NAVAL POSTGRADUATE SCHOOL
MONTEREY, CALIFORNIA

THESIS

TOTAL SHIP INTEGRATION OF A FREE ELECTRON LASER (FEL)

by

Eric J. Anderson

September 1996

Thesis Co-Advisors: Charles N. Calvano
William B. Colson

Approved for public release; distribution is unlimited.

REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*	2. REPORT DATE September 1996	3. REPORT TYPE AND DATES COVERED Master's Thesis

4. TITLE AND SUBTITLE TOTAL SHIP INTEGRATION OF A FREE ELECTRON LASER (FEL)

5. FUNDING NUMBERS

6. AUTHOR(S) Eric J. Anderson

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Naval Postgraduate School
Monterey CA 93943-5000

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government.

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT *(maximum 200 words)*

High-power Free Electron Lasers (FELs), capable of stopping an incoming anti-ship missile, can be an effective addition to the self-defense system of a modern naval combatant. A shipboard FEL must be compact, efficient, and capable of reliable operation in a naval environment. This thesis explores the feasibility of integrating a 1MW infrared FEL aboard a surface combatant from a Total Ships Systems perspective. A study of system aspects including vibrational effects and ship/weapon interfaces will be addressed to determine the overall ship impact.

A 1 MW FEL requires 10 MW of electrical power from the shipboard prime power system if run continuously or approximately 2 MW using energy storage. A DDG-51 Arleigh Burke class Destroyer has sufficient reserve generating capacity to produce the required electrical power for the FEL. This prime power electrical distribution system is compatible with the ship's main propulsion gas turbines and weighs 42900 kg and occupies 35 m^3. Shipboard vibrations, which will have the greatest influence on the FEL, are generally characterized at frequencies below 50 Hz and have amplitudes approaching 900μm. The effect of these vibrations can be reduced to an acceptable level which will permit continuous operation of the FEL in the maritime environment. From a Total Ship Systems perspective the FEL can be accommodated in a DDG-51 class Destroyer with negligible impact.

14. SUBJECT TERMS free electron laser, ship design, ship integration

15. NUMBER OF PAGES 65

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT Unclassified	18. SECURITY CLASSIFICATION OF THIS PAGE Unclassified	19. SECURITY CLASSIFICATION OF ABSTRACT Unclassified	20. LIMITATION OF ABSTRACT UL

NSN 7540-01-280-5500

Standard Form 298 (Rev. 28)
Prescribed by ANSI Std. 239-18 298-102

Approved for public release; distribution is unlimited

TOTAL SHIP INTEGRATION OF A FREE ELECTRON LASER (FEL)

Eric J. Anderson
Lieutenant, United States Navy
B.S. Naval Architecture, United States Naval Academy, 1990

Submitted in partial fulfillment
of the requirements for the degree of

MASTER OF SCIENCE IN MECHANICAL ENGINEERING

from the

NAVAL POSTGRADUATE SCHOOL

September 1996

Author: ______________________________
Eric J. Anderson

Approved by: ______________________________
Charles N. Calvano, Thesis Advisor

____
William B. Colson, Thesis Advisor

____
Terry R. McNelley, Chairman
Department of Mechanical Engineering

ABSTRACT

High-power Free Electron Lasers (FELs), capable of stopping an incoming anti-ship missile, can be an effective addition to the self-defense system of a modern naval combatant. A shipboard FEL must be compact, efficient, and capable of reliable operation in a naval environment. This thesis explores the feasibility of integrating a 1 MW infrared FEL aboard a surface combatant from a Total Ship Systems perspective. A study of system aspects including prime power systems and vibrational effects, will be addressed to determine the overall ship impact.

A 1 MW FEL requires about 10 MW of electrical power from the shipboard prime power system if run continuously or approximately 2 MW using energy storage. A DDG-51 Arleigh Burke class Destroyer has sufficient reserve generating capacity to produce the required electrical power for the FEL. This prime power electrical distribution system is compatible with the ship's main propulsion gas turbines and weighs 42900 kg and occupies 35 m^3. Shipboard vibrations, which will have the greatest influence on the FEL, are generally characterized at frequencies below 50 Hz and have amplitudes approaching $900\mu m$. The effect of these vibrations can be reduced to an acceptable level which will permit continuous operation of the FEL in the maritime environment. From a Total Ship Systems perspective the FEL can be accommodated in a DDG-51 class Destroyer with negligible impact.

TABLE OF CONTENTS

I. INTRODUCTION 1

II. BACKGROUND 5

A. EXISTING SHIP SELF-DEFENSE 5

B. FEL PRINCIPLES OF OPERATION 12

C. FEL POWER OUTPUT 13

D. FEL OPERATIONAL REQUIREMENTS 15

III. FREE ELECTRON LASER SYSTEM DEFINITION 17

A. SYSTEM ARCHITECTURE 17

B. MAJOR FUNCTIONAL COMPONENTS 19

C. PRIME POWER DISTRIBUTION 20

1. Direct Power Generation 22

2. Energy Storage in Flywheels 24

3. Energy Storage in Capacitors 25

4. Summary of FEL Prime Power 26

D. SUPPORT SYSTEMS 28

E. SYSTEM SUMMARY 30

IV. FEL OPERATIONAL ENVIRONMENT 31

A. SHIPBOARD VIBRATIONS 31

B. ENERGY MODULATION DUE TO VIBRATIONS 33

C. VIBRATION ISOLATION 37

V. FEASIBILITY 41

A. BASELINE SHIP 41

B. ADVANCED SURFACE SHIP EVALUATION TOOL 42

1. Performance Parameters 42

2. Model Development 43

3. ASSET Results 43

C. SHIP IMPACTS.. 46
VI. CONCLUSIONS AND RECOMMENDATIONS..................................... 47
LIST OF REFERENCES.. 49
INITIAL DISTRIBUTION LIST.. 53

ACKNOWLEDGMENT

The author gratefully acknowledges the guidance and through support of this research provided by Professor Charles Calvano and Dr. William Colson. The author would also like to thank George Neil, Alan Todd, and Lyon Mandelcorn for their efforts in assisting this project. Their contributions advanced this project considerably. Finally, this project would not have been possible without the love and support of my wife Sandra and daughter Kirstin. Thank you.

I. INTRODUCTION

Today's naval combatants face an increasingly difficult challenge of defending against state-of-the-art anti-ship missiles. These threats travel at high velocities with pin-point accuracy and require a defensive system capable of stopping the missile while preventing damage to the warship. Current gun and missile technology has advanced to near the limits of their capability. The cost of increased performance has become extremely high while only slight gains in performance have been achieved. The best approach for a new weapon may be to pursue a system with "light speed" technology. This leads to the development of a shipboard laser weapon system.

Currently, various types of lasers exist, and they all vary in power, operation, wavelength, and complexity. These include solid state, gas, semiconductor (diode), and free electron lasers (FEL). However, of these lasers only the FEL offers the tunability, efficiency, and flexibility in design that is needed for a shipboard weapon system. There are two significant advantages of an FEL over other types of lasers. One advantage is the unique characteristic of tunability. This allows the optical output to be tuned or adjusted over a range of wavelengths. The second advantage makes the FEL ideal for high power applications. Most lasers are inherently inefficient. A typical gas or solid state laser has an efficiency of only a couple percent, where most of the energy is lost to heat generation. The efficiency of a FEL may theoretically approach 20%, which makes it a useful tool for science, industry, and the military [1].

The concept of a free electron laser was first put forth by John Madey in 1971 [2]. His research was aimed at producing stimulated emission in the infrared spectrum using an electron beam from a radio-frequency (rf) linear accelerator. During the 1980's, FEL research received extensive funding as part of the Strategic Defense Initiative (SDI), and rapid developments occurred in FEL theory and design. Currently, FEL technology has advanced to where high-average power FELs appear feasible.

The FEL uses an accelerated electron beam traveling near the speed of light. This beam of electrons enters the undulator which produces a periodic magnetic field using a series of magnets. As the electrons pass from the influence of one magnetic element to the next, their paths are bent by the magnetic field and they are accelerated in the transverse direction, causing them to emit radiation in the form of light. Some of the light is then stored between two mirrors called an optical resonator cavity. As subsequent electrons pass through the undulator, the light in the optical resonator is amplified. A diagram of a simple FEL is shown in Figure 1.

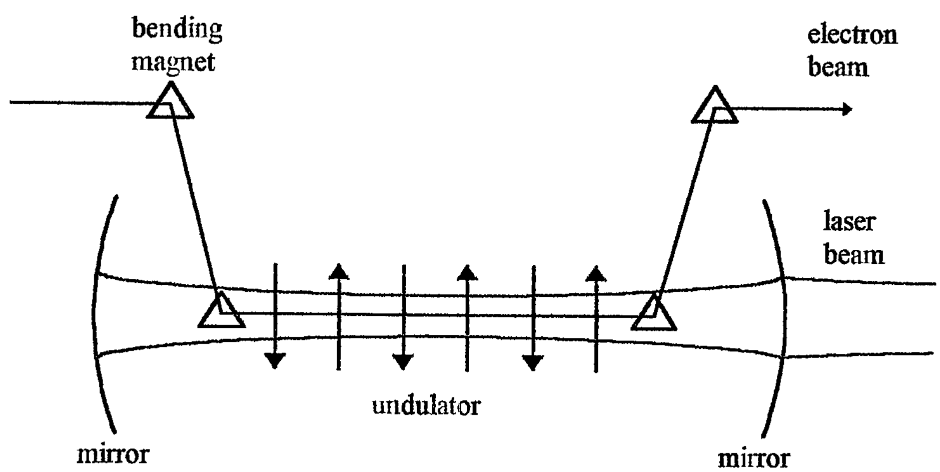

Figure 1 - Simple FEL diagram

The FEL weapon has many promising aspects as well as some technological risks. Currently, the most powerful FEL has been limited to only about 10 watts in average power. A kilowatt level FEL is being constructed by the FEL Group at the Thomas

Jefferson National Accelerator Facility. The feasibility of a high-average power FEL for ship self-defense will depend upon advances in technology over the next 7-10 years.

The shortcomings associated with ship self-defense using the Phalanx Close In Weapon System (CIWS) are discussed in Chapter II along with the supporting argument for an FEL weapon. In addition, the physics explaining the operation of the FEL and the operational requirements to make the FEL an effective naval laser system are outlined.

The FEL is made up of several components described in Chapter III. The FEL must also be adaptable to the maritime environment in terms of vibration received from the ship. The FEL performance in conjunction with these vibrations is examined in Chapter IV to determine their effect and outline possible methods of isolation.

The integration of a FEL as part of a ship's Combat System Suite requires numerous aspects to be considered. The Advanced Surface Ship Evaluation Tool (ASSET) is used to determine the overall ship impact of replacing the forward 32 cell VLS launcher with a 1 MW FEL weapon on board a DDG-51, Arleigh Burke class Destroyer.

This thesis investigates many aspects of the FEL and how it will be integrated aboard the ship. There are numerous design decisions which must be made that define the FEL architecture and may change as technology advances. The model for the FEL weapon is based on a theoretical design by the Thomas Jefferson National Accelerator Facility. The feasibility of using this design aboard a state-of-the-art naval combatant is explored.

