below provides an overview between the current point defense systems in the USN inventory and the FEL system.

	FEL	***Phalanx***	***RAM***
Range	5 km	1 km	9.6 km
Number of Targets	2 sec per target	4 to 7	10
Cost per engagement	$2.25	$13,500 Assume 225 rds per engagement	$0.914 M Assume 2 missiles per engagement
Unit Cost	$55 M	Mount = $3.2055M Ammo = 1470 × $60 = $88,240 Total = $3.2393 M	Launcher =$7.924 M Missiles = $7.597 M Total = $17.522 M

Table 3 – Comparison of Inner Layer Defense Systems (after [6] & [7])

The range of RAM is based on the rocket's motor capability and not the actual performance range. This will be tied closely with performance capability of the detection, acquisition and tracking of the incoming ASCM with respect to the ship radar system and the RAM seeker head. The 1 km range for Phalanx is based on extremely optimistic figures. The dispersion of the Phalanx has been recorded at 2 mrad; thus at 1000m range, the projectiles are spread over an area 12.57 m^2. A typical missile is 0.35m in diameter and if a random distribution is assumed, a single round has a 3% chance of hitting it. Closed looped tracking of outgoing projectiles will minimize these errors. However, it has been found that the hit probability approaches 60% only when the target is within 200m.[18]

The 10 targets that RAM can engage is an estimation using the Mk 49 21 cell Launcher, where two RAM missiles will be fired against each incoming subsonic ASCM. The two missiles fired are to ensure high kill probabilities and to counter any possible missile failures. The number of targets will decrease if the incoming ASCM is supersonic as more missiles may have to be fired to ensure a kill. The number of targets that Phalanx can engage is based on the ammunition capacity of 1470. This figure is only a rough estimate based on 3 seconds of firing at 4500rpm per target. The number of targets for FEL will be based on the method of implementing the power supply to the system. If it is linked directly to the shipboard supply, then the number of targets will only be limited by the available power. If storage devices are used (like flywheel or capacitors), it will be dependant on the power density of the device.

The cost of an engagement is linked to the number of possible targets engaged. As the estimated cost of one RAM missile is $0.366M [7], two missiles will cost $0.732M. FEL cost is linked to the amount of fuel consumed to generate the requisite power for 1 engagement. The $0.45 was obtained using the specific fuel consumption of an LM2500+ Gas turbine engine that can generate the requisite power for this application. If 1MW of laser power hitting the target for 2 seconds is necessary for killing the target and it is further assumed that the FEL system has 10% efficiency in converting the power supplied to laser power, it will require 10MW for 2 seconds from the LM2500+. This translates to 20 MJ, the turbines may only be 20% efficient. The final energy required would then be 100MJ, since the specific fuel consumption for LM2500+ is 235 g/kwh, consequently 6.5 kg or 2.15 gallons of F76 fuel is consumed. Given that the cost of F76 fuel is $1.05 per gallon, the cost of 1 engagement is only $2.25.

The $55M unit cost for FEL is an estimation, and though the unit cost is higher than RAM or Phalanx, the total operating cost has yet to be factored into the total life cycle cost. The FEL will not require replenishment or a stockpile of missiles and projectiles but only be dependant on shipboard power supply. Thus the high capital cost will be offset by the reduced operating costs.

B. FEL ADVANTAGES

An FEL weapon employed to provide inner-layer defense would enhance ship survivability when compared to the RAM system. This system will have a proposed effective range of 5000 meters and it will employ laser power to defeat a missile by structurally destroying sections of the target. The advantages are listed below.

- Almost zero time of flight – A light beam will only take 16.7 microseconds to reach 5000 meters. In contrast, RAM will typically require 7.3 seconds to traverse the same range. Ostensibly, the beam travels faster than RAM by 437,125 times. The extremely short time of flight will allow for almost instantaneous engagement. In this frame, a Mach 2 missile will have only traveled 11mm. The ASCM would travel 5000m in the time it takes the RAM to reach the target. It is an essential benefit in targeting incoming ASCMs as the hit probability of ASCMs' increases as time of flight shortens. This is because the fire control solutions for the RAM and Phalanx have to predict a point in space where the enemy ASCM will be. This is necessary as projectiles and missiles require significant times of flight to reach the engagement point. It can also be exacerbated by the ASCM maneuvering profiles used to confuse defensive weapon systems. Thus, a FEL system will sidestep all the problems associated with target prediction and ASCM maneuvers with the speed of light directed energy beam.
- True Line of Sight Weapon – The FEL system will require a beam director to channel the light to the target; essentially this will be high performance Electro Optical (EO) system. This optical system will be providing the tracking function against any targets. Thus, when the system has a proper lock onto an ASCM, the FEL weapon will be firing at the same point as the tracking system. This is attributed to the negligible time of flight and to the beam of light not being affected by gravity. This provides great advantages, as it will

be a “What You See is What You Get (WYSIWYG)” weapon. It will confirm to the operator that firing the directed energy weapon will hit the target. In effect, it will ensure almost perfect hit probability (in consideration to Murphy’s Law) when it is fired. The other benefit is to allow the operator to ascertain whether the target has been effectively destroyed. This is important, as missile engagements require a “Shoot-Shoot-Look or “Shoot-Look-Shoot” strategy for ship self defense against ASCMs. The “look” portion is a waiting time to establish whether the missile has destroyed the target. This increases the time required for each engagement and wastes precious time in a combat environment.

- No extra supply requirements – Currently, RAM has 21 missiles in a launcher and a certain number stored for replenishment. Similarly, Phalanx has 1470 rounds ready to use, with extra rounds stored for spares. The FEL weapon will utilize shipboard power supply for its engagement and will be limited only to the amount of power available. It will not require extra supplies to support engagements, as replenishment will not be required.
- Quick reaction and reengagement time – In littoral warfare, a possibility exists that the enemy will be able to fire missiles undetected at close ranges. This cuts down the reaction time of all combat systems to engage the threat. The negligible time of flight for the beam will allow target destruction at further ranges then compared to RAM. The FEL system only requires an approximate dwell time of 2 seconds for a target kill. This coupled with the almost zero time of flight, will allow for quick reengagement of other targets. Section III. C. will analyze this issue in more depth.
- Low utilization cost – As mentioned, the cost of the light beam is coupled with the utilization of shipboard power supplies. The initial cost of acquiring the complete system will be inherently more than that of a missile system. However, the total life cycle cost may be

lower than a missile system as the replenishment, training utilization, and the necessity for stock piling missiles may bring the total costs up.

- High reliability – Current scientific Free Electron Lasers have extremely high reliabilities; components are left running for extremely long periods (weeks) with only infrequent component failures. In addition, the actual beam of light that destroys the target, will have no reliability issues attached with it. This is different for missiles as there are many failure points in its flight towards the target. For instance, the missiles have to contend with the reliability of the rocket motor, target seeker, fuze and warhead.
- Low Radar Cross Section (RCS) on Ship – The beam director will be the only component that will be placed topside for the weapon system. The other components will be installed within the ship. The director will not have special structural requirements and this will allow it to be easily shaped for a low radar cross section.

C. TIME ENGAGEMENT ANALYSIS

An important methodology to establish the effectiveness of a weapon system is to analyze the time engagement scenario against targets. This will assess the reaction time of the system, the number of targets it can engage and the range of interception. In any engagement analysis, the following sequence with respect to the target has to occur -

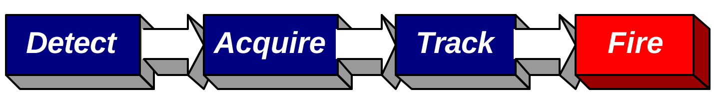

Figure 3 – Combat Engagement Sequence

The sensor system has to first be able to detect the target, subsequently an acquisition process has to follow. This phase also differentiates whether the target is an enemy or friendly force. If it has been assessed to be a foe, the sensor suite would track the target, and require the system to predict target motion and calculate fire control solutions before firing a weapon against it. This chain of events occurs both in radar and optical systems.

To have an estimation of the maximum possible detection range using a radar system against a sea skimming ASCM, the following equation is used [3]

$$H = \sqrt{0.672}\left(R - 1.22\sqrt{h}\right)^2 \quad (1.1)$$

where H is target height in feet, h antenna height in feet, R is the radar range in nautical miles. This equation is plotted with a target at different heights, while varying the antenna heights. It can be seen from the plots that target height plays a critical role in the radar horizon. If a target is moved from 5 feet to sea level, the maximum radar horizon is reduced by 5km.

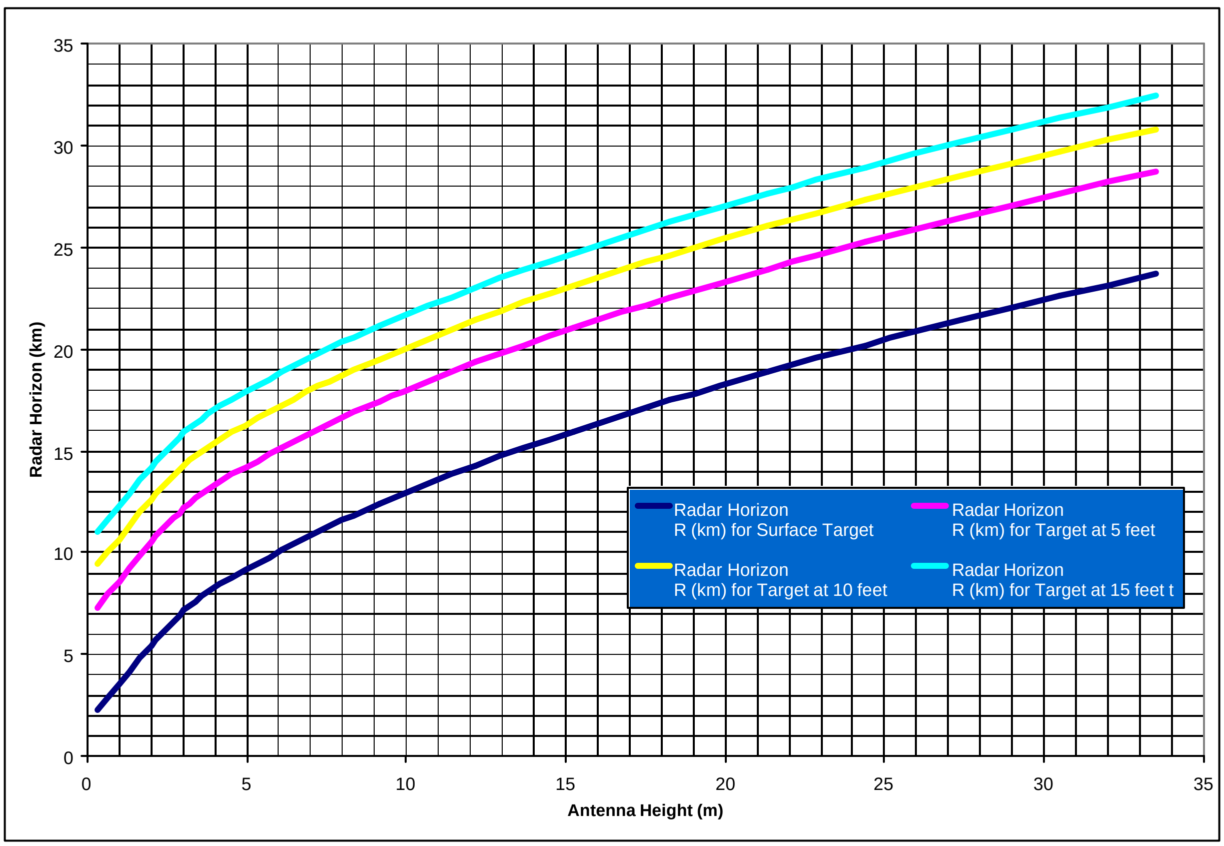

Figure 4 – Radar Horizon with target height at different target heights

Assuming a radar is placed on an aircraft carrier at a height of 20m above sea level, the estimated radar range will only be about 23 km for a 5 feet target height. This range is the maximum physical distance in which the radars can reach the ASCM. It does not consider the signal to noise ratio capability of the radar system or the sea clutter noise created by flying near the surface or even the radar cross section of the target. Any of these effects can change the detection range. To have a sense of scale, the typical RCS of ships range from 3,000 m^2 to 1,000,000 m^2 [3] while missiles are only 0.5 m^2. It can then be inferred that the detection range for a stealthy sea skimming missile may be even lower than calculated by (1.1). Due to the sensitivity of this information, detection ranges for various targets are classified. As such, the detection ranges used are only educated guesses.

To proceed with the analysis, the following assumptions are made

Speed of ASCM is	Mach 2 (686 m/s)
Speed of RAM is	Mach 2 (686 m/s)
Detection range of ASCM is	10 km
Time between 2 RAM launches is	3 seconds
Time to detect ASCM is Time to acquire ASCM is Time to track ASCM is Time to Launch RAM is Total is	1 second 1 second 1 second 1 second 4 seconds

Table 4 – ASCM Assumptions

The detection range of 10km is an estimated distance based on the size of the target and the sea skimming profile the ASCM will perform. The time between launches is taken to be 3 seconds; this was obtained from a video of RAM firings against ASCM [8]. A time lag exists between subsequent RAM missiles because firing simultaneously will cause the rocket blast to affect each other. In addition, the time between each launch has also to be long enough so that the plume from the first missile does not affect the IR seeker of the second missile. Based on these assumptions, a time engagement sequence was performed subsequently.