II. BACKGROUND

A Free Electron Laser (FEL) offers improved self-defense capabilities for a naval surface combatant of the future. Highly maneuverable, supersonic cruise missiles can appear within minutes and cause severe damage to a ship. In the missile attacks involving the *USS Stark* and *HMS Sheffield* even though the warhead failed to explode, significant losses in terms of human lives and equipment were inflicted. These anti-ship weapons are becoming more sophisticated and more widely proliferated among littoral nations. This requires a self-defense weapon that is highly versatile in stopping incoming missile threats. Not only must these threats be defeated, but the intercept range must be at an adequate distance to prevent missile fragments from reaching the ship and causing damage. The FEL provides a near instantaneous response to missile threats using a weapon traveling at the speed of light, and it accomplishes this task at greater ranges to provide enhanced self-defense capability.

A. EXISTING SHIP SELF-DEFENSE

The U.S. Navy standard weapon for point defense is the Phalanx Close In Weapon System (CIWS) which consists of a multi-barreled gatling gun capable of firing 3000 rounds per minute at a maximum range of 2 kilometers. The depleted uranium rounds are fired at a speed of 1200 m/s which is not adequate kinetic energy to overcome the forces of gravity and drag during the bullets' trajectory. To reduce these effects, CIWS employs a closed loop spotting system which tracks both the incoming missile and the outgoing bursts of fire. It predicts the rounds' point of closest approach to the incoming target and corrects the aim of the following burst(s). This correction makes it possible to intercept an incoming missile with a short burst of rounds. CIWS provides the innermost layer of defense against anti-ship missiles. Its magazine is capable of holding up to 1000 rounds and it will fire continuously at a target until all rounds have been expended or the target is destroyed. However, firing must be limited to 5 second bursts to prevent the gun barrels from overheating. Reloading the magazine is not a trivial task. It requires up to 30 minutes, which is an unacceptable amount of time considering the likelihood of repeated missile attack. CIWS has many years of fleet experience and has been modified over time, but its performance against sophisticated cruise missiles is questionable.

The high firing rate of CIWS is achieved through the high speed angular rotation of the six gun barrels. This angular rotation coupled with inherent system vibrations, leads to small angular deviations in the gun barrels. Such deviation projected over the bullet's trajectory results in highly inaccurate targeting. Figure 2 shows an example of the projectile spread at a distance of 800 m from the CIWS gun. In this figure, 300 shots were fired with a dispersion of 0.002 radians. Assuming the incoming missile "target" was 0.2m in diameter, only 5 out 300 (1.7%) projectiles hit the target. The closed loop technology helps to reduce these effects, but the probability of destroying the missile outside of 300m is less than 15%. As the incoming missile approaches the ship, the projectiles' trajectory is shortened and CIWS accuracy steadily improves.

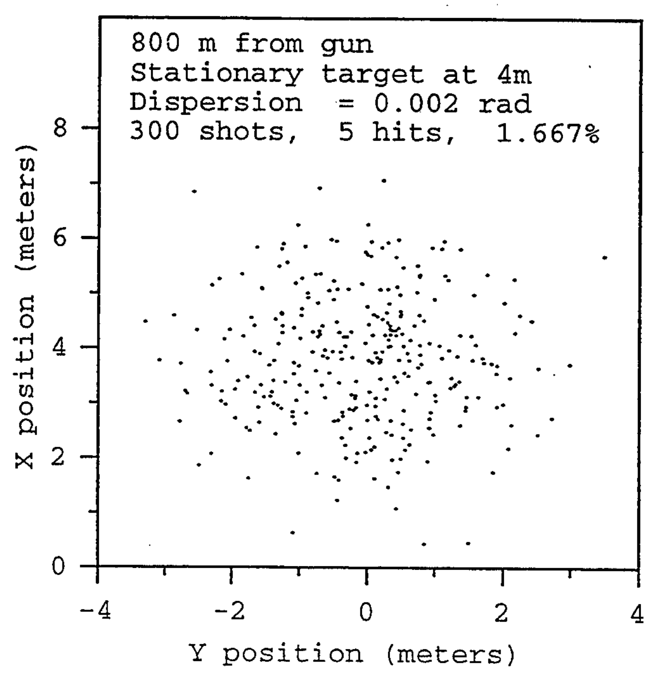

Figure 2 - Projectile spread from CIWS gun

Figure 3 shows the hit probability versus range for a typical CIWS engagement. For this case 5000 rounds were fired at each 100m increment against a target 0.2m in diameter in order to more accurately determine the probability. The hit probability is extremely low until the missile is inside 200 m. Assuming several hits are needed to kill a typical missile and the low percentage of hits as shown in figure 3, CIWS does not provide adequate self-defense capability.

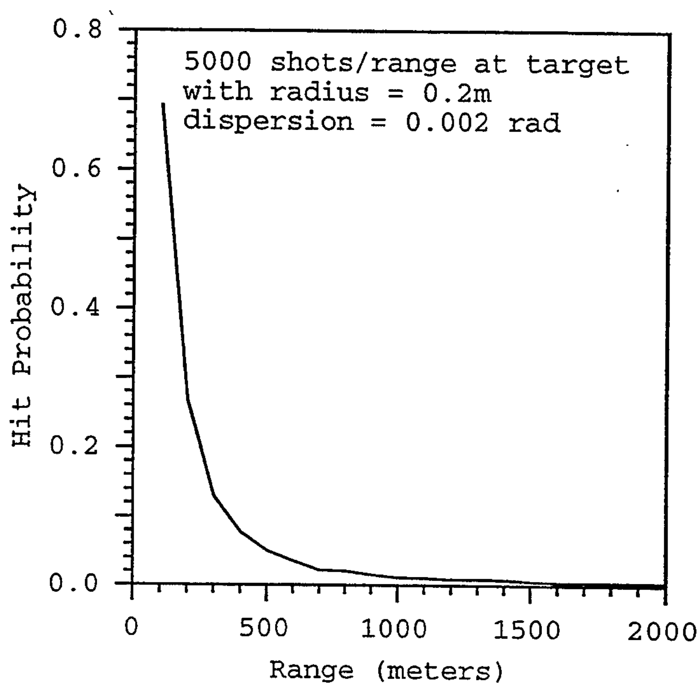

Figure 3 - Hit probability for typical CIWS engagement

The CIWS has a limited range which does not allow it to intercept the missile at sufficient distances from the ship. Given the scenario in which an incoming missile has been effectively penetrated by several CIWS rounds, the missile may break up into smaller fragments which contain sizeable velocity components in the direction of the ship. These fragments contain enough momentum to hit and damage the ship with possible loss of mission capability or human lives. In this scenario, the ship may be saved from a direct hit, but the leftover missile debris is not stopped due the short intercept range and may cause significant damage.

To gain a better perspective for the number of missile fragments that may impact the ship, a computer simulation was developed utilizing the characteristics for a typical incoming missile, such as the Exocet. For the Exocet missile, it is assumed that the initial velocity is 300 m/s at a height of 5 meters above sea level. The typical characteristics of one missile fragment has a mass of 50 kg, a cross-sectional of 0.2 m^2, and a coefficient of friction, C = 1. It is also assumed that the velocity of these fragments are distributed as a Gaussian with standard deviation σ_V = 30 m/s. The program simulates 1000 fragments then returns values for 10 typical fragments.

To simulate missile fragments approaching an actual ship, the ship was modeled as a box with dimensions equal to an Arleigh Burke class Destroyer. The box is 154 m in length, 21 m in beam, and the superstructure is 20 m above the waterline. The height of the mast extends 8 m above the superstructure. The simulation was run against the ship profile from both a broadside and end-on or bow/stern aspect.

Figure 4 shows the effect of 10 typical fragments approaching the ship from these two perspectives. Due to the greater surface area of the broadside aspect, about twice as many fragments collide with the ship as compared to the bow or stern aspect. Figure 4 shows that although the incoming missile will be destroyed, some debris will impact the ship.

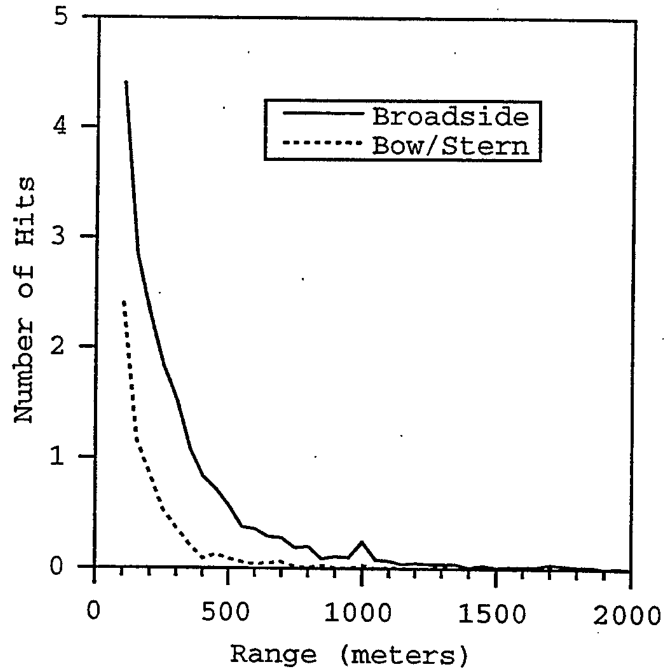

Figure 4 - Number of Missile Fragments Impacting the Ship

One method of estimating the damage that may be imparted to the ship is to calculate the energy of the fragments when they impact the ship. Figure 5 shows the total kinetic energy received by the ship from the impacting fragments over the range from 2000 meters to 100 meters. This figure shows that for a typical cruise missile such as the Exocet, approximately 6.5 MJ will be imparted on the broadside of the ship and 3.5 MJ on the bow or stern. The modulus of elasticity for steel and aluminum are 79 and 28 GPa, respectively. With such high modulae of elasticity, one concludes that although damage may be incurred by the ship, there is minimal danger that the impact of the fragments will sink the ship. Naturally, more delicate systems may suffer and a lucky fragment could always cause the loss of a vital mission area, but the probability is low that the fragments will sink the ship. Figure 5 shows that a missile with the characteristics of an Exocet stopped outside of 2 km from the ship will impart significantly less energy to the ship.

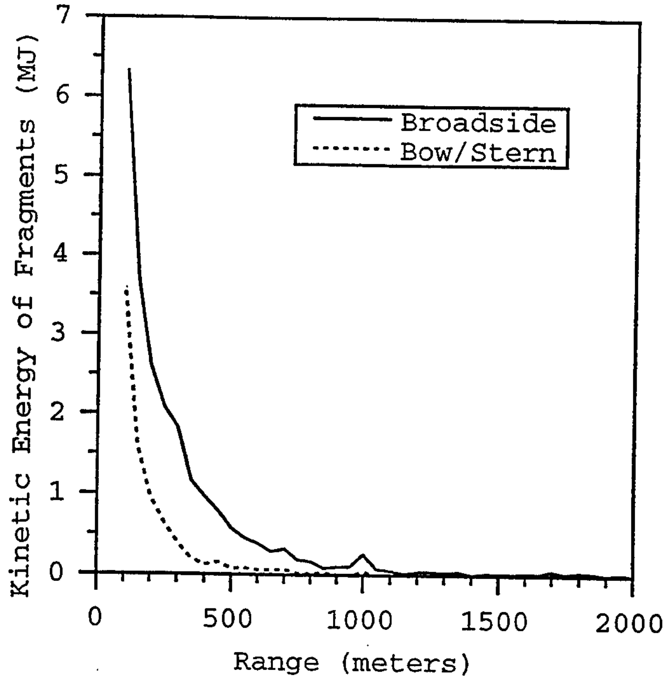

Figure 5 - Kinetic Energy of Missile Fragments Impacting the Ship

In contrast, consider a FEL which is capable of directing a beam of laser light, traveling at the speed of light. This beam would provide near instantaneous defense against anti-ship missiles. The FEL ballistics are simple; gravity has no effect on the beam of light and the muzzle velocity is so great that ballistic correction is not required. The beam must dwell on its target for 2-3 seconds to inflict enough damage for effective destruction. Depending upon the "hardness" of the missile, the kill mechanism may be removing a chunk of material from the missile or altering the aerodynamics of the missile, causing it to heat up and fly off course.