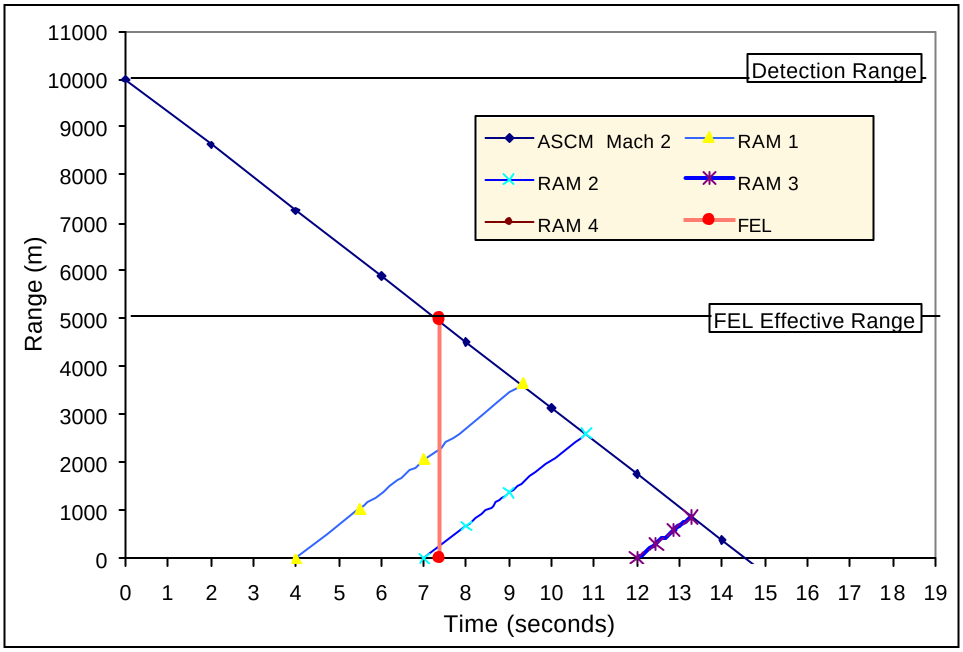

Figure 5 – Time Engagement Analysis for Mach 2 ASCM

It can be seen from the figure above that the FEL can intercept the ASCM at 5000m, with more than 7 seconds available to track the incoming target. With a two second dwell time, the ASCM will be destroyed by 3628m. If the "Shoot-Shoot-Look" strategy is employed, the first RAM is launched at 4 seconds and intercepts the ASCM at 3656m. If the missile is not destroyed, the second interception range will be at 2606 m. A third possible intercept occurs at 800m given a one second "look" before launching the third RAM.

Another scenario would be to increase the speed of the ASCM to Mach 3 and the rest of the parameters remain the same. The FEL can fire when the ASCM reaches 5km as there will be 5 seconds for the system to detect, acquire and track. The RAM will fire again at 4 seconds and intercept the missile at 2440m. The second missile intercepts 1255 m. There will be no time left for a third launch of RAM if the previous 2 missiles failed to destroy the target as the Mach 3 ASCM will have hit the ship.

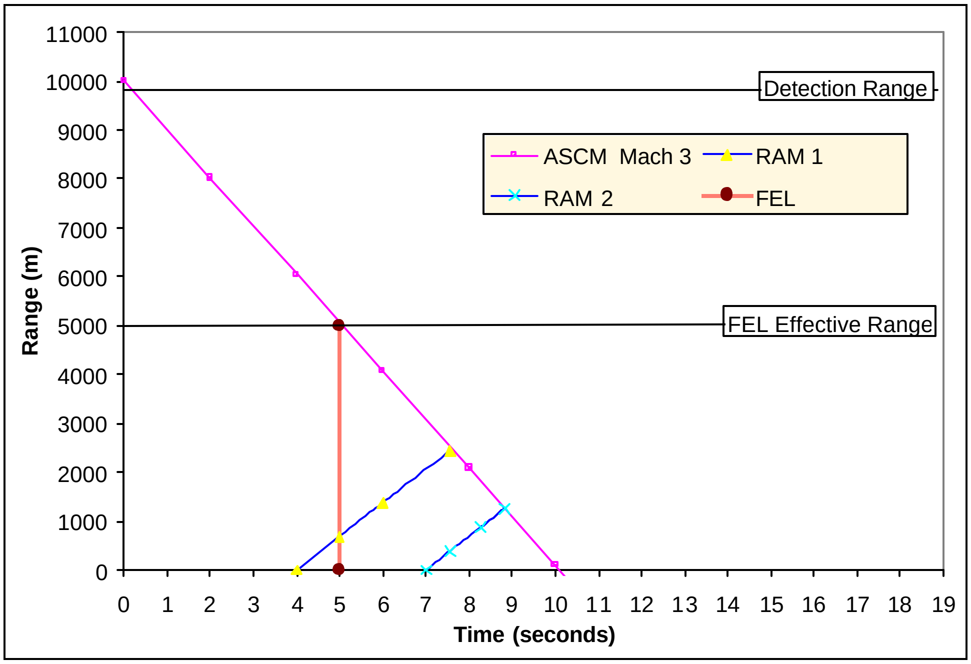

Figure 6 – Time Engagement with Mach 3 ASCM

It can be observed in both engagements that FEL will allow the target to be destroyed at longer ranges than RAM. The lethality of the FEL will also ensure that there will be no requirement for reengagement of the target. For a Mach 3 ASCM engagement, the danger is that if the RAM missiles do not destroy the target within two shots, the ASCM will be able hit the ship. Another inference is the importance of detection range of the ASCM. If it is reduced further, the reaction time of the combat system must be shortened further. When a missile is used to counter the ASCM, there may not be adequate time for the missile to reach the target as it.

In littoral warfare, this can weaken missile defense because enemy missiles can be fired at close ranges in the congested waters. This significantly reduces the reaction time for all weapon systems. In these scenarios, the FEL will be able to achieve greater success.

IV. THEORY & SIMULATIONS OF FEL OPERATIONS

The laser beam generation in the FEL weapon system consists of three essential components; an electron accelerator, a static periodic magnetic field produced by a series of magnets known as a “wiggler”, and an optical resonator. The process begins with a beam of electrons being energized by a particle accelerator. The electron beam then enters the wiggler which causes the electron path to be bent sinusoidally and emit radiation. A percentage of the emitted light is then stored between two mirrors forming the optical resonator cavity. The light beam in the cavity is further amplified by the subsequent injection of electrons into the wiggler. The amount of light that escapes on each pass is usually determined by one of the mirrors having a slightly less than perfect reflection coefficient and being partially transmissive. If too much light is allowed to escape, the FEL would not have sufficient gain to operate. Conversely allowing too little light to escape prevents the light beam from achieving sufficient output for target destruction. A simplified diagram for the FEL is shown below.

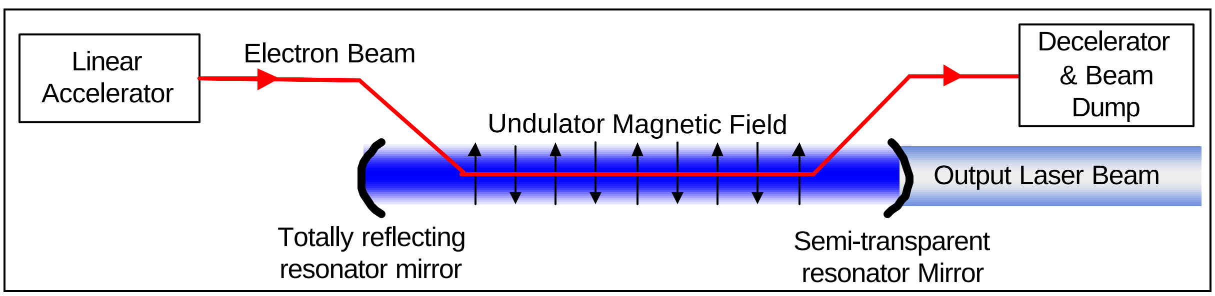

Figure 7 – Simplified Free Electron Laser Diagram

These elements interact to produce stimulated emission that leads to coherent radiation in the optical resonator. This stimulated emission of radiation is produced at a wavelength l as determined by the resonance condition in the wiggler,

$$l = \frac{l_0}{2g^2}\left(1+K^2\right) \qquad (2.1)$$

where

$$K = \frac{eBl_o}{2p\,mc^2} \qquad (2.2)$$

l_o	undulator wavelength
K	undulator parameter
B	rms undulator magnetic field
g	E_e / mc^2 relativistic Lorentz factor
m	Mass of Electron
c^2	Speed of light

Table 5 – FEL Parameters

One benefit of an FEL compared to solid state lasers is the tunability of the wavelength of light. It can be seen from (2.1) and (2.2) that this can be achieved by varying the wiggler wavelength l_o, the initial electron energy, or the undulator magnetic field B. The most expedient method for tuning the wavelength would be varying the wiggler gap to provide different magnetic field strength values. Fast changes can be made on the microsecond time scale by varying the electron beam energy g.

In a combat environment, this tunability of wavelength will allow the weapon to be optimized for conditions in which it will be employed. Atmospheric conditions, like rain, fog, humidity and dust, will cause attenuation; this brings about scattering and absorption of the beam that will severely affect the performance. Section B. will provide an analysis on the optimum wavelength for use in a naval environment to minimize the effects of atmospheric conditions and optimize laser beam propagation.

A. NON-DIMENSIONAL PARAMETERS

Dimensionless parameters are used to describe the physics of the FEL design. This is to simplify recurring combinations of physical parameters, especially in complex problems like FELs. The dimensionless current density at the peak of the electron pulse is defined as

$$j = \frac{8N(epKL)^2 r}{g^3 mc^2} = 40 \qquad (2.3)$$

		Parameters used
N	Number of undulator periods	36
e	Electron charge	1.6021×10^{-19} C
L	Undulator length	2.88 m
r	Electron density	1.081×10^{12} C /m^3
g	Lorentz factor	410
m	Mass of the element	9.109×10^{-31} kg
c	Speed of light	2.9979×10^{8} m/s

Table 6 – Parameters for *j*

The dimensionless optical field amplitude is defined as

$$|a| = \frac{4pNeKLE}{g^2 mc^2} \qquad (2.4)$$

where *E* is the amplitude of the electric field of the optical mode.

The Rayleigh length is defined as the distance in which the optical mode area doubles in size, and is given by

$$Z_O = \frac{p w_O^2}{l} \qquad (2.5)$$

where w_O is the radius at the waist of the optical beam and the normalized Rayleigh length is $z_o = Z_o / L$.

The dimensionless optical beam width is

$$\tilde{w} = \sqrt{z_o + \frac{\left(t - \frac{1}{2}\right)^2}{z_o}} \qquad (2.6)$$

where $t = z/L$ is the dimensionless position along the wiggler z-axis, The equation shows that smaller values of Rayleigh length z_o would produce a larger spot size at the mirrors at $t = \pm 10$. A short Rayleigh length also gives a small mode waist where the optical amplitude will be much larger than at the mirrors.[9]

B. SIMULATIONS FOR SHORT RAYLEIGH LENGTH

The Thomas Jefferson National Accelerator Facility (TJNAF) currently has the highest average power FEL at 2kW. The FEL can be increased to 10 kW of output power in the near future, and studies are underway to modify the components to increase output to 100kW. The changes will involve increasing the electron beam energy to E_e = 210 MeV with a pulse repetition rate of W = 750 MHz while maintaining a peak current of $\hat{I}$ = 270A in an electron pulse length of l_e = 0.1mm. The resulting electron beam power is P_e = 14 MW in an electron beam radius of r_e = 0.3mm. An extraction efficiency of $h \approx 0.7$ % is needed to reach the 100kW optical output. Energy spread and emittance will give only small degradation to weak field gain and steady-state power. The undulator wavelength is l_o = 8 cm with N = 36 periods and an rms undulator parameter of K = 1.7. This will result in a radiation wavelength l » 1μm in an optical resonator S = 32m, long with an output mirror transmission of 21 % corresponding to resonator quality factor Q = 4.2.

Utilizing the parameter requirements for the TJNAF FEL, the power densities on the mirrors were calculated for dimensionless Rayleigh length z_0 = 0.1 to 0.5. Figure 8 shows the shape of the optical mode and the power density on the mirrors. Reducing the Rayleigh length from z_o= 0.3 to 0.1 reduces the power density on the mirrors by 300%. This will greatly alleviate the requirements for the mirrors to handle high power densities and bring it one step closer as a weapon system. Otherwise, a large mirror separation is required to reduce the beam intensity on the mirrors.

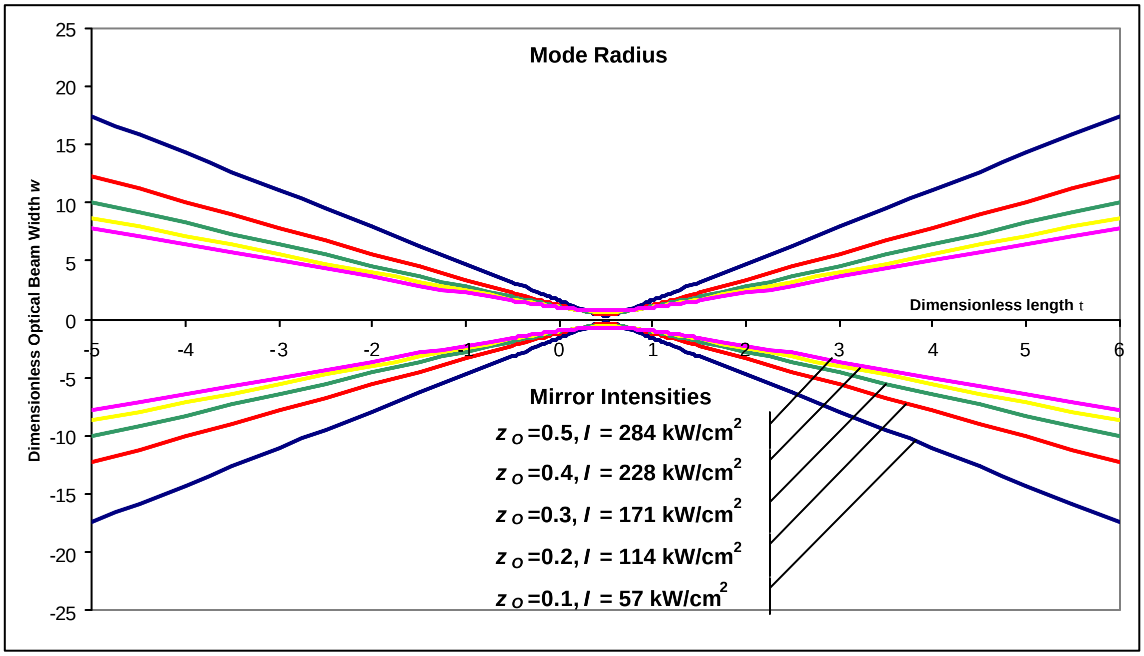

Figure 8 - Optical mode shapes for various Rayleigh lengths

To support the TJNAF upgrade, multimode simulations were peformed to model the optical mode interaction with the electron beam. The purpose was to investigate power and gain response while varying the Rayleigh length, beam size and electron phase velocity.

1. Transverse Mode Effects

Figure 9 presents a three-dimensional simulation of the proposed TJNAF laser in *x, y* and *t*. The upper-right table presents the dimensionless parameters describing the 100kW design, along with the color scale for the intensity plots of the optical amplitude |*a*|. Transverse dimensions are normalized to $(L l/p)^{1/2}$, and the longitudinal dimensions are normalized to the undulator length *L*. The dimensionless electron beam radius is $s_{x,y}$ = 0.2 in the *x* and *y* dimensions. The betatron oscillation frequency w_b is unity over the undulator length indicating about 1/6 of a betatron oscillation along the wiggler. The electron beam is focused in the middle of the undulator at t_b =0.5. The beam's angular spread $s_{qx,y}$ = 0.04 is determined by the matching requirement $s_{q\,x,y} = w_b{}^2 s_{x,y}{}^2$ so that neither the beam's radial extent nor the angular spread dominates beam quality. The mirror radius is r_m = 7.2, while the mirror curvature is r_c = 1.5 yielding a normalized Rayleigh length z_o = 0.1. The quality factor Q = 4.2 corresponds to an approximate 21 % mirror transmission, and edge losses around the mirrors are 1% per pass(e = 0.01).

The top-left plot, |*a(x,n)*|, presents the development of a slice through the middle of the optical mode over N=32 passes showing how steady-state develops. The top-center plot, |*a(x,y)*|, presents the final optical wavefront at the wiggler exit t = 1 showing the electron beam (red) centered in the mode. The center plot, |*a(x,t)*|, shows a section through the optical wavefront during the final pass. The mirror separation was shortened to three times the wiggler length instead of 11 times the wiggler for numerical convenience. The additional resonator length does not affect the optical field and is neglected in the simulations. The bottom-left plot, *f*(*n*,*n*), shows the development of the electron phase velocity distribution, and next to it is the final electron phase space plot showing a spread of *Dn* =25 and efficiency *h* =2.2%. In the bottom-right is the development of optical power *P*(*n*) and gain *G*(*n*) over *n*= 16 passes.

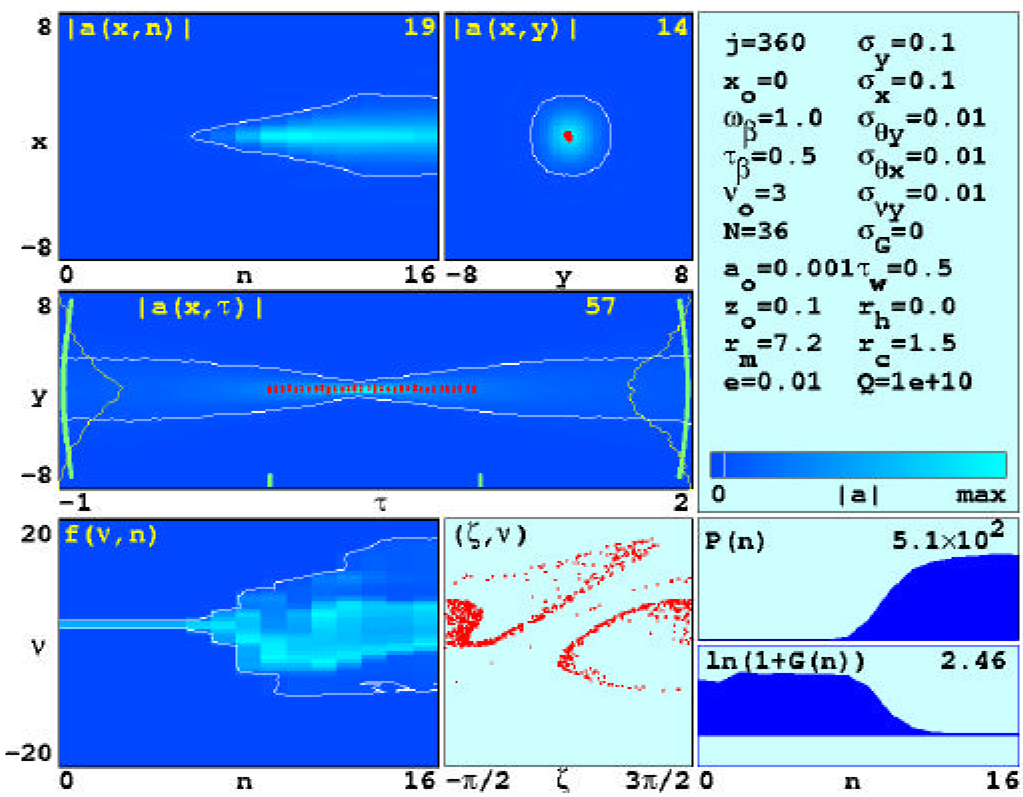

Figure 9 – Three dimensional simulation in *x, y* and *t*

2. Weak Field Gain

Simulations were conducted to estimate the weak-field gain for the proposed parameters. The normalized Rayleigh length was varied from $z_0 = 0.1$ to 0.5. For each z_o, the phase velocity was varied from $n_o = 1$ to 15 to determine the optimum value. In each case, the optimum phase velocity was found to be about $n_o \approx 4$. Figure 10 shows small perturbations in the gain when n_o was increased from 9 to 14, contradictory to the downward trend in gain. This is may be attributed to multimode optical effects in the beam; these features can be ignored as they are considered small.

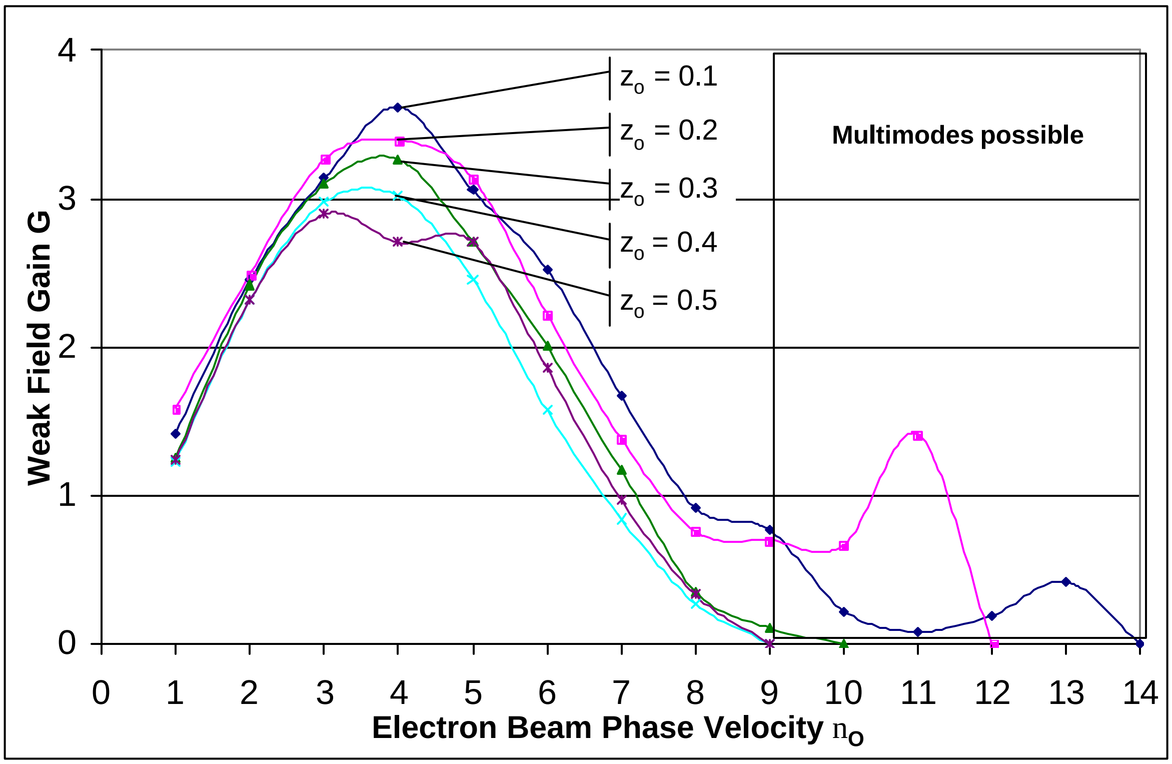

Figure 10 – Weak Field Gain vs Electron Beam Phase Velocity n_o

For each value of z_o, the peak gain in weak fields ($|a|<p$) was then plotted for values of s_x =0.1 to 0.5 as shown in Figure 11.

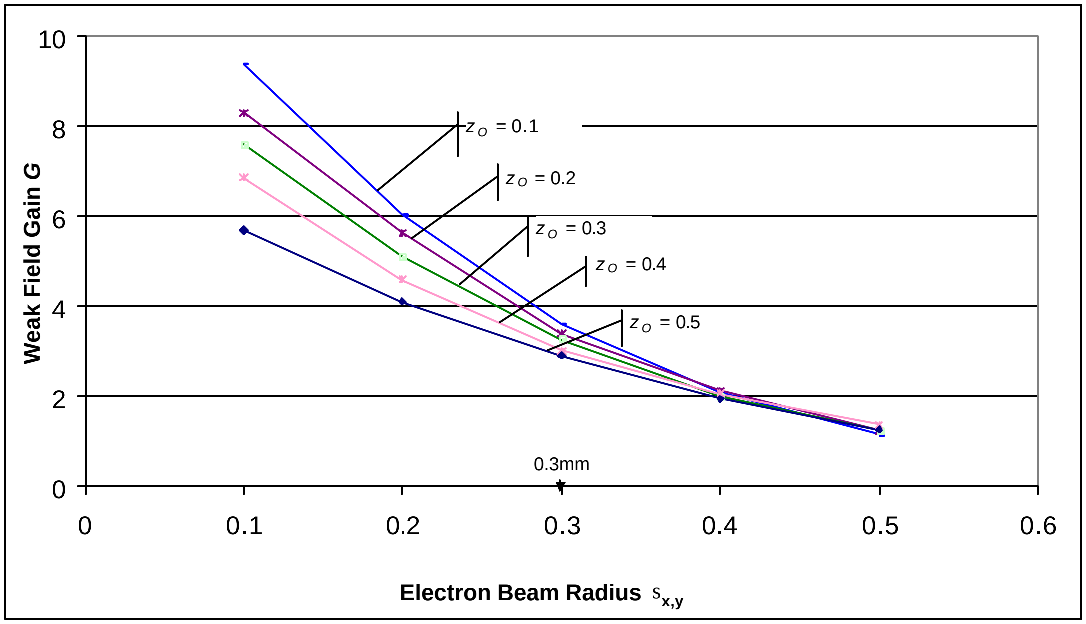

Figure 11 – Weak Field Gain vs Electron Beam Radius $s_{x,y}$

The maximum gain of 9.4 was obtained with a small electron beam radius $s_{x,y}$ = 0.1 and small Rayleigh length z_o at 0.1. As the electron beam radius s_x was increased, gain decreased for all values of z_0. Lower values of z_o produced higher values of gain at each s_x. This contradicts basic FEL theory [2], where the maximum gain occurs when the electron beam size is only slightly smaller than the optical mode, which corresponds to z_o = 0.3. It appears that a short Rayleigh length and correspondingly smaller electron beam provides a higher beam density to amplify the optical mode, which enhances the gain. In some cases, the larger electron beam is outside the optical mode, which would reduce the gain. The current density is too small for optical guiding [9], however the weak-field simulation results show significant mode distortion, which could enhance the gain. With larger electron beams, there is less optical mode distortion.