The FEL has a maximum range of about 10km which provides an extended margin of defense over CIWS. This contributes to increased time for threat evaluation and target destruction. The enhanced self-defense capability allows missiles to be intercepted at greater distances from the ship, saving the ship and its crew from casualties. Referencing the missile attack on the *USS Stark* in May 1987, losses due to a single anti-ship missile attack can be costly in terms of equipment and American lives.

One of the most difficult problems associated with a missile engagement is the lag time between the threat detection and its destruction. The most significant portion of this lag time is the time between the employment of a missile system and the destruction of the threat. In the case of a typical short range (10km) missile engagement with a modern defensive missile system, time between employment and threat destruction can be greater than 10 seconds. During this time lag, the threat missile has the opportunity to move closer to the ship. If the shot is evaluated as a miss, a second SAM or defensive missile would have to be fired. If the target is at very short range, CIWS would have to be engaged. In reality, there is little time for missile re-engagement and a kill by CIWS at close range would probably result in damage to the ship. In contrast, a FEL directs a beam of energy which can travel 10km in less than 1msec, to meet the threat. The laser beam would only need to dwell on its target for 2-3 seconds to destroy the target. This fast response provides a clear advantage over new, sophisticated anti-ship missiles and reduced time between engagement and destruction.

Using energy generated through the ship's present electrical plant instead of rounds for its ammunition, the FEL provides a weapon magazine limited only by the ship's fuel capacity rather than a finite number of projectiles or missiles. While the threat of defending against hundreds of missiles within a few minutes' time is unlikely in the current political environment, the FEL offers enhanced self-defense capability for both the ship and other units within its coverage. The " limitless" magazine reduces the cost per target intercept as well due to the absence of costly rounds or defensive intercept missiles.

For these reasons, the FEL should be pursued as an attractive alternative to CIWS or other short range defensive missiles such as RAM or Sea Sparrow. The addition of the FEL to a ship's combat system suite provides a more flexible, cost effective response to missile threats. The FEL's fast response and high lethality rate provide formidable short range protection. This conserves standard missiles that cost hundreds of thousands of dollars each for longer range engagements outside the range of the FEL. The mixture of long range missiles and a FEL gives the surface combatant an enhanced defensive and offensive capability to meet threats into the 21st Century.

B. FEL PRINCIPLES OF OPERATION

The FEL oscillator consists of four basic components: an electron accelerator, a co-propagating optical beam, a static periodic magnetic field produced by a series of magnets known as a "wiggler" or undulator, and an optical resonator. These elements interact to produce stimulated emission which leads to coherent radiation in the optical resonator.

The accelerator produces an electron beam traveling at relativistic speeds close to the speed of light. The relativistic electrons travel along the axis of the wiggler and experience regular transverse accelerations due to the periodic magnetic field strength and direction. As the electrons pass from the influence of one magnetic element to the next, the magnetic field bends their paths, causing them to accelerate and emit radiation. This stimulated emission of radiation is produced at a wavelength λ as determined by the resonance condition in the undulator described by

$$\lambda = \frac{\lambda_0}{2\gamma^2}\left(1 + K^2\right) \tag{2.1}$$

$$\text{and } K = \frac{eB\lambda_0}{2\pi mc^2} \tag{2.2}$$

where λ_0 is the wiggler wavelength, K is the wiggler parameter, B is the rms wiggler magnetic field, and $\gamma = E / mc^2$ is the relativistic Lorentz factor. The wavelength can be tuned by varying the transverse separation of the magnets, which are fixed after construction, or the initial electron energy, or the undulator gap which changes the field strength K. The relationship between wavelength and electron energy $\lambda \propto 1/\gamma^2$ provides the easiest method of tunability. The wavelength can be tuned over a wide range with small adjustments to the electron energy to compensate for varying environmental conditions such as rain, fog, sea spray, smoke and dust. The FEL provides a flexible means of designability in order to reach the optimum wavelength that will travel through the atmosphere with minimal absorption.

C. FEL POWER OUTPUT

To estimate the FEL power output needed for ship self-defense, examine a typical incoming anti-ship missile scenario. In order to kill the missile, it is assumed that a chunk of material 10 cm square and 3 cm deep must be removed from the missile. This will destroy the airframe aerodynamics so that the missile will hit the water, or turn and breakup. The number of atoms in this volume is about $9X10^{24}$ and it is assumed that the amount of energy needed to make one atom melt is about one electron-volt. The total energy needed to melt and destroy this volume is then

$$(9 \times 10^{24}\,\text{atoms})\left(1\text{eV}/_{\text{atom}}\right)\left(1.6 \times 10^{-19}\,\text{J}/_{1\text{eV}}\right) \approx 1\text{MJ}. \tag{2.3}$$

In order to destroy the missile, the FEL must deliver approximately 1 MJ of energy. It is reasonable to deliver this amount of energy in roughly 2-3 seconds. Therefore, the total power required at the missile must be several hundred kilowatts where $\text{MJ}/3\sec \approx 300$ kW. This would effectively remove a sizeable chuck of material from the incoming missile and cause its destruction.

An alternate means of determining the power output begins with the diffraction of a laser beam as described by

$$Z_o \lambda = \pi w_o^2 \tag{2.4}$$

where Z_o is the Rayleigh length, and w_o is the initial spot radius. The Rayleigh length is the characteristic distance for laser beam expansion and describes the distance for the spot radius to double in size from a flat phase front. The laser spot radius at the target is described by

$$w(Z) = w_o \left(1 + \frac{Z^2}{Z_o^2}\right)^{1/2} \tag{2.5}$$

where Z is the distance to the target. Equation (2.5) can be approximated at long range, assuming $Z/Z_o >> 1$ and substituting in (2.4), to get

$$w(z) \approx \frac{w_o Z}{Z_o} = \frac{Z\lambda}{\pi w_o} \tag{2.6}$$

Using (2.4) and (2.6) above with $\lambda = 1\mu m$, $w_o = 0.5m$ is the initial laser spot radius at the ship's mirror, and target range, Z = 10km, yields $Z_o = 800X10^3$ km. With such a long Rayleigh length, the laser diffraction does not cause significant spreading of the beam. In fact, the ship's mirror surface would be slightly curved in order to focus the beam down to a 5 cm radius on the missile.

The common measure of "hardness" of a missile is called fluence, F, since it describes the amount of energy absorbed by the skin which destroys it. Fluence is calculated by [3]

$$F = \frac{P\Delta t}{A}, \tag{2.7}$$

where P is the actual power received by the missile, A is the spot size, and Δt is the dwell time that is required to incapacitate it. A moderately hardened missile may require a fluence of 10 kJ/cm^2. The 5cm spot radius calculated earlier translates to a spot size of 78 cm^2. Using a dwell time of 3 seconds the total power required at the missile calculated from (2.7) is P = 260 kW. This supports the power output calculated previously.

In the laser beam's path to the missile, the beam encounters aerosols in the atmosphere which remove power from the beam. For a beam wavelength of $1\mu m$ the extinction coefficient due to aerosols at sea level is $\alpha = 0.05 km^{-1}$ and $e^{-\alpha Z}$ describes the removal of power over a distance Z. The power required at the ship, P_s, can be determined from the relation

$$P_s = \frac{P}{e^{-\alpha Z}}. \tag{2.8}$$

At a target range of 10 km and P = 300 kW, the required power at the ship must be approximately 500 kW to destroy the missile. The FEL used for this study has an average power of 1 MW and the required power at the ship is well within its capability.

Assuming the missile is traveling at Mach 1 or roughly 340m/s, the time for the laser beam to reach the missile at 10km is

$$T = \frac{10000\text{m}}{3\text{x}10^8\,\text{m/s}} \approx 33\mu\,\text{sec}. \qquad (2.9)$$

Meanwhile, the distance the missile will travel during this time is

$$D_{\text{missile}} = (340\text{m/s})(33\mu\text{s}) \approx 11\text{mm}. \qquad (2.10)$$

This shows that the missile will move a small distance during the engagement, but tracking systems are capable of following this motion.

The equations described above define the power output and beam dimensions required of an FEL to destroy an incoming anti-ship missiles at ranges out to 10km.

D. FEL OPERATIONAL REQUIREMENTS

To achieve an adequate weapon design, an operational scenario which reflects the future threat must be considered throughout the design process. While the traits of projected threats cannot be predicted exactly, the operational scenario used for this study assumes that a ship must be capable of defending itself against raids of three anti-ship cruise missiles (ASCMs) within one minute. It is assumed that the laser will operate no longer than 10 seconds for each missile engagement. This time interval is sufficient to engage an incoming 1.0 Mach missile over a distance of about 3.4km.

As a naval weapon system, the FEL must be capable of producing high output power and the system must have physical dimensions that will allow its placement on a current naval combatant. The following chapters describe a FEL that has these attributes along with the components that make up a naval laser weapon system.

III. FREE ELECTRON LASER SYSTEM DEFINITION

In the previous chapter, the case for a high powered shipboard FEL was established. Numerous FELs have been constructed; however, they have been limited to relatively low average-power on the order of a few watts. A FEL designed for shipboard use must be efficient to maximize use of the ship's power supply, compact to fit within the ship's structure, and capable of producing high average-power levels for ship self-defense. This chapter will describe the components of the FEL along with the system architecture and support systems required for shipboard operation.

A. SYSTEM ARCHITECTURE

The Free Electron Laser used in this study was designed by a collaboration between the Naval Postgraduate School and the Thomas Jefferson National Accelerator Facility FEL Group. The design is based on technology that is currently in use or under development for FEL applications. This design was selected for this study based on its relatively compact size and high efficiency. The FEL consists of five basic functional components: the electron injector, the linear accelerator, the undulator, the optical resonator, and the electron beam dump.

The 1 MW FEL architecture uses an energy recovery system to optimize system power efficiency, system size and weight, and personnel radiation hazards. An illustration of this architecture is shown in Figure 6. The electron pulses are injected into the linear accelerator with a small initial energy of about 10 MeV. The rf field in the accelerator increases the beam energy by many orders of magnitude to several hundred MeV. After acceleration, the beam is directed into the undulator by a series of bending magnets. A small percentage of the beam energy is converted to optical energy in the undulator. Bending magnets then direct the beam back into the accelerator where it enters 180 degrees out of phase with respect to the rf accelerating fields. This allows the energy of the decelerating electron beam to be transferred back to the rf fields. The energy recovered from the decelerating electron is then used to accelerate another electron pulse repeating the cycle. After passing through the accelerator, the decelerated electron pulses are guided into a beam dump where the remaining energy of about 5 MeV is dissipated.