3. Steady State Power

Simulations were run until steady state power was obtained for values of normalized Rayleigh length z_o=0.1 to 0.5 and electron beam radius $s_{x,y}$ = 0.1 to 0.5. At each value of z_o and $s_{x,y}$, the phase velocity was varied from n_o = 1 to 14 as shown in Figure 12. As in the case of weak field gain, there were slight increases in the efficiency for z_o = 0.1 and 0.2, when n_o was increased from 10 onwards. Once more, this can be attributed to multimode effects that the laser beam exhibits as seen in Figure 12.

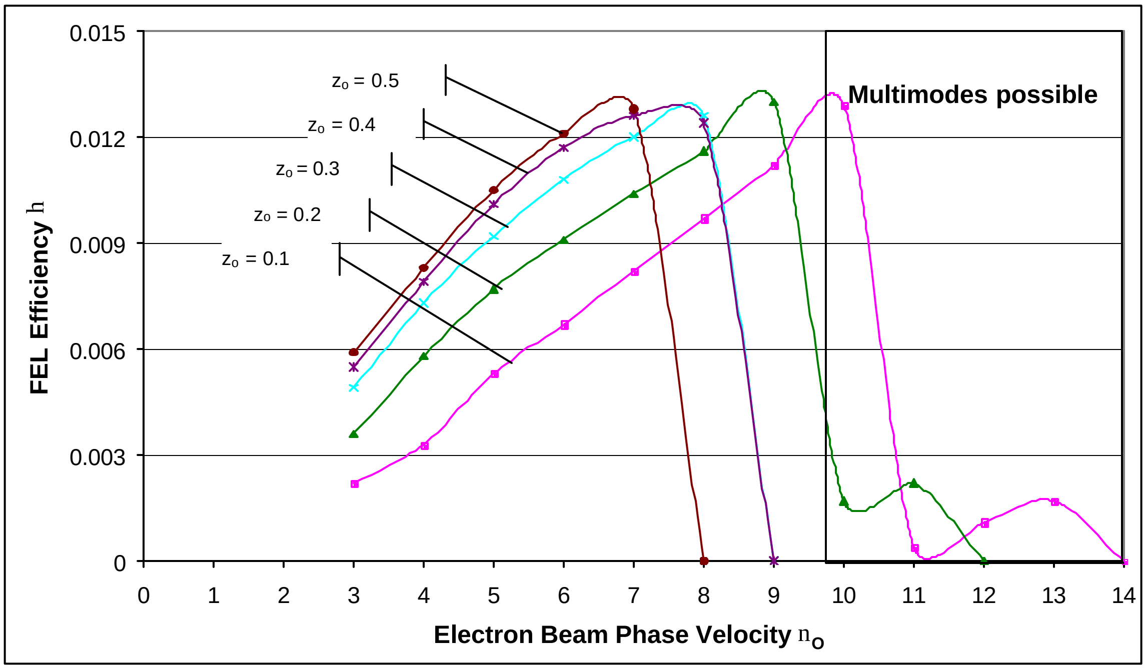

Figure 12 – Efficiency vs Electron Beam Phase Velocity

The highest peak power for each value of z_o was selected, and the extraction efficiency h at that power was then plotted against s_x. The results in Figure 13 show that a smaller electron beam enhances efficiency. It was also discovered that for short Rayleigh lengths, the optimum phase velocity n_o increases, but good efficiency is still maintained. Maximum efficiency was at 2% with z_o = 0.3, $s_{x,y}$=0.1 and n_o = 11. For a small electron beam size $s_{x,y}$ = 0.1 and small Rayleigh length z_o = 0.1, we observed multiple optical modes with power oscillating by as much as 20 %. However, these multi-modes could be suppressed with larger electron beams. Multi-modes seem to develop higher power and efficiency.

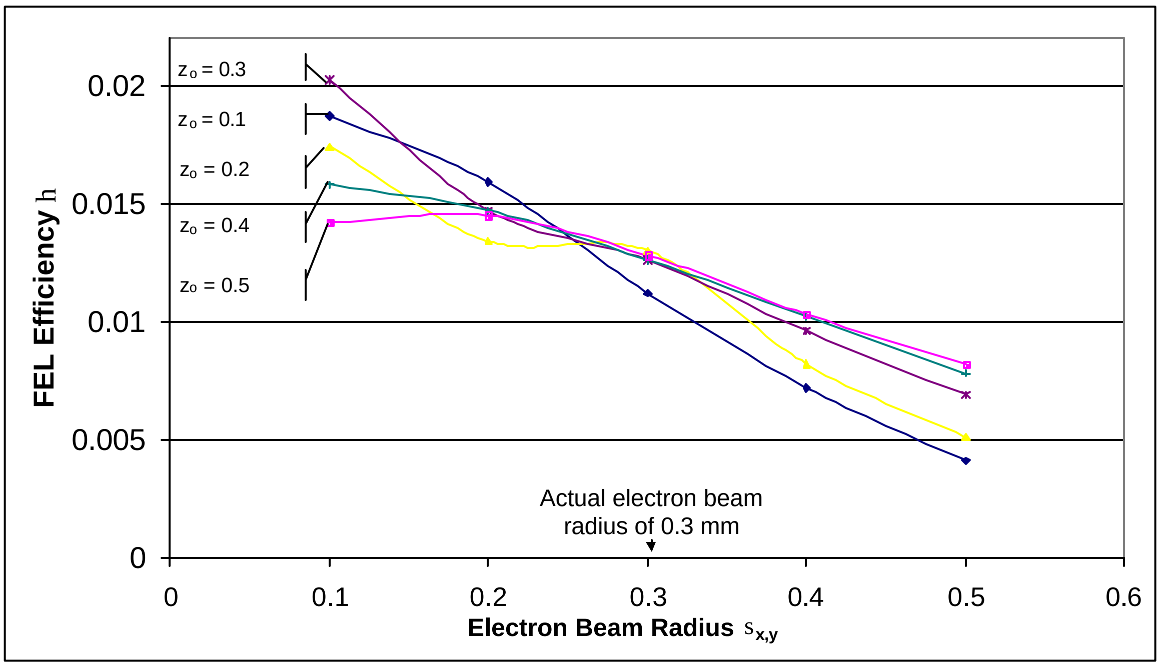

Figure 13 – Efficiency vs Electron Beam Radius at optimum electron Beam Phase velocity n_o

Based on the simulations for TJNAF, it was found that an FEL that utilizes short Rayleigh lengths provide good gains and efficiency while lowering the power density at the mirrors. It would then be prudent that a FEL weapon system utilize short Rayleigh lengths.

V. REQUIREMENTS

A. TARGET LETHALITY

To destroy an ASCM in flight with a light beam there are several possible approaches. One is to damage the missile seeker and prevent the missile from acquiring the target, while another is to cause the warhead or rocket fuel to detonate prematurely. It is also possible to damage the flight controls and force the missile into an uncontrollable flight path. The most common method is o structurally weaken the missile body so that the missile breaks up in flight. Throughout these destruction methods, the ways in which missile material reacts to laser irradiation is threefold:

- light coupling to the material – the optical reflectivity of the material determines what fraction of the energy is absorbed and thus converted to thermal and mechanical energy.
- propagation of Thermal/Mechanical effects – this characteristic determines the efficiency in which the heat or shock transmits through the material.
- induced effects of the propagation of thermal/mechanical energy - the resulting process occurs when high energy is deposited on a material. For instance, melting, vaporization, shock loading, crack propagation and spalling.

A quick estimate to the amount of energy required to destroy a missile is to assume that a 3 cm penetration with a 10 cm radius spot size would be sufficient for destruction. If it is further supposed that the material is made of aluminum and the melting of the aluminum is assumed to be the kill mechanism. Then the energy required would be [4]

$$\text{Melting Energy} = rV\left[C\left(T_m - T_o\right) + \Delta H_m\right] \tag{3.1}$$

where

		Aluminium Properties
r	Mass Density	2.7 g/cm^3
V	Volume of material	942.5 cm^3
C	Specific Heat Capacity	896 J/kg-K
T_m	Melting Temperature	933 K
T_o	Ambient Temperature	300 K
DH_m	Latent Heat of Fusion	4×10^5 J/kg

Table 7 – Properties of Aluminum

Using the material properties of aluminium listed above, the energy required is 2.5 MJ. If the time for engagement is fixed at two seconds, the irradiation would then be 2.5/2 ≈ 1 MW of beam power.

These destruction mechanisms have not considered thermal conductivity and the impulse effects on the target due to rapid temperature changes.

The effectiveness of the damage mechanism is also dependant on the FEL beam, pulse duration, wavelength, the target material and the finish of the target surface. The absorption for each material varies for different wavelength. For instance, the absorption of a ruby laser light at 0.694 μm is 11 % for aluminium, 35 % for light coloured painted metals and 20% for white paint. The corresponding numbers for a CO_2 laser (at 10.6 μm) are 1.9%, 95% and 90%. For many materials, the surface is blackened quickly so that light is absorbed more readily than indicated by the low power absorption.

B. LASER PROPAGATION EFFECTS

One of the main weaknesses with a directed energy weapon system is the effect of the atmosphere and weather conditions on its propagation capabilities. Effects include

- *thermal blooming* or beam spreading due to the absorption of radiation by the atmosphere, which in turn causes refraction.
- *windage* or bending due to local refractive effects caused by differential cooling of the upwind side of the beam.
- *turbulence* caused by changes in the atmospheric conditions produces a variation in the refractive index.
- increased extinction due to strong ionization and high temperature attributed to the absorption of beam energy.

To provide an estimation of the power required for missile destruction, linear propagation effects like atmospheric attenuation and beam spreading by turbulence must be taken into account. Non-linear effects like thermal blooming must then be added to provide more realistic figures.

1. Atmospheric Attenuation

Atmospheric attenuation consists of two components; scattering and absorption. This is caused by air, water and dust particles interacting with the beam. To mitigate their effects certain wavelengths can be selected for beam propagation. Figure 14 gives the coefficient of absorption, scattering and extinction for infra-red region wavelengths at the Sea of Japan. Current laser systems like the Mid Infra-Red Advanced Chemical Laser (MIRACL) operates at 3.8 µm, while the Chemical Oxygen Iodine Laser (COIL) at 1.315 µm. Both these wavelengths exhibits strong absorption and extinction characteristics. The more appropriate wavelength for our naval application should be around 1.06 µm, 1.35µm or 1.62 µm.

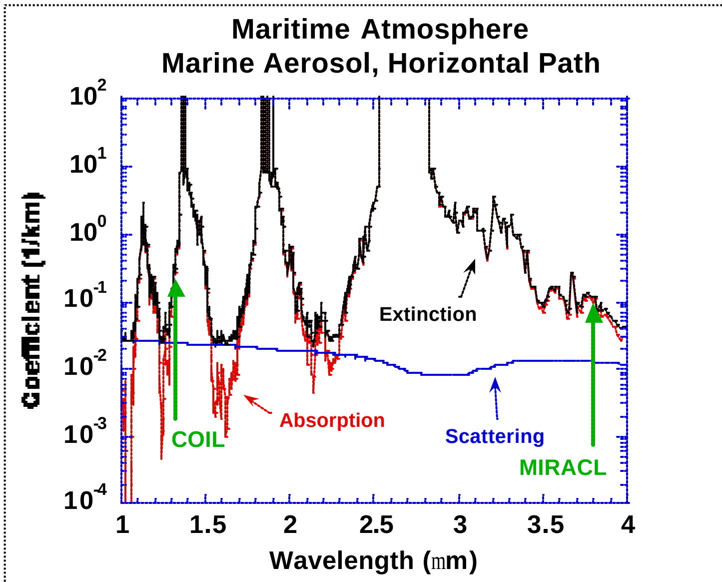

Figure 14 – Atmospheric Attenuation at Sea Level (from [5])

Therefore, the percentage of power that arrives on the target after 5km is shown in Figure 15 for the various wavelengths. it can be seen that the best propagation wavelength is at 1.06 μm.

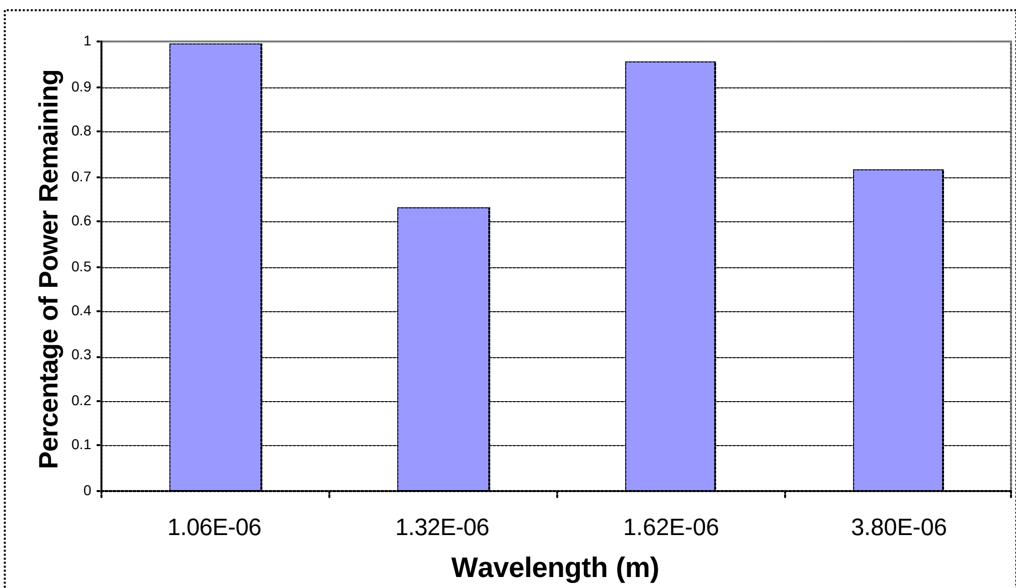

Figure 15 – Absorption Characteristics

The actual power output from the beam would have to include losses from attenuation. Thus actual beam power output would then be

$$\text{Power Output} = \frac{P_{TOT}}{e^{-eR}} \qquad (3.2)$$

where e = extinction coefficient and R is the range and P_{TOT} = requisite beam power on target before extinction. For a 1.06 μm wavelength target destruction would entail only an extra 2% in power. A 3% increase in power is required out to 8km range to ensure a 1 MW beam on target.