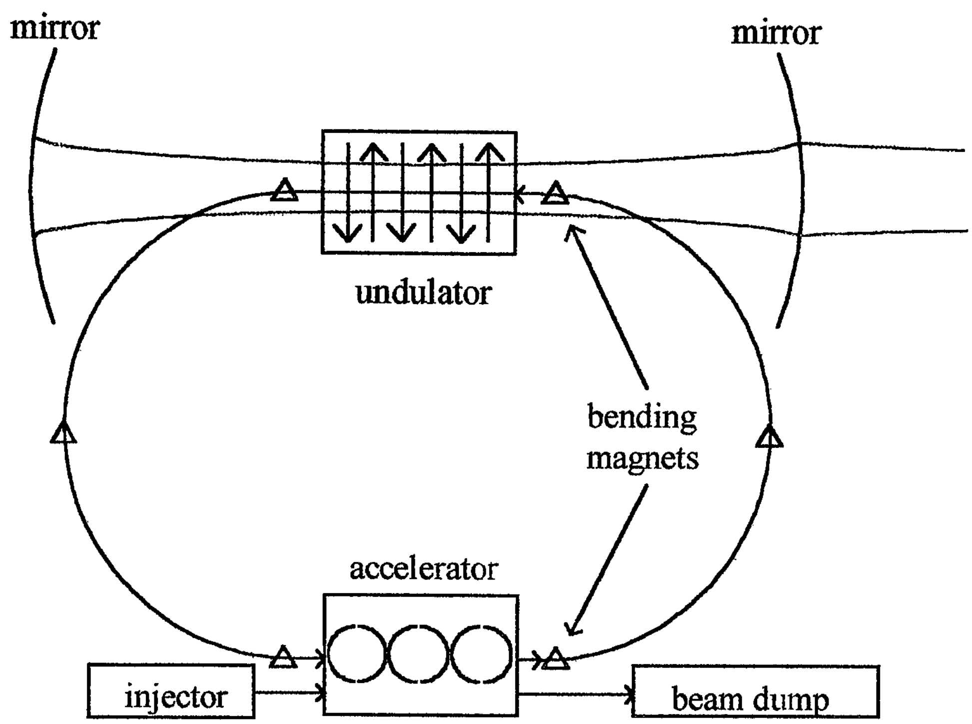

Figure 6 - FEL architecture

The energy recovery architecture makes a significant contribution to the FEL's potential as a shipboard weapon system. It provides increased energy efficiency to reduce the demands placed on the shipboard power supply. The reduced physical size makes the FEL comparable in volume with current shipboard weapon systems such as the Mk 45 5in/54 gun or a 32 cell VLS launcher. Most importantly, the energy recovery feature of this architecture reduces the personnel radiation hazards to manageable levels.

B. MAJOR FUNCTIONAL COMPONENTS

The electron injector is used to produce high density pulses of electron current and inject them into the linear accelerator with the proper phase relation with respect to the accelerating rf field. The injector is comprised of two components: the electron gun and the buncher. The electron gun uses a 500 kV dc photocathode which is capable of accelerating the electrons to a kinetic energy of 500 keV before they enter the buncher. The buncher contains a series of cavities which are designed to produce bunched electron pulses with low emittance. The dc photocathode requires 500 kV at 0.5 A dc [4].

Once the electrons leave the buncher they are then injected into the linear accelerator which consist of a series of cavities fabricated from a superconducting (SC) material such as niobium (Nb). The SC accelerator permits reduced operating power requirements, higher accelerating fields, greater accelerating gradients, and larger apertures between cells structure as compared to a room temperature (RT) structure. The larger aperture between cells permits lower ohmic losses in the accelerating cavity walls. The rf sources which power the SC accelerator require 100 kV at 100 A dc [4]. The SC accelerator has many advantages over a RT accelerator, as noted above, but it is more expensive and difficult to fabricate and requires the support of a liquid helium refrigeration system to maintain operating temperature. However, after many years of experience, SC technology has become much more commonplace. The SC linear accelerator weighs 32000 kg and has a volume of 81 m^3 [5].

The undulator and optical resonator form the heart of the FEL where the energy is extracted from a relativistic electron beam and radiated as coherent optical light. In the resonator, megawatts of power circulate between the mirrors. This requires a special mirror configuration as well as adequate spacing between the mirrors to limit the power density on the mirrors. Modern optical components can support a power density up to 100 kW/cm^2. As a result of this limitation, the optical cavity is 22 m long and 0.5 m in diameter. This translates into a volume of 5.5 m^3 with a weight of 2200 kg. As more advanced optics are developed with greater power densities, the length of the optical cavity can be reduced.

The electron beam path terminates in the beam dump which provides a location for the residual energy of the decelerated electrons to dissipate. The residual energy of the beam is about 5 MeV, therefore, neutron radiation can be neglected as long as the structural materials used to construct the beam dump have neutron production thresholds greater than 5 MeV. Among the structural materials commonly used in shipboard applications only beryllium (Be) has a neutron threshold below 5 MeV [4][6]. Accordingly, neutron generation does not occur as long as beryllium is excluded from the beam dump structural materials.

The functional components of the FEL described above, coupled with the architecture from Figure 6, can be packaged into a volume approximately 9 m x 6 m x 1.5 m which is equal to approximately 81 m^3. Only the optical resonator cavity, which is 22 m long and 0.5 m in diameter, projects out from this volume. In comparison to other shipboard weapon systems, a 32 cell VLS missile launcher occupies 367 m^3 and a Mk 45 5in/54 gun occupies 252 m^3 [7]. However, the FEL requires additional support systems which will be discussed in the next section and which increase the overall volume and weight of the system.

C. PRIME POWER DISTRIBUTION

The FEL requires a dedicated electrical distribution system to generate high voltage dc power for the photocathode and the linear accelerator. The prime power requirements for a high-average power FEL were calculated in Ref. [4] and are summarized in Table 1.

	rf sources	dc photocathode
voltage	100 kV	500 kV
power	10 MW	250 kW
type	dc	dc
duration	10 sec	10 sec

Table 1 - Prime power requirements to support a 1 MW FEL [4]

Assuming a 10% wall plug efficiency for the FEL, continuous operation at 1 MW of optical power requires about 10 MW of electrical power. Considering that the FEL operates at 10 second intervals, energy storage devices can also be used which will decrease the electrical power demand on the ship. The following sections outline various prime power systems that can be used with the FEL including direct power generation and energy storage in flywheels and capacitors.

The DDG-51 class destroyer is mechanical drive and has 4 gas turbine engines (LM2500) each of which produce 25,000 shaft horsepower (SHP) or 18.6 MW for main propulsion. An additional 3 ship service gas turbine generators (SSGTG) each produce 2.5 MW for the ships service (SS) electrical distribution. In total, 74.4 MW of power can be generated for main propulsion and 7.5 MW for SS electrical distribution. The SS electrical distribution normally uses only 2 of the 3 SSGTGs leaving one as an emergency/backup which can potentially power the FEL, but one SSGTG provides only 2.5 MW. The 74.4 MW of main propulsion power enables the ship to reach a top speed of 31 knots, but only half this power (or 37.2 MW) is needed to achieve 27 knots. Taking this into account, many megawatts of power is available from main propulsion if top speeds are not required while the FEL is in operation. This shows that sufficient power is available from the existing ship's generators to provide power to support the FEL [4][8].

Several means of diverting this power for the dc photocathode and rf sources will be examined.

1. Direct Power Generation

One method of power generation, without using energy storage, is to divert power from a LM2500 through the reduction gears. The DDG-51 has two propellers, each driven by two gas turbine engines through a common reduction gear. The reduction gears were designed to accommodate a Franco Tosi hydraulic reversing system. Considering that Controllable Pitch Propellers (CPP) were chosen to provide astern propulsion, the Franco Tosi connection is unused. This provides an ideal location to interface an auxiliary generator for the FEL. To enable one engine in each gearbox to operate independently of the ship's speed, a clutch lockout feature must be added. This arrangement allows the auxiliary generator size to be optimized based on turbine operation at a full speed condition while the other turbine independently provides propulsion power. The use of a step up gear to increase the turbine output from 3600 rpm to 8000 rpm optimizes the auxiliary generator size with an output frequency of 800 Hz at 5 kV [9]. This step up gear weighs 1800 kg and has a volume of 1.2 m^3 [8]. The output of the auxiliary generator is then directed topside where it can be stepped up in voltage and rectified to dc for the FEL. An illustration of this architecture is shown in Figure 7.

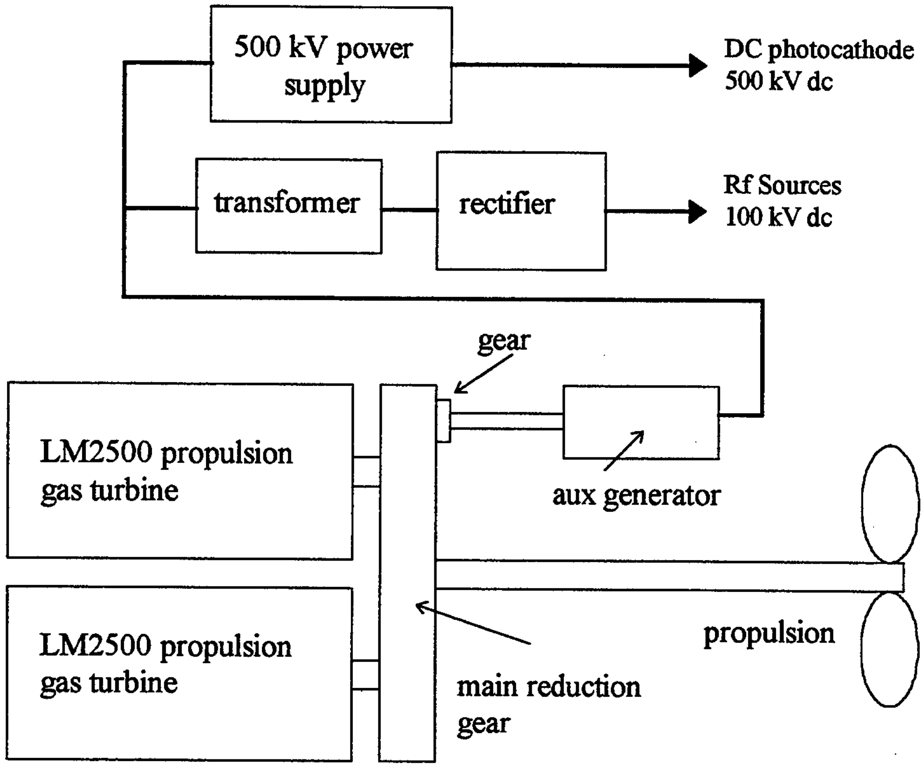

Figure 7 - Direct Generation Architecture. After Ref. [8]

The 10 MW auxiliary generator weighs approximately 6000 kg and occupies 5m^3 [10]. To step this power up to 100 kV for the rf sources a 10 MVA transformer is used. This transformer is oil cooled to reduce size and weight. An adiabatic (room temperature) transformer would weigh significantly more due to the extra copper and insulation that is required to maintain operating temperatures. The 10 MVA transformer weighs 15,000 kg and occupies 5m^3 [10]. The 100 kV rectifier would consist of three air cooled enclosures weighing 1600 kg with a volume of 9.5m^3 [10]. A 500 kV high voltage power supply is also required for the dc photocathode and would consist of two components: a high voltage section and a regulator section. Combined, these two components would weigh approximately 14,000 kg and occupy 14m^3 [11]. A summary of the weight and volume calculations for the direct generation architecture is shown in Table 2.

component	weight (kg)	volume (m^3)
aux. generator	6000	4.3
gear	1800	1.2
transformer	15000	5
rectifier	1600	9.5
500 kV HVPS	14000	14
total	38400	34

Table 2 - Prime Power Weight and Volume Summary
for Direct Generation Architecture

While this architecture provides a continuous source of power to the FEL, it may take several minutes for the LM2500, auxiliary generator, and power supply to get on-line. Next, a couple of devices that can provide power instantly are examined.