2. Turbulence

Turbulence is caused by the convective motion of the air due to small temperature gradients in the atmosphere. The effect on the beam would be to spread it out and at the same time cause it's centroid to wander and jitter. Scintillation is also observed with atmospheric turbulence. The degree of spreading can be characterised by Fried's characteristic coherent length [14]

$$
\begin{aligned}
r_o &= \left[2.1 \times 1.46 \left(\frac{2p}{l} \right)^2 \int_0^R C_N^2 \left(1 - \frac{z}{R} \right) dz \right]^{5/3} \\
&= \left[3.066 \left(\frac{2p}{l} \right)^2 \int_0^R C_N^2 \left(1 - \frac{z}{\infty} \right) dz \right]^{5/3} \quad \text{since } R = \infty \text{ for planewaves yielding,} \\
&= \left[3.066 \left(\frac{2p}{l} \right)^2 C_N^2 \int_0^R 1\, dz \right]^{5/3} \\
&= \left[12.264 \left(\frac{p}{l} \right)^2 C_N^2 R \right]^{5/3}
\end{aligned}
\tag{3.3}
$$

where $C_N{}^2$ is the turbulence strength parameter, R is the range. For large distances, the beam spreading is then given as

$$q_T \approx \frac{l}{r_o} \tag{3.4}$$

where l is the optical wavelength. The turbulent beam size on the target at range R would then be

$$w_t = R q_T \tag{3.5}$$

Comparing two turbulence strengths of $C_N^2 = 1\times10^{-14}$ m $^{-2/3}$ (high turbulence) and 1×10^{-16} m $^{-2/3}$ (low turbulence) at a target range of 5000m, the turbulent spot sizes were calculated for the various wavelengths in question and are shown in Figure 16.

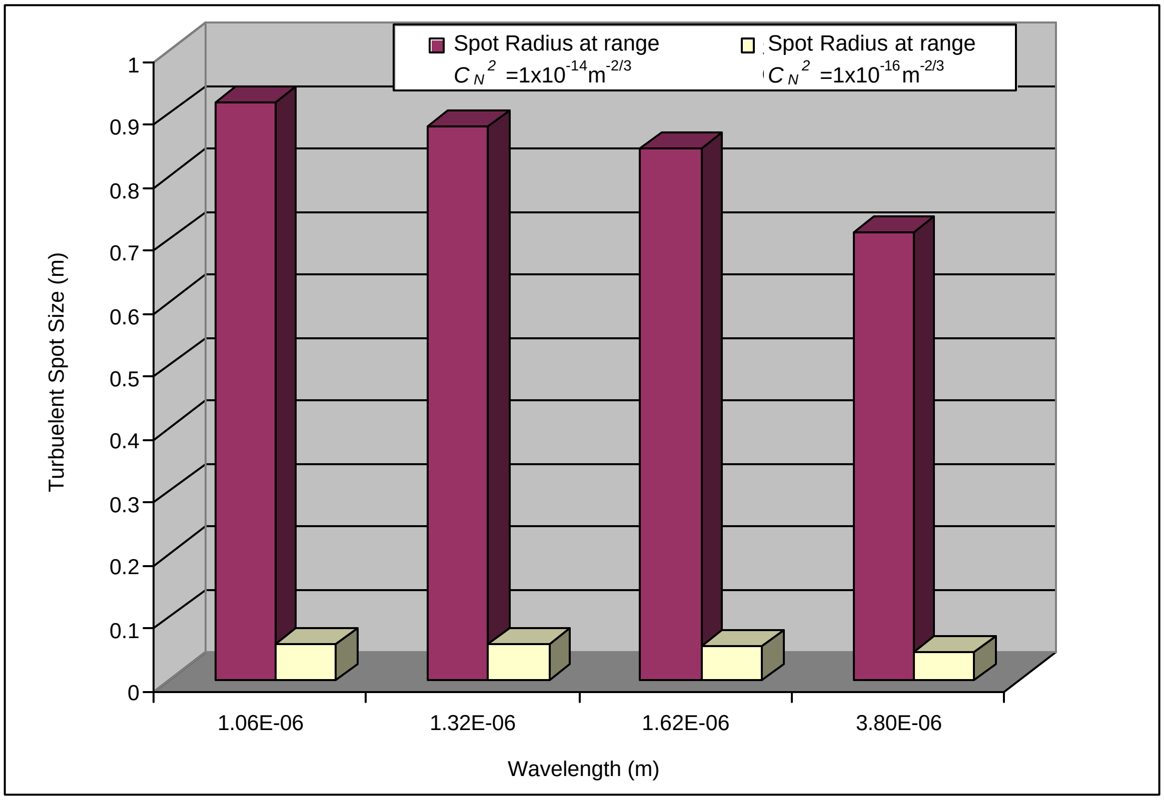

Figure 16 – Turbulent Spot Size

It can be seen that smaller wavelengths produces larger spot sizes, which would thus lower the intensity of the beam and reduce its effectiveness against a target. High turbulence also increases the spot size significantly.

The intensity profiles were also modeled using a 1μm wavelength Gaussian beam with different turbulence strengths. This is a different assumption from the previous calculation for turbulent spot size where the beam was assumed to be a plane wave. This is simply the analysis of the intensity profile as Gaussian profiles allow easier comparison between different turbulence strengths than plane wave profiles. The beam was focused at 1000m and a "snapshot" was taken at 5000m.

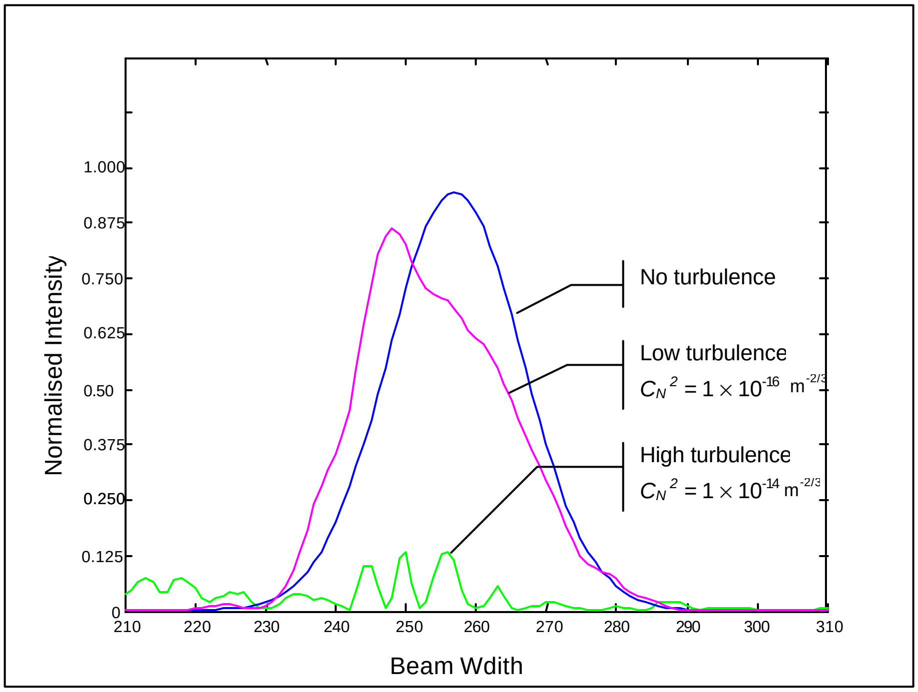

Figure 17 – Intensity Plot with Different Amounts of Turbulence

It can be observed that intensity has decreased with higher turbulence. The Strehl Ratio is often used to compare intensities, this ratio is the actual maximum intensity of the beam at the aim point divided by the maximum intensity in a quiescent environment. For high turbulence ($C_N^2 = 1 \times 10^{-14}$ m$^{-2/3}$), the Strehl ratio is 0.14, while for low turbulence, the Strehl ratio is 0.95. The beam width stated in the model above is based on normalized units and can be correlated to the beam widths calculated previously.

A possible method to minimize the effects of turbulence would be to use adaptive optics. This process begins by emitting a low power laser beam in the target direction, where detectors would then analyse the reflection and measure the effects of turbulence. The system would then adjust the mirrors by deforming them so that the outgoing wavefront would be corrected to compensate for the distortion it will experience on its beam path. Figure 18 utilizes a simulation to demonstrate the benefits of adaptive optics. Without adaptive optics the Strehl Ratio is only 0.027 in the case chosen. With adaptive optics the system can achieve a Strehl Ratio of 0.669.

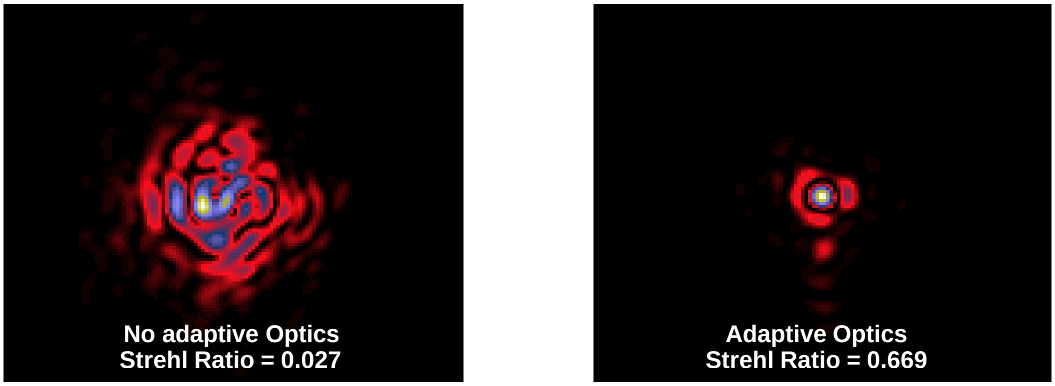

Figure 18 – Intensity profile for laser spot on target (after [5])

The adaptive optics arrays required for a weapon application will be approximately 8 by 8 size. This reduces the complexity of the system and has been proven effective[14]. As such, the benefits of utilizing a shorter wavelength can be achieved though the use of adaptive optics to remove the degradation caused by turbulence.

3. Thermal Blooming

As a beam of light traverses through the atmosphere, the air molecules heat up because they absorb energy. This decreases the density of the air and thus the index of refraction. Since electromagnetic waves move slightly faster in lower density air, a wave front becomes more convex in the direction of the propagation where the air is hotter. The Gaussian beam intensity profile heats the air near the axis more than the edges of the beam; consequently, the density becomes lower on the beam axis than on the edge, and the beam will diverge radially. This spreading of beam will cause the centerline intensity to decrease rapidly. It can be inferred that higher absorption coefficients will result in a greater thermal blooming problem.

Some models exist to estimate the time taken for blooming to occur. One of them is the t^3 – Blooming model. It states that [15]

$$t_c = \left(\frac{2}{p}\right)^{1/3}\left(\frac{a_o w}{f}\right)^{2/3}\frac{K^{2/3}}{a^{1/3}}\frac{1}{I_P^{1/3}} \qquad (3.6)$$

where

t_c	Critical Blooming time
I_P	Intensity
a_o	Exit Mirror radius
f	Focal Length
w	Beam Waist radius at focal plane
a	Atmospheric absorption coefficient
K	Constant

Table 8 – Parameters for Thermal Blooming

or,

$$t_c \propto \frac{1}{a^{1/3}} \qquad (3.7)$$

The absorption coefficients at the Sea of Japan for the various wavelengths shown in Table 9.

Wavelength	1.06 µm	1.315µm	1.62µm	3.815µm
Attenuation*	0.0003 km^{-1}	0.0919 km^{-1}	0.0087 km^{-1}	0.0671 km^{-1}

Table 9 – Absorption Coefficients for Different Wavelengths

Using these values, the normalized critical blooming times are shown in Figure 19. It shows that 1.06 µm wavelength takes approximately 6 times longer than the 1.32µm or 3.8µm for blooming to occur.

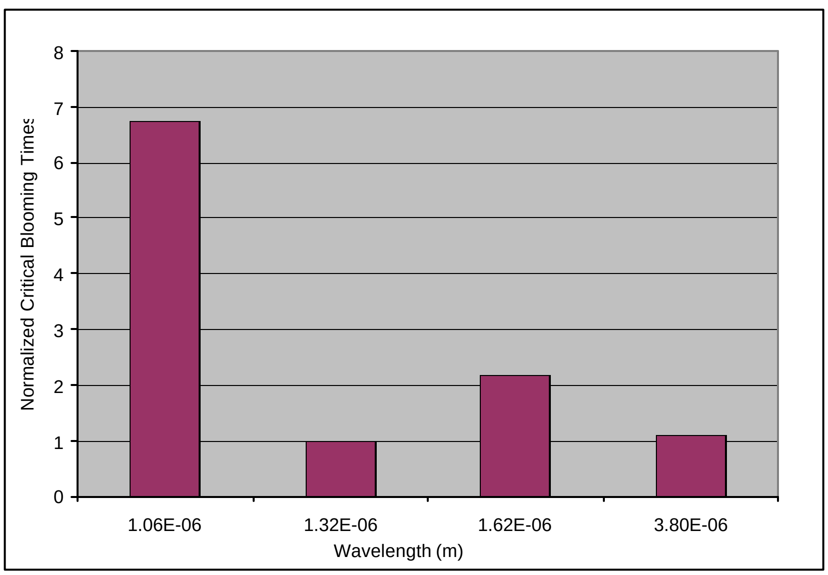

Figure 19 – Critical blooming Times (T3 Model) for different wavelengths

Selection of an appropriate wavelength is considered critical to minimize the effects of thermal blooming but other methods and circumstances can also alleviate the these effects –

- Clearing of the heated gas in the beam by a cross wind or slewing of the beam as it tracks the target.
- Pulsed beams with clearing times taken into consideration to avoid blooming.

The models used did not consider effects of wind, which would assist in clearing the channel and mitigate the thermal blooming. If the target is crossing, channel clearing would also then occur. For a continuous-wave directed energy beam, it may be also prudent to send the pulse-formed beams with sufficient intervals for beam clearing. As the FEL beam is propagated in the MHz regime, it may be necessary to turn the beam off to allow for channel clearing. Whether this would be required in a naval environment where wind speed is predominantly high would require more analysis. To give an indication of clearing time, a cross wind speed of 20 m/s will clear a beam radius of 0.1m in 0.01 seconds.

An added benefit of engaging crossing targets for an FEL system would be an increased target profile for the beam to interact. Since the side profile presents the propellant stage of the missile to the beam, a lower energy interaction is required to cause target destruction. It is noteworthy that crossing targets are extremely difficult for missile systems to engage as the amount of *g* maneuvers required would often be too large for it to perform.

4. FEL Parameters

In summary, the FEL weapon system should be a 1.06 μm wavelength beam of approximately 1.5 MW beam power. This choice will mitigate the effects of thermal blooming and atmospheric absorption. It will utilize adaptive optics to minimize turbulent effects to produce a spot target size of 0.2 m. To maintain this spot radius of 0.1m, the Rayleigh length Z_o will be very large. The exit mirror radius will then be approximately the same as the spot radius. If we consider that the beam profile is Gaussian, the radius will then have to be 0.13 m in radius to prevent clipping of the tails of the Gaussian beam.

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VI. SYSTEM ARCHITECTURE

An FEL installed onboard a vessel would have to consider system power requirements, weight, sizing and radiation hazards. To optimize all concerns, it appears desirable to use an energy recovery concept in the FEL. This will ensure a higher wall-plug efficiency reducing the required input power. Electron beam bends will also have to be employed rather than straight configurations to enable a more compact shipboard installation. Concept studies have shown that straight configurations for the electron beam would require a length of 26 m, while bends would reduce the length to about 12 m. This is especially important in shipboard installations as it will minimize the number of bulkheads the FEL system has to traverse.

The proposed architecture is shown in Figure 21. Electron beams are initially injected into the linear accelerator with 7 MeV energy. A superconducting RF (SRF) linear accelerator (LINAC) then increases the electron beam energy to 100 MeV along its 6.7 m path. The electron beam is then turned by a series of bending magnets to be injected into the wiggler. The wiggler will have an energy extraction efficiency of approximately 2% and produce a laser beam of 1.5MW. A second set of bending magnets will take the residual electron beam from the wiggler and transport it back to the accelerator where it enters out of phase with respect to the accelerating fields. As a result, the energy from the decelerating electrons is then transferred back into the RF fields, which in turn are used to accelerate subsequent electron pulses. The decelerated electrons retain about 7MeV of residual energy which is transferred to the beam dump for dissipation. The optical cavity, where the light beam is amplified, is 12 m in length.

The light beam from the optical cavity will be guided through a series of mirrors to either one or both of the two beam directors. Adaptive optics will also be used for these mirrors to handle beam fluctuations from ship vibration and motion.

This configuration dramatically reduces the radiation from the beam dump as the residual energy will only be at 7MeV. If a energy recovery is not used, the electron energy leaving the wiggler would be at 100 MeV, making it difficult to prevent the materials in the beam from generating neutron radiation. Shielding for neutron radiation is much more extensive.

The complete system will be installed at the center of the ship to minimize the effects of hull flexure on the beam transport system as shown in Figure 20.

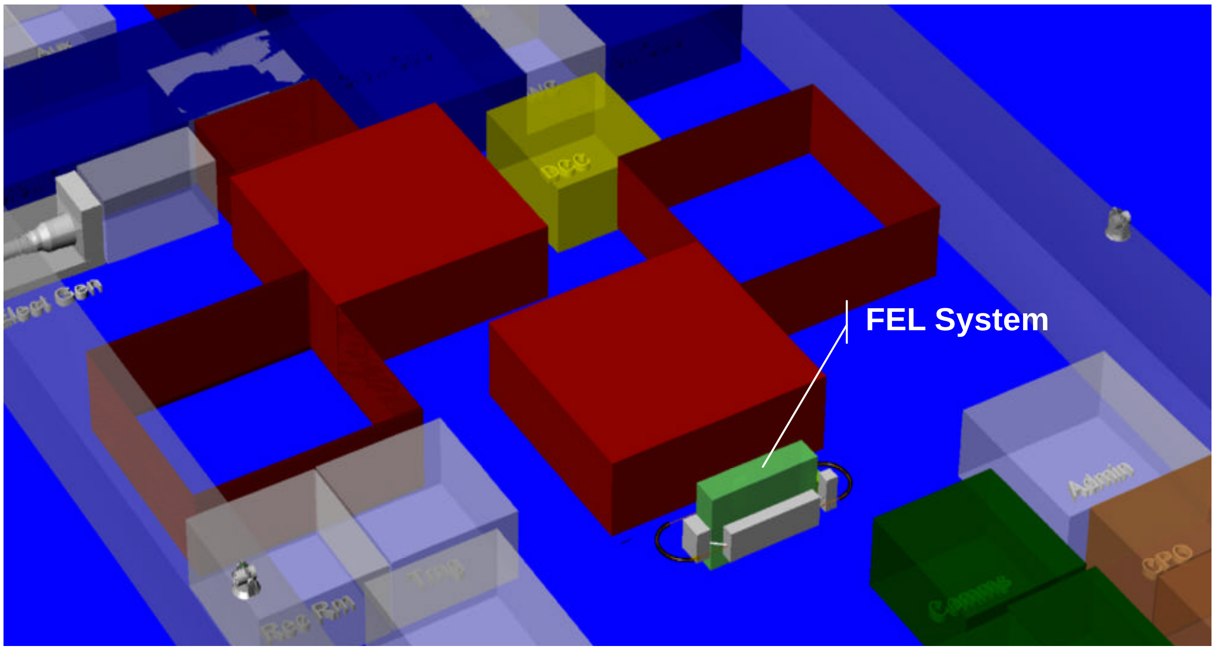

Figure 20 – FEL System Location

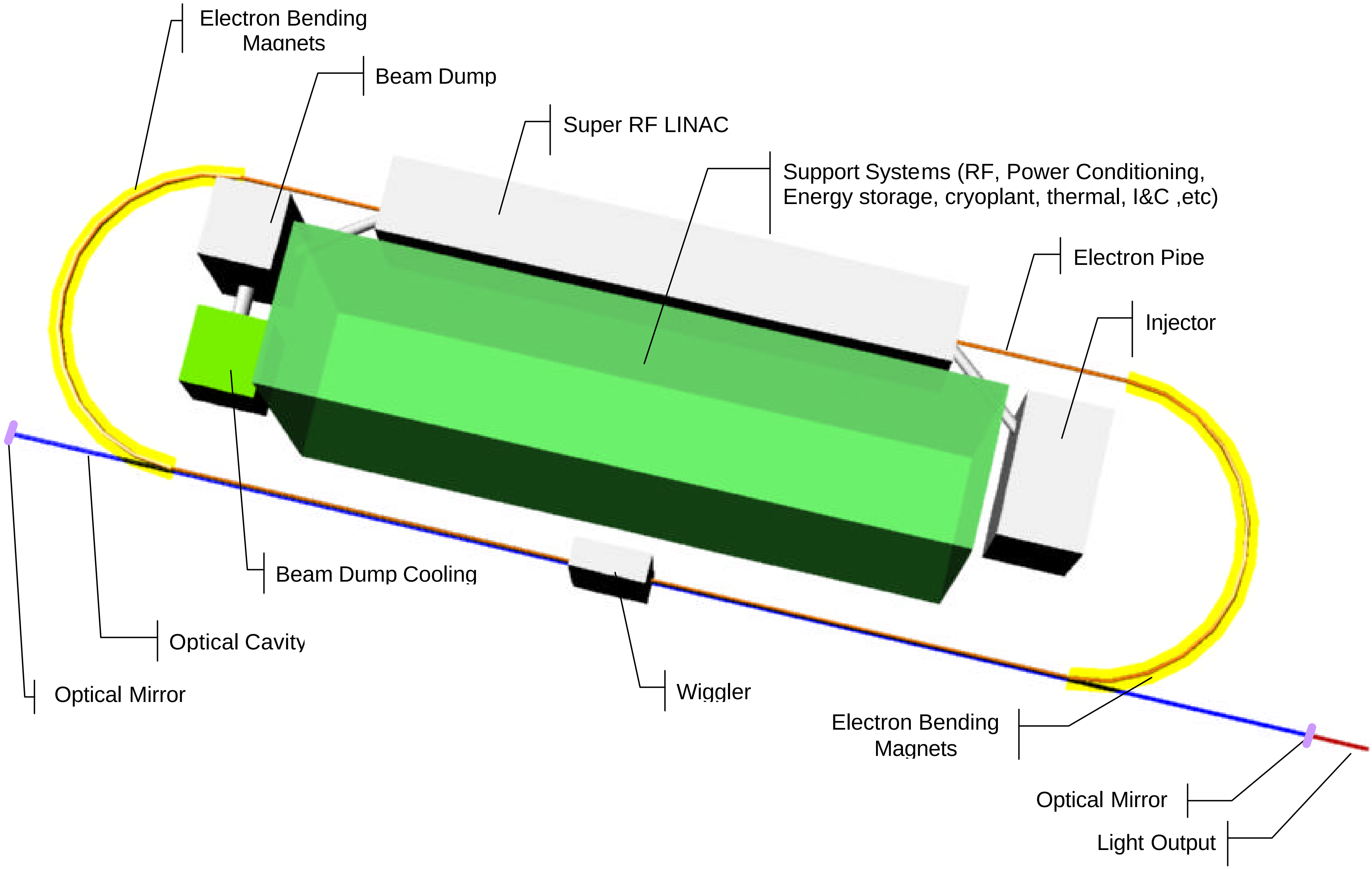

Figure 21 – FEL System Architecture

A. FEL SYSTEM BREAKDOWN

1. Electron Injectors

The electron beam injector consist of two components, the electron gun and the buncher. The electron gun will use a 700 kV dc photocathode. Electrons will be injected and then accelerated to 7 MeV. Subsequently, it will enter the buncher to produce bunched electrons with low emittance. Finally, the electrons will be injected into the RF LINAC at 7 MeV. The injector would produce a 1nC charge per bunch of with a pulse length of 1ps to yield a current of 0.75 A

2. Linear Accelerator

The size constraints placed on the system installation will require a superconducting RF accelerator as this will provide the highest possible energy gradient (at approximately 15 MeV/m). A 100 MeV conventional cryogenic accelerator with accelerating gradient of 6 MeV/M, would have to be approximately 20 m long. The SRF accelerator will demand less operating power and will have larger apertures between cell structures compared to Room Temperature (RT) structures. The downside would be the high cost, fabrication difficulties and the need for liquid helium refrigeration system for maintaining operating temperatures. The accelerator would be 6.7m in length and operate at 750 Mhz RF frequency.

3. Wiggler

This is the portion of the system where laser energy is extracted from the electrons injected from the SRF LINAC. Due to the high energy, there will be approximately 6 MW of power stored between the mirrors. It is expected that the optical cavity mirror would have a radius of 0.025m , consequently the intensity on the mirrors is expected to be 200 kW/cm^2. Current mirror configurations are able to handle up to 300 kW/cm^2 power densities. It is expected that future optics developments will allow the FEL system to handle the necessary beam power. The extraction efficiency of the FEL will be approximately 2% and as power output for the FEL system is defined as,

$$\text{Power} = h_{wiggler} E_e \bar{I} \quad (3.9)$$

where $h_{wiggler}$ = 2% is the wiggler extraction frequency , E_e = 100 MeV is the beam voltage and I = 0.75A is the average beam current (charge $\times$ frequency). This would then provide the necessary power beam output of 1.5 MW.

4. Cooling Requirements

The beam dump will be required to dissipate approximately 5 MW of heat generated from the residual electron energy. This amount of heat will necessitate that the enclosure of the FEL system have some forced air cooling mechanisms similar to steam propulsion systems. Alternatively, water jackets surrounding the beam dump can be used to permit forced water cooling. This amount of heat removal will not be as high as the steam plants onboard ships which generate heat in excess of 50 MW.