2. Energy Storage in Flywheels

Another method of supplying power for the FEL is through a flywheel which can be used to store energy generated either through the ship's main propulsion engineering plant or from SS electrical distribution. A flywheel consists of a motor-generator set connected to a rotating disk. Electrical energy is used to operate a motor which spins or "charges" the disk to store energy in the form of mechanical energy. When energy is needed, the disk drives the generator which then produces electrical energy. This technology is receiving a great deal attention and is envisioned as a power source for future cars and buses, space vehicles, and backup power supplies for computer systems [12][13]. A proposed flywheel for the FEL must be capable of storing energy for 30 seconds (3 missiles with a 10 second engagement time for each missile). The required energy is then (10 MW)(30 sec) = 300 MJ. The energy densities of a modern flywheel are approximately 36 MJ/m^3 and 47 kJ/kg [14]. From these numbers 300 MJ can be stored in a volume of 8.3 m^3 and weigh 6400 kg. These numbers make flywheels an attractive option when compared to massive transformers and rectifiers. One point that must be considered is that a single flywheel cannot produce 100 kV as needed by the rf sources. Modern flywheels are only capable of producing approximately 300 V. This would require a transformer to step up the voltage or series of flywheels to produce the required voltage output. The most important aspect of using flywheel energy storage is that the energy can be discharged instantly unlike the direct power generation architecture.

This configuration of flywheels can be charged from either source of shipboard power. The SS electrical distribution system has an emergency/backup SSGTG with 2.5 MW of available power, which would take a significant amount of time to charge or recharge the flywheel based on (300 MJ)/(2.5 MW) = 120 sec. Using the main propulsion system with a 10 MW auxiliary generator as defined earlier could store 300 MJ in 30 seconds which is a four fold improvement; however, the auxiliary generator adds to the overall weight and volume.

3. Energy Storage in Capacitors

A third means of supplying power for the FEL is through the use of capacitors. Electrical energy would be required to charge up the capacitors. This electrical energy would then be stored until needed by the FEL. This is similar to a flywheel, but electrical energy is stored vice mechanical energy. As before, 300 MJ of energy must be stored for 3 missile engagements. Modern carbon-organic electrolyte based ultracapacitors have energy densities of 39 MJ/m^3 and 30 kJ/kg [10][15]. This translates into a volume of 7.7 m^3 and a weight of 10000 kg. Similar to the flywheel, the capacitor is also available only in small voltages of a few hundred volts, but can discharge energy instantly. In comparison to the flywheel, the capacitor has an increased weight, but a slightly decreased volume.

4. Summary of FEL Prime Power

Flywheels and capacitors both offer high energy densities as compared to the direct generation architecture which includes massive transformers and generators. However, both of these storage devices suffer from a decline in voltage as they discharge. Since the rf sources and dc phototcathode require a specific voltage to ensure optimum operation of the FEL, a voltage regulator is required to maintain the output voltage during discharge. In addition to the components already discussed, transmission cables are needed to deliver this high voltage power to the FEL. The basis for the weight and volume of cable required is contained in Appendix B of Ref [8]. Table 3 shows a comparison of the prime power systems using flywheels and capacitors with the 2.5 MW SSGTG as the power source.

component	flywheel		capacitor	
	weight (kg)	volume (m^3)	weight (kg)	volume (m^3)
storage	6400	8.3	10000	7.7
voltage regulator	1600	2	1600	2
500 kV HVPS	14000	14	14000	14
cable	4500	1	4500	1
total	26500	25.3	30100	24.7

Table 3 - Summary of Prime Power Using 2.5 MW SSGTG

The use of flywheels or capacitors in combination with the 10 MW auxiliary generator connected to a LM2500 main propulsion gas turbine is another configuration that is considered. Its main advantage is a decreased charge/recharge time because there is more available power (18.6 MW versus 2.5 MW). A summary of the system configurations using the LM2500 as the power source is contained in Table 4.

component	direct generation		flywheel		capacitor	
	weight (kg)	volume (m^3)	weight (kg)	volume (m^3)	weight (kg)	volume (m^3)
total from table 2	38400	34	-	-	-	-
aux. generator	-	-	6000	4.3	6000	4.3
gear	-	-	1800	1.2	1800	1.2
storage	-	-	6400	8.3	10000	7.7
voltage regulator	-	-	1600	2	1600	2
500 kV HVPS	-	-	14000	14	14000	14
cable	4500	1	4500	1	4500	1
total	42900	35	34300	30.8	37900	30.2

Table 4 - Summary of Prime Power Using 18.6 MW LM2500

A comparison between the flywheel and capacitor totals in Table 3 and Table 4 shows a penalty of 7800 kg and 5.5 m^3 for the advantage of a 400% reduction in recharge time. This is a significant improvement, however, it is not essential to the FEL's performance due to the prime power systems being sized for three continuous engagements. One issue that must be considered is that dedicating the backup/emergency SSGTG for the FEL, even for a short period of time, can be catastrophic if there is a power failure. During battle conditions, power from the SSGTGs is critical to powering all ship systems including vital equipment such as radar, sonar, and other combat system elements. This load can be supported by 2 of the 3 SSGTG's, but ship operators place a great deal of emphasis on having the third SSGTG available if and when needed. In addition, the main propulsion LM2500 has greater generating capacity. For these reasons, the LM2500 would be a more suitable source to power the FEL.

The results from Table 4 provide a reasonable estimate for the weight and volume of a proposed FEL prime power system. The direct generation architecture has the greatest volume and weight; however, flywheel and capacitor storage systems offer reductions in these figures. The energy storage devices also discharge energy instantly which is an advantage over the direct generation architecture. For the purpose of this thesis, the direct generation architecture is chosen as the prime power system which has a weight of 42900 kg and a volume of 35 m^3. These are the numbers that will be used as part of the overall FEL system weight and volume.

D. SUPPORT SYSTEMS

A variety of systems are required for the FEL to support shipboard operation. The primary requirements include: liquid helium refrigeration for the SC linear accelerator, a fire control system to direct the beam energy at the target during a missile engagement, and an active stabilization system for the mirrors to maintain alignment as the ship structure undergoes vibration, bending, flexing, and torsion.

The SC accelerator described in the previous section requires a liquid helium refrigeration system for cooling. As the accelerator is in operation, it emits heat which is absorbed by the liquid helium. The refrigerator must recompress and boil off the liquid helium to maintain the required operating temperature. When the accelerator is in operation there is a significant load on the refrigeration system. A refrigeration system designed to support the SC accelerator on a full-time basis would be large, heavy, and have a significant power draw on the ship. However, when the accelerator is not in operation, heat is not produced and the load on the refrigeration system is small. Therefore, adequate cooling can be supplied with a much smaller refrigeration system which has the capacity to handle three engagements or 30 seconds of accelerator operation. Based on this time of operation, the refrigeration system can be designed to recompress and refrigerate the liquid helium over a longer period of time. This will reduce the power draw when the accelerator is not in use. The power required for the refrigeration system is 3.5 kW [4] and it is expected to weigh approximately 47400 kg and occupy a volume of 12 m^3 [5].

Another support system is the network of bending magnets, which transport the electron beam between the undulator and accelerator. Two types of magnets, electromagnets and permanent magnets, can serve this purpose. The 1 MW has been designed with electromagnets which are less expensive and smaller than permanent magnets but require an external source of electrical power. A battery backup system to power the electromagnets weighs approximately 23700 kg and has a volume of 6 m^3 [5].

The fire control system for a FEL weapon would require significant accuracy. A bullet which travels at relatively slow speeds suffers from windage factors and gravity. However, the optical energy from a FEL arrives at its target almost instantaneously with no gravitational effects. This leads one to believe the fire control system is a matter of point and shoot. From Chapter II, the laser beam spot radius was calculated to be 5 cm. Maintaining this small beam size on a consistent location on a target 10 km away for 2-3 seconds requires a highly accurate electro-optical system with a tracking precision greater than $1\,\mu\text{radian}$. Typically, laser trackers have an angle tracking precision of approximately $20\,\mu\text{radians}$ so improvements to this system may be required to support FEL operation [16]. However, lasers have demonstrated the capability to shoot down missiles in flight [17][18].

Alignment of the FEL components is critical to ensuring that the system operates safely and efficiently. Based on the length of the optical cavity, approximately 22m, significant bending and torsion of the cavity is likely to occur to follow suit with the ship's structure. To maintain alignment, complete isolation of the optical cavity from the ship is required. However, adaptive optics may be applied to the mirrors which allow the cavity to flex and contort while the mirrors conform to this movement and maintain the necessary alignment of the optical energy [19][20].

From the description of the components and support systems of the FEL, significant features are needed to transform the FEL into a weapon system that is adaptable to a naval surface combatant. These components and subsystems require additional volume and place greater electrical loads upon the ship.

E. SYSTEM SUMMARY

The weight and volume of all significant subsystems and components which make up the FEL weapon system are summarized in Table 5.

	weight (kg)	volume (m^3)
linac	32000	81
optical cavity	2200	5.5
prime power	42900	35
refrigerator	47400	12
magnet power	23700	6
total	148200	139.5

Table 5 - Weight and Volume Summary of the FEL Weapon System

This table shows that the FEL including the 10 MW prime power system, weighs 148200 kg and require a volume of 140 m^3. In comparison to another weapon system, the FEL has approximately the same weight as a 32 cell VLS missile launcher with one-half of its volume.

IV. FEL OPERATIONAL ENVIRONMENT

The FEL weapon, like all Combat System equipment, must be capable of withstanding and, in many cases operating through, all shipboard environmental conditions, such as ship motion and attitude, temperature fluctuations, humidity, and vibration. One area of concern is the FEL's performance in an environment of shipboard vibrations. These vibrations originate in main propulsion and other machinery, the propeller, and in the hull as it responds to cyclic wave motion. Vibrational forces are transmitted through the ship's structure and can result in degraded performance of equipment, including the FEL being considered in this study.

A. SHIPBOARD VIBRATIONS

Characterization of shipboard vibrations is complex due to the various sources and the variation in characteristics between various ship structures. One source that imparts considerable vibration to the ship is the propeller excitation force. A naval combatant, such as the DDG-51 class Destroyer, operates at propeller speeds between 10 and 160 rpm. The excitation frequency can be calculated by

$$f = \frac{nz(\mathrm{rpm})_P}{60} \qquad (4.1)$$

where n is an integer value for the harmonic of the blade frequency, z is the number of propeller blades and $(\mathrm{rpm})_P$ is the revolutions per minute of the propeller. For the first harmonic (n =1) and a 5 bladed propeller, the driving frequency of the propeller is between 0.83 and 13.33 Hz. The amplitude of vibration that is imparted to the ship's structure within this frequency range is on the order of less than 1 mm [21][22].