The main concern will be the superconducting structures within the FEL. A helium refrigeration system will be used to maintain cooling. The required power from the ship can be estimated by [19],

$$P_R = P_L \frac{T_a - T_{He}}{T_{He}} \frac{1}{h_R} \quad (3.11)$$

where T_a is the ambient temperature, T_{He} is the liquid helium boiling temperature (approximately 4.2K) and h_R is the refrigeration efficiency. Typical efficiencies are between 25% to 35%. If the FEL system is operating continuously, a load P_L = 1.2 kW is expected at the LINAC[19]. The P_R would then be 250 kW. This is considered a significant amount of power consumption and would entail a large refrigeration system. If the FEL system was not to operate continuously but in specific engagement sequences (for example, 150 seconds over 20 minutes), the power consumption and the refrigerator size could be reduced significantly. It has been estimated that continuous operation would require the size of the FEL system to be 12 by 4 by 4m, compared with 12 by 4 by 2m if non-continuous operation is employed.[21]

For this design, it was decided that the system should operate non-continously as the power draw of the system may affect other combat systems when the FEL is firing. Section VI. B. will discuss this further.

In summary, the parameters for the FEL system architecture necessary for the requisite 1.5 MW beam power is shown in Table 10.

Nominal Beam Output Power	1.5 MW
Operating Wavelength	1 μm
Engagement Time	2 to 3 seconds per target
Beam Quality	Near diffraction limited
Beam Energy at Wiggler	100 MeV
Accelerating gradient	15 MeV/m
Electron Current	0.75 A
Bunch Charge	1 nC
Pulse Repetition Frequency (PRF)	750 MHz
Wiggler Extraction Efficiency	2%
Cryoplant Temperature	2.1 – 4.2 °K
Injector Dump Power	2.1 MW
RF Power	4 MW
RF Frequency	750 MHz
Beam Dump Power	5.25 MW
Size	$12 \times 4 \times 2$ m^3
Undulator Period l_o	2.17 cm
Number of Undulator periods	25
Undulator length	54 cm
Optical Cavity Length	12 m

Table 10 – 1.5 MW Class FEL Weapon System Parameters [21]

A caveat for the parameters is that they are only initial estimates. Due to the developmental requirements of the system, it is constantly subject to new discoveries which alter the parameters.

5. Beam Director

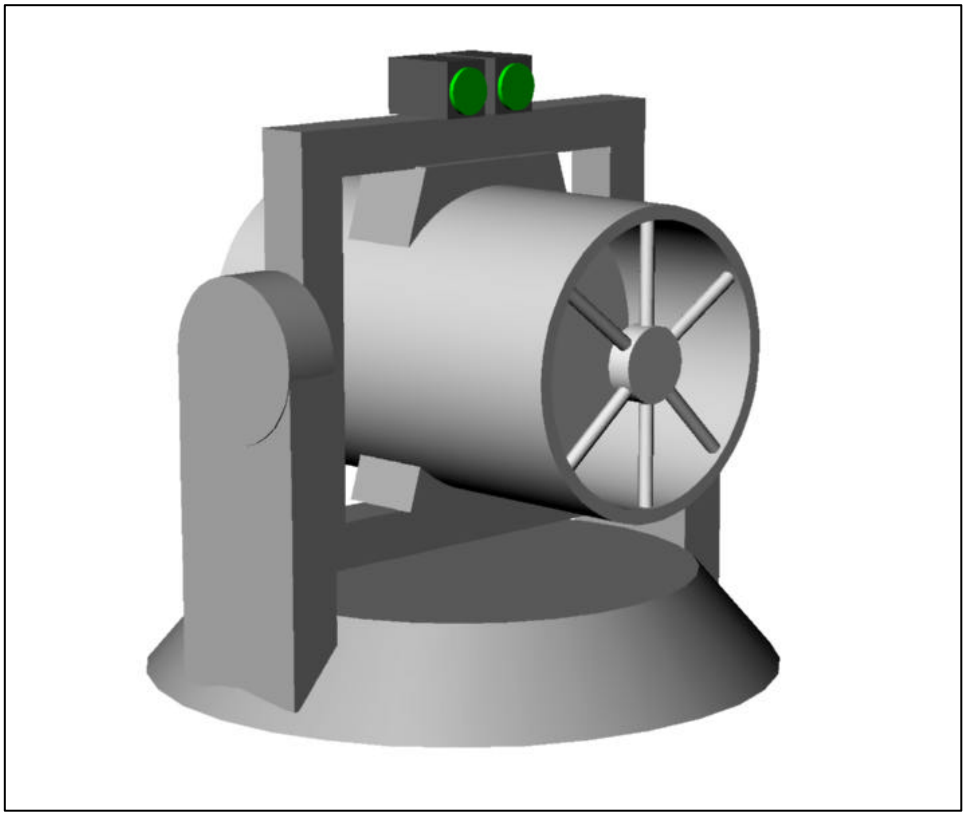

Figure 22 - Beam Director for Sea Archer

This 2-axis system will direct the 1.5 MW laser beam output. The exit mirror radius will be around 0.3 m, which is larger than the calculated exit mirror radius of 0.13m that provides a 0.1m size spot radius on the target. This increase is reserved for a tracker system that uses the outer annulus of the exit mirror. An aperture-sharing element in the high power beam path ensures that it would be possible to track the target visually even when firing the FEL laser. Such technology is already employed in the MIRACL program and by the SEALITE Beam Director. High power density mirrors will employ adaptive optics to minimize turbulence effects.

The beam director will also have a separate independent infra-red camera operating in the 3 to 5 μm wavelength range on top of the beam director. This will provide target detection and cueing for the beam director itself. It allows the beam director to maintain multiple target track profiles while the director is firing at a specific target.

The beam director will require a high slew rate to engage crossing targets. If a Mach 2 crossing target at 500m is envisaged, it translates to a slew rate of 82 degrees/s. This will not be a difficult requirement to fulfil as gun systems in fleet today can perform slew rates up to 140 degrees/s.

A major requirement for the targeting of the system will be the tracking accuracy of the beam director. There must be minimal dispersion errors in tracking as the beam would then be misdirected. For engaging missile targets out to 5000m, the dispersion error has to be less than 0.06 mrad, assuming a typical missile diameter of 0.3 m, to ensure that the beam is held on the target. Though it is more stringent than current naval tracking system (for example, optical systems and fire control radars), the tracking systems has been proved viable by the SEALITE Beam director and the Army's Tactical High Energy Laser System. The difference would be the pitch and roll of the sea.

A typical engagement sequence for the FEL system would be the initial detection of incoming threats from the sensor suites onboard Sea Archer. This encompasses the Multi-Function Radar, Volume Search Radar, Infra-Red Search and Track and Electronic Warfare systems. Once the target has been identified and classified as a threat, the combat system will cue the appropriate beam director to the proper elevation and bearing. The wide Field of View (FOV) of the camera on the beam director will perform a quick scan and acquire and track the target. This allows the system to have sufficient resolution for the beam director to track the target. Furthermore, the outer annular exit mirror can perform visual confirmation of proper target tracking. Firing can then be automated or commanded by the operator once the target has reached the firing range. This entire sequence of cueing from the sensors to tracking of the beam director should be performed in 2 seconds or less.

Multiple tracks should be maintained by the wide FOV infrared camera to ensure that a target file with the proper resolution is maintained by the FEL system. That is the reason why the camera has independent movement from the beam director itself. Subsequently the FEL can quickly engage another target when the first target has been destroyed.

The location of the beam director is at the port and starboard of Sea Archer. This will be the most advantageous position as the hull flexure for a ship will be the lowest at the centre of the ship. Also, a beam transport system through the length of a ship would be unnecessary as the FEL system is co-located at the centre of the ship. The beam director itself has been placed on a pedestal that provides a 180° firing arc. When the system is on standby, an automatic cover would protect it. Firing sequences can commence when the covers is recessed into the ship as shown in Figure 23.

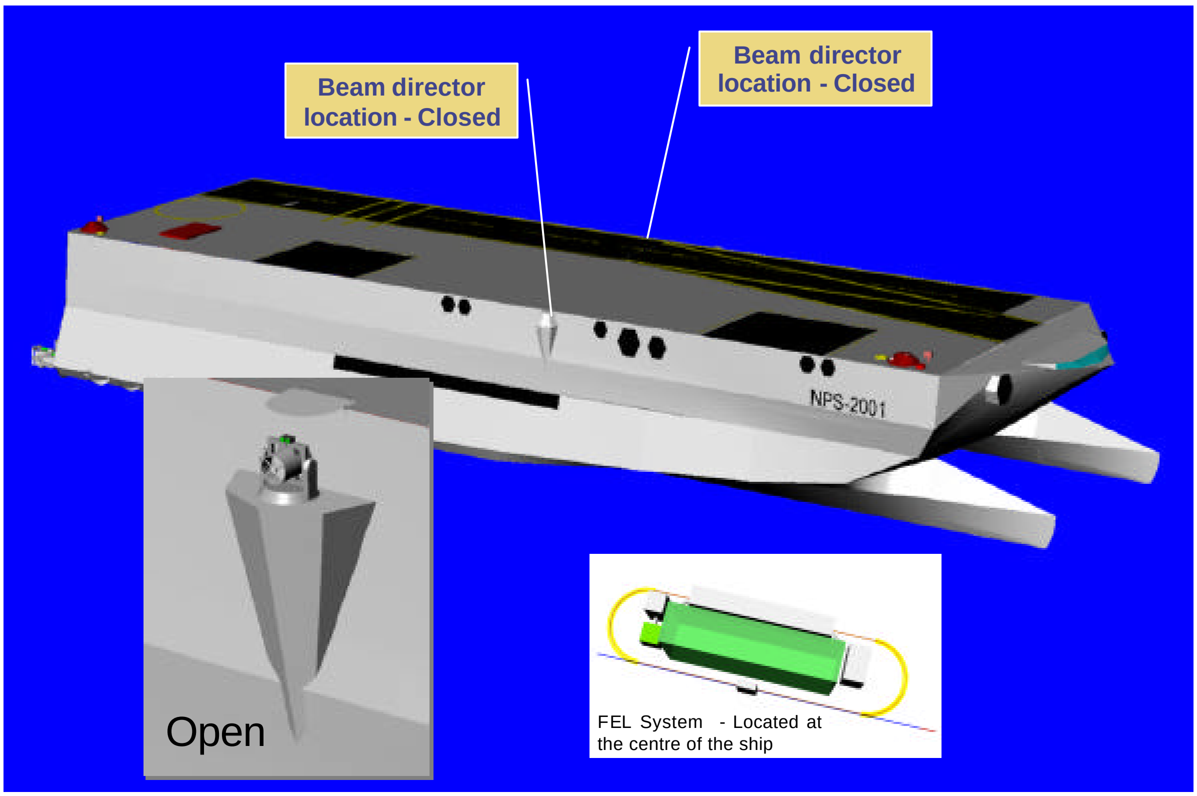

Figure 23 – Beam Director Location

B. PRIME POWER GENERATION

It has been frequently mentioned that the amount of beam power required for an FEL system to effectively engage missile targets require is approximately 10 MW. Current naval platforms require extensive modifications to cater to this power consumption before they can be introduced into the fleet.

Two possible methods are viable alternatives to drive this system

- Direct power generation

- Energy Storage devices

1. Direct Power Generation

The power allocated to drive a propulsion system in the DDG-51 Areligh Burke class destroyer is about 74 MW, with auxiliary generators providing an extra 7.5 MW for other shipboard use. Both E. Anderson and R. Lyon have proposed viable installations for an FEL weapon system installation onboard this class of vessel [18] [19]. The difficulty in implementation is that the ship was not designed for such power uses. The size of the installation would also exceed the growth margin of the ship. As such, other combat systems will have to be sacrificed if installed. The amount of rework required on the ship to fulfil the installation requirements may also be cost prohibitive.

The US Navy has embarked on the next generation power supply for their future warships. This system is called an Integrated Power System (IPS) and is basically the grouping of power generation for ship propulsion and shipboard supply as one source. Electric drive motors, rather than reduction gears connected directly from the turbines, would drive the propellers. Consequently, more efficient use of power can be afforded to other ship uses. An FEL installation would then be easier to implement; designing a ship with the necessary power requirements for a7 directed energy weapon can further enhance it.

The Sea Archer prime power design did not implement an IPS design but rather a hybrid version. The reason was due to the extremely high power requirements to drive the ship to 60 knots. Dedicated turbine generators were necessary to provide the propulsion for the water jet engines. Other generators were required for the blowers to inject air into the air cavities it operated as a Surface Effect Ship (SES) at high speeds. Nonetheless, the power requirements for combat system was initially sized based on a 1.5 MW FEL weapon drawing 10 MW of power with 1 MW of extra power supporting the cooling systems and other ancillary devices. It was decided that the requirements for direct power generation for the Sea Archer make it impractical as the increase in power draw from 1 MW for a standby mode [23] to 10 MW almost instantly would affect the other shipboard systems. As such, storage devices were deemed a more attractive solution for this design.

2. Energy Storage devices

Energy storage devices like flywheels and capacitors provide an alternative method to power the FEL system. Flywheels usually consist of a motor-generator set connected to a rotating disk, which in turn is linked to a generator. Electrical power is drawn and used to run the motor that spins or "charges" the disk to store energy in the form of mechanical energy. When the power is required, the flywheel would then "spin" and run another generator that produces power. This imparts an instant available power source to the FEL system. Figure 24 shows a generic schematic a flywheel.