To insure ships are built free from excessive or damaging vibration, design criteria have been established by the Code for Shipboard Hull Vibration Measurements, CSHVM [22]. Under this code, shipboard equipment must be designed to meet the shipboard environmental vibration criterion of $\pm 0.25g$. The conversion from acceleration in g's to amplitude is accomplished by considering position as a function of time

$$x(t) = A\cos(\omega t) \tag{4.2}$$

where A is the amplitude and $\cos(\omega t)$ describes the sinusoidal oscillation. ω is defined as the frequency in rad/sec and t is time in seconds. Taking the derivative of x(t) with respect to time, the velocity is

$$v(t) = \dot{x}(t) = -\omega A\sin(\omega t). \tag{4.3}$$

The acceleration is determined by taking the derivative of v(t), or the second derivative of x(t), with respect to time and substituting in (4.2) where

$$a(t) = \ddot{x}(t) = -\omega^2 A\cos(\omega t) = -\omega^2 x(t). \tag{4.4}$$

This can be simplified by substituting $\omega = 2\pi f$, where f is the frequency in Hz and dropping the minus sign to get

$$a(t) = (2\pi f)^2 x(t). \tag{4.5}$$

Using (4.5) with the vibration criterion of 0.25g, at f = 45 Hz and t = 0, the amplitude is $30.7\mu m$.

Additional environmental vibration requirements are contained in MIL-STD-167B which provides testing procedures and criteria for equipment which will be installed aboard naval ships [23]. Equipment which is designed for shipboard use must be subjected to a simulated environmental vibration. This standard provides an amplitude sufficiently large within the selected frequency range to obtain a high degree of confidence that the equipment will not malfunction due to vibrational degradation. Table 6 shows the comparison between the amplitudes of vibration as required by the CSHVM and MIL-STD-167B for the given frequency range.

Frequency (Hz)	Amplitude (μm) CSHVM	Amplitude (μm) MIL-STD-167B
4 - 15	327.7 ± 60.6	760.0 ± 152.5
16 - 25	171.0 ± 71.6	508.0 ± 101.6
26 - 33	74.5 ± 17.5	254.0 ± 50.8
24 - 40	46.3 ±7.5	127.0 ± 25.4
41 - 50	30.9 ± 6.1	50.8 ± 25.4

Table 6 - Environmental vibration standards for shipboard deck mounted equipment.

From Table 6 it can be seen that the vibration standard established by MIL-STD - 167B is more conservative and provides a greater margin of safety. Assuming these standards represent the typical vibrations seen in the shipboard environment, this presents reasonable justification that shipboard vibrations can be characterized as having frequencies below 50 Hz. In addition, the greatest vibrational amplitudes are found between 4 and 15 Hz, which is also the range for the driving frequency of the propeller.

B. ENERGY MODULATION DUE TO VIBRATIONS

The FEL is an attractive source of light which is ideal for shipboard self-defense due to its high power and tunability characteristics. These features also make the FEL susceptible to vibrations from its operating environment. The tunability of the FEL can be described in relation to the variable Lorentz contraction and Doppler shift. Consider a single electron entering the undulator with energy γmc^2. In the electron frame of reference, the undulator is Lorentz contracted by a factor of $1/\gamma$. The electron then radiates at a wavelength of λ_0/γ in its own frame of reference where λ_0 is the undulator wavelength and γ is the Lorentz factor. This radiation is then Doppler shifted so that its wavelength is decreased by a factor of 2γ when observed in the lab frame of reference. The optical wavelength output of the FEL is then described by

$$\lambda = \frac{\lambda_0}{2\gamma^2}(1+K^2) \tag{4.6}$$

where K is a constant called the undulator parameter. The undulator parameter is a correction factor based on the undulator rms magnetic field strength, $\overline{B}_o$, and the undulator wavelength, and described by

$$K = \frac{e\overline{B}_o\lambda_o}{2\pi mc^2}. \tag{4.7}$$

These relations show the relationship between the optical wavelength of the FEL and the electron beam energy.

The mechanical vibrations imparted on the superconducting linear accelerator structure can adversely affect the stability of the electron beam and create energy modulation within the RF cavity. The effects of this energy modulation are transmitted to the optical wavelength of the FEL. The study of these vibrational effects, known as microphonics, has been conducted by A. Marziali [24]. His research has shown that the peak energy modulation can be defined as

$$\frac{\Delta U}{U} = \frac{-2ATN}{\Gamma L} \tag{4.8}$$

where A is the vibration amplitude, N is the number of cells in the accelerator, L is the length of each cell, Γ is the cell to cell coupling factor, and T is defined as

$$T = \frac{df/f}{dL/L}, \tag{4.9}$$

Where cell tuning rate is df/dL and f is the operating frequency of the RF cavity. Figure 8 shows the relationship between the vibration amplitude and the energy modulation for the 1 MW FEL considered in this study.

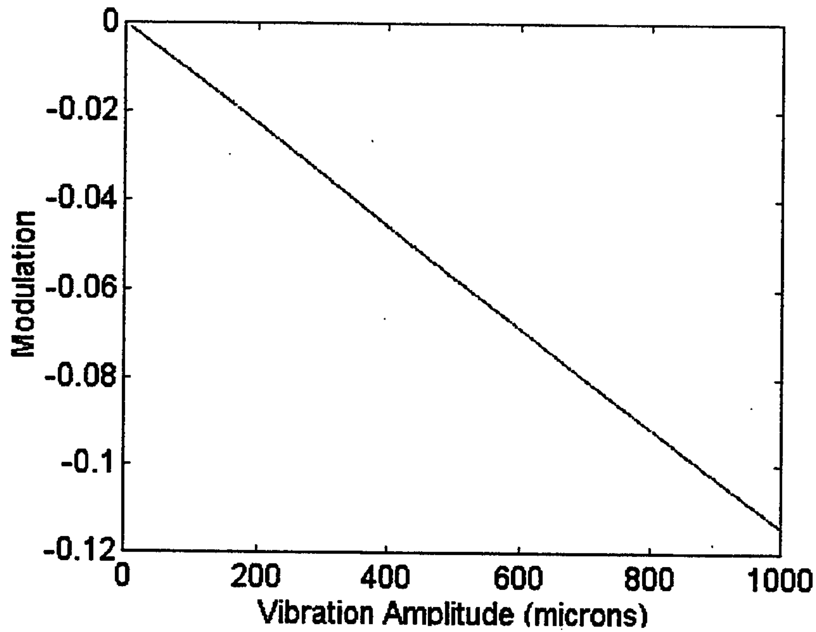

Figure 8 - Peak Energy Modulation

The energy modulation due to microphonics is significant at large vibrational amplitudes. Referring to table 6 and MIL-STD-167B, vibration amplitudes as large as 900μm are expected at frequencies below 15 Hz. According to (4.8) and Figure 8 this amplitude, which is within the range of expected shipboard vibrations, produces an energy modulation of $\Delta U / U = -0.1$ or -10%. When the designed RF energy output is 100 MeV and the modulation is -0.1, there is a loss of 10 MeV of energy due to microphonics. The optical wavelength fluctuation or wavelength error resulting from energy modulation is shown in Figure 9.

Given the energy modulation $\Delta U / U = -0.1$, the wavelength error of 25% can be determined from Figure 9. Wavelength error approaching 25% is unacceptable for continuous FEL operational performance. For the application of this FEL, it is not required to have the accuracy of a scientific tool, but accuracy must be maintained at a level to ensure a high quality laser beam with sufficient range can be produced to defend a ship against incoming missiles. The optical wavelength is critical due to the narrow line width for propagation in the atmosphere [25][26].

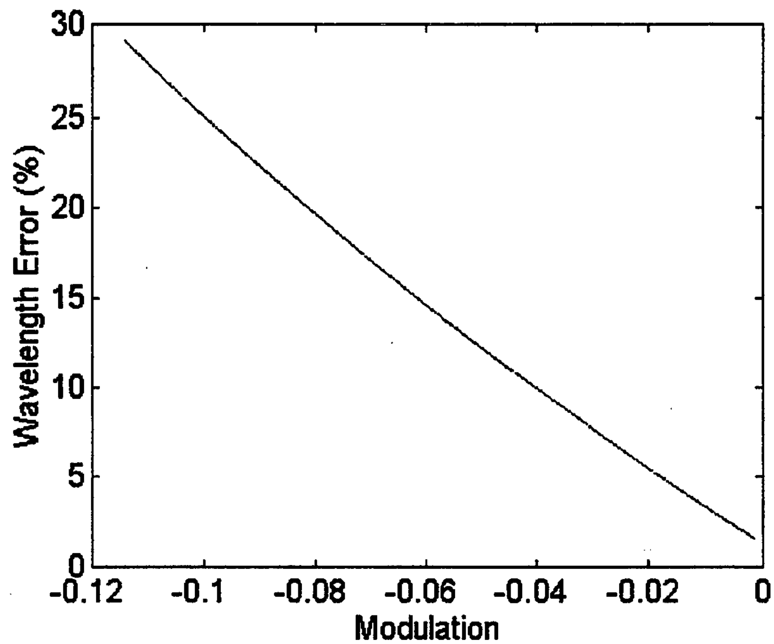

Figure 9 - Optical Wavelength Fluctuation

There are two principal wavelength bands suitable for infrared (IR) laser propagation in the maritime environment. Each band has several operating windows, which are typically $0.1\,\mu m$ in width. The short wave infrared (SWIR) band is in the region of 1-5 μm and the long wave infrared (LWIR) is in the region of $8-12\mu m$. The 1MW FEL is designed to operate at approximately $1\,\mu m$. Deviation outside of the SWIR band causes excessive dissipation and spreading due to atmospheric conditions, resulting in degraded range and beam quality. This defines the requirement for a stable beam pattern in the FEL design.

C. VIBRATION ISOLATION

The use of proper isolation techniques will lower vibration amplitudes to an acceptable level where the FEL can effectively operate within a shipboard environment. Low frequency vibrations are much more difficult to damp out. If these frequencies can be isolated, the higher frequencies will be reduced as well. The goal is to isolate the critical components of the FEL from these mechanical vibrations where the wavelength error is less than 0.1% or the modulation in RF energy output is less than $\Delta U / U = -0.05 \times 10^{-3}$. Based on a design value of 100 MeV, the change must be no more than 0.05 MeV.

One method of isolation is through the use of feedback stabilization in the RF cavity. This system measures the optical wavelength and sends a signal to correct the electron beam energy to maintain a constant wavelength. Feedback stabilization has been shown to reduce wavelength fluctuation by an order of magnitude or greater [24]. This improvement alone reduces the wavelength variation from 25% to 2.5% and energy modulation from $\Delta U / U = -0.1$ to $\Delta U / U = -0.012$. The limiting factor in wavelength stabilization is the frequency response of the RF stabilization loop. The maximum frequency of the loop is determined from

$$f = \frac{\omega_{rf}}{4\pi Q A_o} \tag{4.10}$$

where ω_{rf} is the RF frequency of the cavity, Q is the cavity quality factor, and A_o is the modulation amplitude. With a higher stabilization loop frequency, greater bandwidth is produced and feedback stabilization will provide further wavelength stability.

Another method of reducing vibration amplitudes is through the use of a vibration isolation system to isolate the accelerator structure from the source of vibration. This can be accomplished by using highly damped materials such as rubber to change the stiffness and damping between source of vibration and the device that is to be protected from vibrations. This is analyzed in terms of reducing the vibration displacement through base excitation as shown in Figure 10.

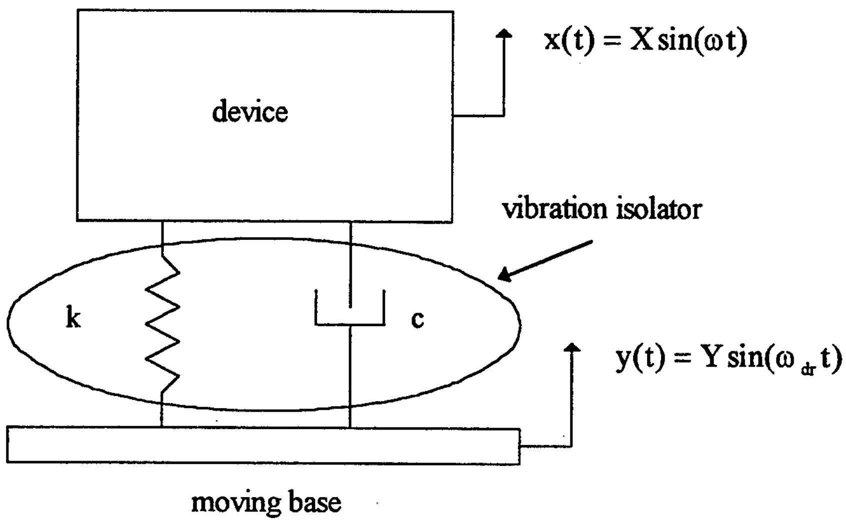

Figure 10 - Vibration Source Modeled as Base Excitation

From figure 10, $y(t) = Y\sin(\omega_{dr} t)$ is the disturbance where Y is the amplitude of vibration, ω_{dr} is the driving frequency, and t is time of the moving base, or in this case, the ship structure. $x(t) = X\sin(\omega t)$ is the response where X is the amplitude of vibration, ω is the undamped natural frequency, and t is time of the accelerator. The natural frequency is

$$\omega = \sqrt{\frac{k}{m}} \tag{4.11}$$

where k is the spring stiffness and m is the mass of the device being isolated, in this case the accelerator structure. The damping coefficient is

$$c = 2m\omega\zeta \tag{4.12}$$

where ζ is the damping ratio. These equations are linked in the displacement transmissibility equation

$$\frac{X}{Y}=\left[\frac{1+(2\zeta r)^2}{(1-r^2)^2+(2\zeta r)^2}\right]^{1/2}. \tag{4.13}$$

where r is the frequency ratio

$$r=\frac{\omega_{dr}}{\omega}. \tag{4.14}$$

As shown in table 6, the largest amplitudes occur at driving frequencies below 15 Hz. For the design of the vibration isolation system, the driving frequency, f_{dr} = 4 Hz or ω_{dr} = 8π rad/s is used which represents the lowest driving frequency with the greatest amplitude. In (4.13) a small X/Y is desirable which represents a small amplitude received by the accelerator, X, based on a much larger vibration amplitude produced by the ship, Y. This can be achieved by selecting a large r and small ζ. From (4.14) with ω_{dr} = 8π rad/s and r = 4, the undamped natural frequency, ω = 2π rad/s. Using $\omega = 2\pi \mathrm{rad/s}$ with an accelerator mass of 32000 kg in (4.11) provides a spring stiffness of $k = 1.26X10^6$ N/m. Selecting ζ = 0.2 with the above values in (4.12) results in the damping coefficient of c = $8.04x10^4$ kg/s. Substituting ζ = 0.2 and r = 4 in (4.13) provides a transmissibility ratio of X/Y = 0.015. This shows that a $900\mu m$ vibration amplitude produced at a driving frequency of 4 Hz will result in the accelerator being displaced 14 μm.

From these calculations, it is determined that a suitable vibration isolation system can be selected with a spring stiffness, k = $1.26x10^6$ N/m, damping coefficient, c = $8.04x10^4$ kg/s, and undamped natural frequency, f_n = 1 Hz. This example of an isolation system provides a 98% reduction in vibration amplitudes received by the accelerator structure. Referring back to Figure 8, the energy modulation can be reduced from $\Delta U / U = -0.1$ to $\Delta U / U = -0.0015$ and wavelength error from 25% to 0.3%.

The vibrational environment on board ship can be detrimental to the FEL's performance through energy modulation and optical wavelength fluctuations; however, isolation techniques exist that are capable of reducing these vibrations to acceptable levels.

The combination of RF feedback stabilization with the vibration isolation system will effectively reduce the wavelength error to less than 0.1% and reduce the modulation in RF energy output less than $\Delta U / U = -0.05\text{x}10^{-3}$. This study has identified two isolation methods which are capable of reducing shipboard vibrations in a FEL. The vibration amplitude equal to 900μm is the worst case and may represent a condition that only exists a small percentage of the time. Actual vibration testing aboard a typical DDG-51 destroyer will provide more accurate vibrational data on which to base this evaluation. This chapter does succeed in tying together the important relationships which will guide further vibrational testing and establishing methods for further reduction of shipboard vibrations if required.

V. FEASIBILITY

In the previous chapters, the FEL operation and system components have been described and outlined. The FEL weapon system has been shown to weigh approximately 148200 kg and occupy a volume of 140 m^3. This size and weight is on par with other shipboard weapon systems such as a 32 cell VLS missile launcher or a 5"/54 gun. The total ship impact of placing the FEL on board a DDG-51 Arleigh Burke class Destroyer will be determined using the Advanced Surface Ship Evaluation Tool (ASSET) computer program.

A. BASELINE SHIP

The baseline ship chosen for this feasibility study is the DDG-51 Arleigh Burke class Destroyer. It represents the most modern class of surface combatants in the U.S. Navy today. There are currently 18 ships of the class in operation and several more are being constructed each year. These ships will likely represent the United States for the next thirty years which is well within the time frame when the FEL weapon could be fielded and installed.

The interior outfitting of the DDG-51 is tight and the ship has negligible margin for volumetric growth. This leaves little or no space available in the current ship layout for the addition of the FEL weapon. The addition would likely result in enlarging the hull or superstructure which would be a costly and time consuming endeavor. An alternate approach is to replace an existing weapon system with the FEL weapon. The ship has two vertical launching systems (VLS), a 32 cell forward and a 64 cell aft. These launchers hold Standard surface-to-air missiles (SAM), Tomahawk land attack and anti-ship missiles (ASCM), and anti-submarine rockets (ASROC). While the FEL cannot support the ship in the mission areas covered by these missiles, it has the capability to enhance self-defense not only for the FEL ship but also for other ships within the FEL's umbrella. This enables the ship to carry out other missions more effectively and provides a reasonable justification for replacing the forward 32 cell VLS with the FEL weapon. A comparison between the weight and volume of each system is shown in Table 7.

	32 cell VLS	1 MW FEL
weight (kg)	146000	148200
volume (m^3)	298	140

Table 7 - Weight and Volume Comparison Between VLS and FEL

B. ADVANCED SURFACE SHIP EVALUATION TOOL

ASSET is a family of interactive computer programs for use in the exploratory and feasibility phases of Navy surface ships. The ship type program within ASSET used for this study is Monohull Surface Combatant (MONOSC). ASSET/MONOSC addresses most of the major technological domains of naval architecture that are relevant to the design of such ships, including geometric definition of hull and superstructure, hull subdivision, hull structure, resistance, appendages, propulsors, machinery, weight, space, hydrostatics, seakeeping, manning and cost. The program features design synthesis capability, database management, and extensive input/output options including interactive graphics and use of either English or Metric units [27]. ASSET/MONOSC version 4.B.08 was used in this study.

1. Performance Parameters

Before working with ASSET, several parameters were chosen to evaluate the performance of replacing the VLS with the FEL. The parameters chosen were: full load displacement and full load center of gravity above the keel (KG). Full load displacement provides a relative gauge of the cost to build a ship. A lighter ship usually costs less to build than a heavier ship. A lighter ship also creates less resistance and therefore achieves greater fuel economy on a given hull. Greater fuel economy increases endurance range, allowing the ship to remain on station longer without having to refuel. Full load KG was chosen because it is a measure of the stability of a ship design. A smaller KG results in a more stable ship which enhances operation in severe weather conditions or in the event of underwater hull damage resulting from enemy action. The theoretical replacement of one system with another transfers weight between various locations within the ship which affects KG. The volume was held constant because the FEL weapon could potentially be installed on an existing DDG-51 and the ship has little margin for volumetric growth.

2. Model Development

The flight I ship contained in the ASSET/MONOSC databank was utilized as the baseline DDG-51 ship. The DDG-FEL was developed from the baseline by making changes to the payload and adjustment tables corresponding to the weight, volume, and location of the FEL components. Placement of the FEL was relatively straightforward. The volume originally occupied by the VLS provided adequate space for the linear accelerator, undulator, and optical cavity components along with the liquid helium refrigeration system, magnet power, and prime power system components. The only component that was not located in the original volume of the VLS was the auxiliary generator because it was mechanically connected to the main propulsion plant. The auxiliary generator was located in an overhead position above the existing main reduction gear (MRG) in the main engineering room (MER) #2. Sufficient volume exists above the MRG for the auxiliary generator, therefore only the additional weight of the generator is included. This configuration was determined to have less impact than locating the auxiliary generator in the auxiliary machinery room (AMR) #2 and connecting it to the MRG with a spacer shaft [28].

3. ASSET Results

Once the VLS components were deleted and all FEL components were added to the payload and adjustment tables a synthesis run was completed. The design summaries for the baseline DDG-51 and DDG-FEL are shown in Figures 11 and 12. These summaries detail the specific characteristics for the two models. The complete printed output for ASSET/MONOSC model runs comprises over 70 pages of data per model. For reasons of brevity, only the design summaries are shown here.

```
ASSET/MONOSC VERSION 4.B.08 - DESIGN SUMMARY

 PRINTED REPORT NO. 1 - SUMMARY

 SHIP COMMENT TABLE
      BASELINE DDG 51

   PRINCIPAL CHARACTERISTICS - M              WEIGHT SUMMARY - MTON
 LBP                            142.0   GROUP 1 - HULL STRUCTURE   3166.4
 LOA                            150.0   GROUP 2 - PROP PLANT        757.1
 BEAM, DWL                       18.0   GROUP 3 - ELECT PLANT       332.0
 BEAM, WEATHER DECK              20.3   GROUP 4 - COMM + SURVEIL    437.2
 DEPTH @ STA 10                  12.7   GROUP 5 - AUX SYSTEMS       835.6
 DRAFT TO KEEL DWL                6.3   GROUP 6 - OUTFIT + FURN     686.3
 DRAFT TO KEEL LWL                6.1   GROUP 7 - ARMAMENT          320.0
 FREEBOARD @ STA 3                8.0   ---------------------------------
 GMT                              1.8   SUM GROUPS 1-7             6534.6
 CP                              .615   DESIGN MARGIN                31.7
 CX                              .822   ---------------------------------
                                        LIGHTSHIP WEIGHT           6566.4
 SPEED(KT):  MAX= 31.3  SUST= 30.0      LOADS                      1700.1
 ENDURANCE:  3807.0 NM AT 20.0 KTS      ---------------------------------
                                        FULL LOAD DISPLACEMENT     8266.5
 TRANSMISSION TYPE:              MECH   FULL LOAD KG:  M              6.9
 MAIN ENG: 4 GT         @ 19220.4 KW
                                        MILITARY PAYLOAD WT - MTON 1115.8
 SHAFT POWER/SHAFT:       37487.0 KW    USABLE FUEL WT - MTON      1145.5
 PROPELLERS: 2 - CP   -   5.2 M  DIA

 SEP GEN:  3 GT         @  2500.0 KW
                                                  OFF  CPO   ENL    TOTAL
 24-HR LOAD                    2356.7   MANNING    26   24   291     341
 MAX MARG ELECT LOAD           3605.5   ACCOM      29   27   321     377

      AREA SUMMARY - M2                      VOLUME SUMMARY - M3
 HULL AREA               -       4498   HULL VOLUME            -    22534
 SUPERSTRUCTURE AREA     -       1867   SUPERSTRUCTURE VOLUME -     5437
 ----------------------------------     ---------------------------------
 TOTAL AREA              -       6365   TOTAL VOLUME           -    27971
```