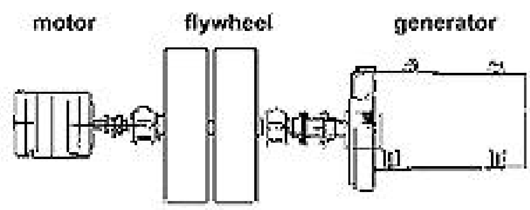

Figure 24 – Flywheel Configuration

To ascertain the *TOTAL* energy required for the FEL weapon system, it may be prudent to assume that such a weapon system should at least handle the same number or even more targets than a Rolling Airframe Missile system. As mentioned in Table 3, the number of targets that a single RAM system can engage is supposedly 10. To destroy a missile target the 1.5 MW beam would need 2 to 3 seconds of irradiation. Since, the efficiency of the system has been assumed at 10%, the total energy required for 10 targets is then 300 to 450 MJ.

Modern flywheels have energy densities of 36 MJ/m^3 and 47 kJ/kg [23], this translates to approximately 12.5 m^3 in volume and weighing 9500 kg. As mentioned previously, the advantage of flywheels over direct power generation is that the power is made available instantly and would not affect other ship loads when the FEL system is operating.

Charging the flywheels would be performed by any shipboard power supply. In the case of Sea Archer, the shipboard generators would produce a total of 82.2 MW. Of this amount 4 to 8 MW may be drawn to charge the FEL system. This takes 37.5 to 75 seconds to have a complete charge of the flywheels. The system would then be ready to fire another set of 20 targets or 60 seconds, if necessary. This is extremely noteworthy as a missile system will not be able to fire as such a short notice once all missiles are expended. It would take a substantial amount of time to reload the missiles before it is operable. Another point to note is that an extra 2 MW of power would then allow the system to run continuously. It was a team design decision not to pursue continuous power generation

Capacitors offer another avenue for storage of power, similar to the flywheels and they can also be instantly discharged when required. The estimated power density of modern capacitors place it at 39 MJ/m^3 and 30 kJ/kg [18], which provides an installation of 11.5 m^3 and 15,000 kg for the capacitor banks. The advantage of capacitors over flywheels is that it affords a combat system graceful degradation in effectiveness. The number of capacitor banks required would be numerically more substantial than the number of flywheels desired, if a failure occurs on single flywheel it would reduce the amount of power available significantly. Conversely, failures of a few capacitors would only reduce the overall available power by a lower percentage. The disadvantage would be the added complexity of maintaining more components with an increased weight. The design philosophy of Sea Archer places survivability as prime importance, capacitors would allow for graceful degradation when components fail and thus ensure higher survivability as the FEL system can still function, albeit at a lower output. Hence, the choice of for energy storage would be capacitor banks even though the weight is 60 % heavier. The prime power layout is shown in Figure 25.

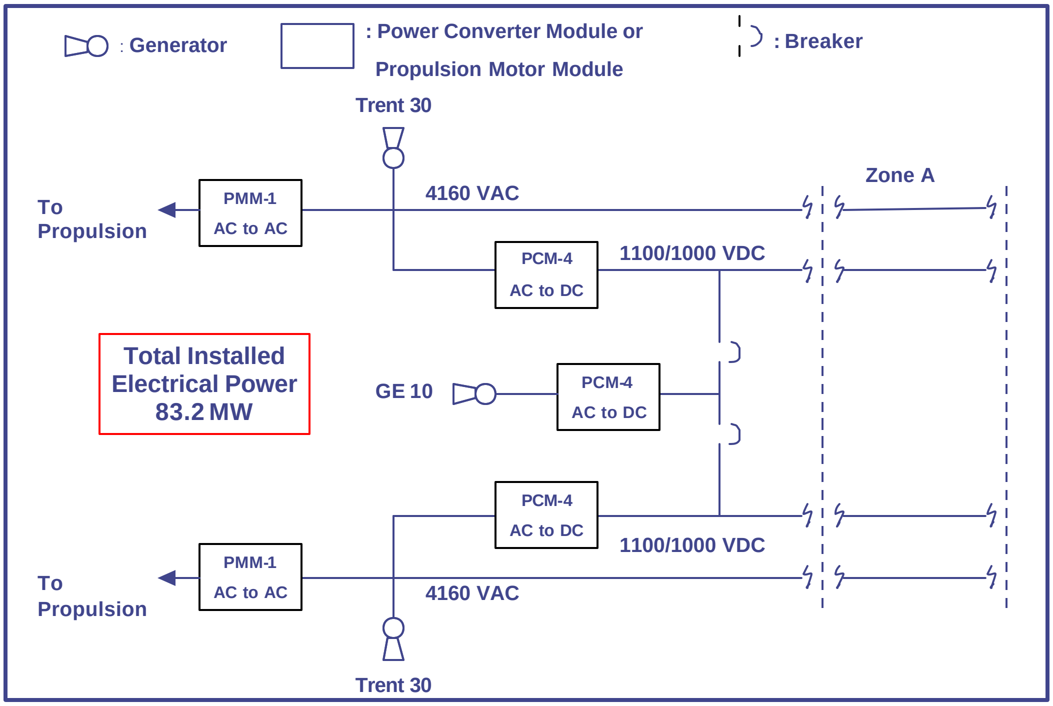

Figure 25 – Sea Archer Prime Power Layout

As mentioned previously, there are a total of 3 turbine generators, with the Trent 30 producing 36 MW each, while the GE 10 produces 11.2 MW. This combined power will be used to generate the necessary power for Sea Archer. Power will be distributed at 1100 VDC, rectifiers would also be installed if required.

C. SHIPBOARD REQUIREMENTS

To qualify a weapon system for shipboard use it must be able to fulfil the requirements set in MIL-STD 810F *Environmental Engineering Considerations and Laboratory Tests*. One of the more serious conditions that can affect the FEL system would be the vibration requirements. It states that non mast mounted systems must be able to operate from 4 to 50 Hz frequency with a 0.03 inches to 0.002 inch amplitude. Vibration in itself would affect the operation of the FEL in many ways, the most direct impact is energy modulation with the RF cavity of the LINAC. Once the electron energy is changed, the output wavelength would be subsequently altered.

This was analysed by E. Anderson [18] to give a wavelength error of 25% for the shipboard vibrations stated, with a rf energy output of 100 MeV. This is a serious consequence as it has been shown that variations from the prime wavelength would cause adverse laser propagation effects.

To mitigate the effects of vibration, feedback stabilization in the RF cavity would be required. This system would measure the optical wavelength and send signals back to correct the electron beam energy to maintain a constant wavelength. The limiting factor in wavelength stabilization would be the frequency response of the rf stabilization loop, which is determined from

$$f = \frac{W_{rf}}{4pQA_o} \tag{3.12}$$

where W_{rf} is the rf frequency of the cavity, Q is the cavity quality factor and A_o the modulation amplitude. As such, a higher stabilization loop frequency would lead to greater stability of the wavelength.

Vibration isolation techniques can also be applied to the LINACs, materials like rubber and springs can be used. This type of technology is already used in nuclear submarines in the US fleet, where whole decks rest on springs to damp their vibrations.

The beam and light transport systems would also require some form of control to alleviate problems associated with vibration and hull flexure. This can be performed by adaptive optics or utilizing active control mechanisms to counter flexure. Several FEL systems now make use of active control in the laboratory. The placement of the FEL system in Sea Archer was selected to minimise the effects of hull flexure.

D. DEVELOPMENTAL ISSUES

The FEL system architecture proposed is still conceptual and no system has yet to be built for shipboard applications. Most of the systems are either currently too large or too low powered to be deployed directly. Certain areas that need to be improved into include,

- High average power injectors – it has been demonstrated that 5mA CW injectors are feasible. Though it may seem a far cry from the required 0.75A, there is a great need within the mainstream physics community for light sources with requirements similar to the FEL weapon parameters. With this parallel developmental need, any work to achieve it would benefit the FEL system. Moreover, Boeing has demonstrated a 1A injector 10 years ago but the system would is too huge for shipboard implementation.
- High peak power density optical elements – present proposals for FEL oscillator design have power densities 3 to 4 times higher than those experienced in the chemical high energy laser systems. Current optical element technology has demonstrated the handling capacity for half the required power density. Consequently, more development is still required. However, one aspect that has not been analysed is the impact of high peak, non-continuous FEL power loading on optical surfaces and coatings.
- SRF and room-temperature acceleration – room-temperature acceleration was not chosen, as a significant amount of RF power loss is experienced because of resistive losses in the acceleration walls. These accelerators have undergone space launches with shock loads exceeding Naval requirements.

E. PROBLEMS ASSOCIATED

No perfect weapon system has yet to be designed and an FEL weapon system also suffers from developmental problems. The most glaring issue with FEL weapon system would be the effect of the atmospheric conditions on its operation. It has been shown that selection of wavelengths and other measures can be used to alleviate their effects but once heavy rain occurs the effect of the weapon system is drastically reduced. Figure 26 shows a plot of the necessary energy required to vaporize a column of rain with a beam radius of 0.2 m and 5000m long, replicating a beam of light that engages a target. Therefore, the energy is the requisite amount necessary to vaporize the water before the beam can engage the target. It shows an exorbitant amount required.

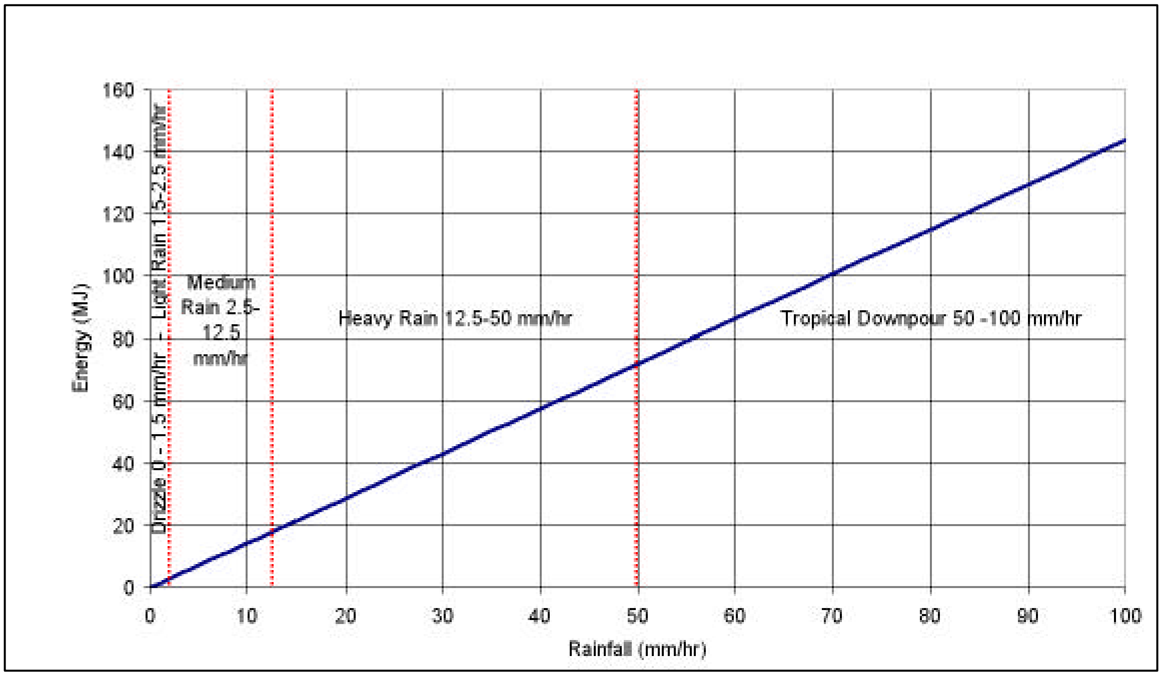

Figure 26 – Energy Required for Vaporization of Rain for a 5 km Engagement

VII. CONCLUSION

The future of Naval ASCM defense may reside with the Free Electron Laser. It provides the leap-frog capability against sea skimming, stealthy, maneuverable missiles at a low cost per engagement, coupled with unlimited firing capability. The speed of light weapon will ensure extremely high hit probabilities with a greater effectiveness against saturation attacks with shorter reaction times.

The system proposed will require a 1.5 MW beam operating at about 1 μm to minimize turbulence, thermal blooming and atmospheric attenuation. While, short Rayleigh lengths will be used within the system to reduce the power densities within the optical mirrors. The complete FEL system architecture will reside within a 12 by 4 by 2m space which includes the injector, SRF LINAC, bending magnets, wiggler, optical cavity and the beam dump. Supporting systems like power conditioning units, capacitor energy storage devices, cryoplants, are also within the space allocated. It has been suggested for Sea Archer that the optimum location would be at the center of the ship to minimize the effects of hull flexure with the beam directors at the port and starboard sides. The weapon can engage up to 10 targets at one time before charging of the capacitor banks will be required. It is estimated that the power drawn from the shipboard power supply will fully replenish it in 75 seconds. It is feasible to run CW if the FEL can receive 10 MW from shipboard power supplies.

For this weapon to be introduced into the fleet, a great deal of development and funding will be required. The stringent size requirements coupled with the shipboard environmental requirements make the success of this directed energy weapon challenging. Nonetheless, the requirements of littoral warfare will ensure that this weapon be a suitable candidate.

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