Figure 11 - Baseline Design Summary

```
ASSET/MONOSC VERSION 4.B.08 - DESIGN SUMMARY

 PRINTED REPORT NO. 1 - SUMMARY

 SHIP COMMENT TABLE
      DDG-FEL MODEL

   PRINCIPAL CHARACTERISTICS - M            WEIGHT SUMMARY - MTON
 LBP                           142.0   GROUP 1 - HULL STRUCTURE  3148.3
 LOA                           150.0   GROUP 2 - PROP PLANT       757.1
 BEAM, DWL                      18.0   GROUP 3 - ELECT PLANT      399.6
 BEAM, WEATHER DECK             20.3   GROUP 4 - COMM + SURVEIL   437.2
 DEPTH @ STA 10                 12.7   GROUP 5 - AUX SYSTEMS      882.7
 DRAFT TO KEEL DWL               6.3   GROUP 6 - OUTFIT + FURN    687.5
 DRAFT TO KEEL LWL               6.1   GROUP 7 - ARMAMENT         267.6
 FREEBOARD @ STA 3               8.0   -------------------------------
 GMT                             1.9   SUM GROUPS 1-7            6580.0
 CP                             .615   DESIGN MARGIN               31.7
 CX                             .822   -------------------------------
                                       LIGHTSHIP WEIGHT          6611.7
 SPEED(KT):  MAX= 31.3  SUST= 30.0     LOADS                     1655.2
 ENDURANCE:  3798.8 NM AT 20.0 KTS     -------------------------------
                                       FULL LOAD DISPLACEMENT    8266.9
 TRANSMISSION TYPE:             MECH   FULL LOAD KG:  M             6.9
 MAIN ENG: 4 GT        @ 19220.4 KW
                                       MILITARY PAYLOAD WT-MTON  1005.8
 SHAFT POWER/SHAFT:      37487.0 KW    USABLE FUEL WT - MTON     1145.5
 PROPELLERS: 2 - CP   -  5.2 M  DIA

 SEP GEN:  3 GT        @  2500.0 KW
                                                 OFF  CPO   ENL   TOTAL
 24-HR LOAD                   2411.0   MANNING    26   24   291     341
 MAX MARG ELECT LOAD          3678.6   ACCOM      29   27   321     377

      AREA SUMMARY - M2                     VOLUME SUMMARY - M3
 HULL AREA                -     4498   HULL VOLUME              -  22534
 SUPERSTRUCTURE AREA      -     1867   SUPERSTRUCTURE VOLUME -      5437
 ---------------------------------     --------------------------------
 TOTAL AREA               -     6365   TOTAL VOLUME             -  27971
```

Figure 12 - DDG-FEL Design Summary

A comparison of the design summaries shows that replacing the 32 cell VLS with the FEL has negligible effect on the ship. The electrical plant weight increased by 67.6 Mtons due to the addition weight of the FEL prime power system. Auxiliary systems weight increased by 47.1 Mtons due to the additional weight of the liquid helium refrigeration system. The removal of the Standard, Tomahawk, and ASROC missiles accounted for the 52.4 Mton decrease in armament weight. Overall, the lightship weight increased by 45.3 Mtons, but the payload decreased by 44.9 Mtons which resulted in a increase to the full load displacement of 0.4 Mtons. The full load KG remained constant at 6.9 m.

C. SHIP IMPACTS

ASSET has shown that the FEL weapon system can be accommodated in the DDG-51 with negligible impact. However, some issues must be considered which are beyond the scope of the ASSET program.

The FEL components must fit into locations which were not originally designed for them. An example is the optical cavity which is 22 m long and has to be configured in a vertical orientation. While this orientation does not affect the FEL operation, one half of the cavity length projects above the main deck. This length can be shortened with the development of mirrors which are capable of withstanding higher power densities or by designing the FEL with a shorter Rayleigh length [29]. The further development and research into these areas is recommended.

The FEL prime power system components generate additional heat when they are in operation and it must be convected away by air or oil circulation. The auxiliary generator is oil cooled but a percentage of its waste heat must be convected away by the ambient air in the engine room. The transformer, rectifier, and 500 kV power supply also produces waste heat. Because these components operate for only 10 second intervals, the additional load on the air conditioning system is not significant.

The issues above illustrate some of the other factors that also must be considered in this design. Integrating the FEL weapon into an existing ship design is more difficult than integrating it into a ship which is in the initial design phase. A new ship design would allow the ship designer to take into account the specific requirements of the FEL such as compartment dimensions, system capacities, and power plant configurations.

VI. CONCLUSIONS AND RECOMMENDATIONS

The shipboard FEL weapon can substantially improve ship self-defense against incoming cruise missiles. It provides a weapon which can project power at the speed of light and defeat missiles by directing a beam of optical energy on the target.

A 1 MW FEL requires about 10 MW of electrical power from the shipboard prime power system if run continuously or approximately 2 MW using energy storage. A DDG-51 Arleigh Burke class Destroyer has sufficient reserve generating capacity to power the FEL from the ship service electrical distribution or main propulsion engineering plant. Prime power configurations can be designed to generate power directly as needed or to generate power and store it as electrical energy in capacitors or as mechanical energy in flywheels. A main propulsion gas turbine can be modified to generate power directly for the FEL. This prime power system will weigh 42900 kg and occupy 35 m^3 within the ship. Modern capacitors have reached an energy density of approximately 30 kJ/kg while flywheels offer a higher energy density of 47 kJ/kg. The use of flywheel or capacitor storage devices will provide an instantaneous source of power while decreasing the prime power system weight and volume. However, storage devices operate at much smaller voltages than needed by the FEL. The development of flywheel and capacitor technology for high voltage applications is recommended.

Vibrational forces transmitted through the ship's structure can result in degraded performance of the FEL by adversely affecting the stability of the electron beam and modulating the energy within the RF cavity. The effect of this energy modulation is transmitted to the optical wavelength of the FEL and results in optical wavelength fluctuation.

Shipboard vibrations which will have the greatest influence on the FEL are generally characterized at frequencies below 50 Hz and have amplitudes approaching 900 μm. With no means of isolation these vibrations may produce wavelength fluctuation or wavelength error as large as 25%, which would be unacceptable. To ensure continuous operation in the maritime environment, wavelength fluctuation should be reduced to less than 0.1%. Through the use of a vibration isolation system and RF feedback stabilization, the modulation and wavelength error can be reduced to acceptable limits.

The FEL possesses attractive qualities necessary to become a naval weapon system. It is a formidable new weapon which is relatively compact and efficient. The shipboard FEL weapon system will weigh 148200 kg and require a volume of 140 m^3. This is equal to the weight of a 32 cell VLS and one-half its volume. Installing the FEL in place of the VLS on a DDG-51 has negligible impact on the ship in terms of full load displacement and center of gravity (KG).

The 1 MW FEL design considered in this thesis requires additional development before it can be built and installed on a ship. Producing high-average power from a FEL has not been achieved to date , however, several organizations including Thomas Jefferson National Accelerator Facility, Boeing and Los Alamos National Laboratory are pursuing kilowatt power FELs. Further development of FEL technology is recommended.

LIST OF REFERENCES

[1] H. P. Freund and T. M. Antonsen, "Principles of Free-electron Lasers," Chapman & Hall, London, 1992

[2] J. M. J. Madey, "Stimulated Emission of Radiation in Periodically Deflected Electron Beams," *Journal of Applied Physics*, Vol. 42, 1971

[3] N. Bloembergen et al, "Report to the American Physical Society of the Study Group on Science and Technology of Directed Energy Weapons," *Reviews of Modern Physics*, Vol. 59, No. 3, Part II, July 1987

[4] R. Lyon, "Prime Power for Shipboard High-Average Power FELs," Master's Thesis, Naval Postgraduate School, December 1994

[5] Personal communication with George Neil, Thomas Jefferson National Accelerator Facility, Newport News, VA., 14 May 1996

[6] NBS Publication 380, Supplement 1, "Photonuclear Data Index 1973-1977," U.S. Department of Commerce National Bureau of Standards, issued August 1978

[7] N. Friedman, "The Naval Institute Guide to World Naval Weapons Systems," Naval Institute Press, Annapolis, MD., 1989

[8] T. J. Doyle et al, "Propulsion Powered Electric Guns - A Comparison of Power System Architectures," DTRC-PAS-91-31, David Taylor Research Center, July 1991

[9] A. M. Trotta et al, "Pulse Power System Component Study," DTRC-TM-27-90-40, David Taylor Research Center, December 1990

[10] Personal communication with Lyon Mandelcorn, Northrop Grumman Science and Technology Center, Pittsburgh, PA., August 15, 1996

[11] Personal communication with Jack McGuire, Hipotronics, August 16, 1996

[12] S. Shulman, "Plotting Revolutions in Electrical Storage," *Technology Review*, November/December 1992

[13] D. Hotter, " Your Next Battery may be a Flywheel," *Machine Design*, December 14, 1995

[14] Personal communication with Alan Todd, Northrop Grumman Science and Technology Center, Princeton, N.J., May 22, 1996

[15] Summary of Ultracapacitor Test Results, Idaho National Engineering Laboratory

[16] D. Frieden, "Principles of Naval Weapon Systems," Naval Institute Press, Annapolis, MD., 1985

[17] J. Albertine, "Ground Based High Energy Laser Beam Control Using the MIRACL/SLBD," *Proceedings from the 18th Annual American Astronautical Society, Guidance and Control Conference*, Keystone, Colorado, February 1-5, 1995

[18] "The Airborne Laser Laboratory (ALL) Completes Successful Tests," *International Defense Review*, Vol. 116, December 1983

[19] D. M. Shemwell et al., "Optical Cavities for FEL Experiments," IEEE Journal of Quantum Electronics, Vol. QE-23, No. 9, September 1987

[20] D. M. Shemwell et al., "Optical Cavities for Visible Free Electron Laser Experiments," *Nuclear Instruments and Methods in Physics* A 259 (1987)

[21] H. Johannessen and K. T. Skaar, "Guidelines for Prevention of Excessive Ship Vibration," *SNAME Transactions*, Vol 88, 1980

[22] E. F. Noonan and S. Feldman, "State of the Art for Shipboard Vibration and Noise Control," *Ship Vibration Symposium*, SNAME, Arlington, VA. October 16-17, 1978

[23] Department of Defense Military Standard, MIL-STD-167B(ships), August 11, 1969

[24] A. Marziali, "Microphonics in Superconducting Linear Accelerators and Wavelength Shifting in Free Electron Lasers," Doctoral Dissertation, Stanford University, December 1994

[25] F. Gebhardt, "High Power Laser Propagation," *Applied Optics*, Vol. 15, No. 6, June 1976

[26] H. Weichel, "Atmospheric Propagation of Laser Beams," *Optics, Electro-Optics, and Laser Applications in Science and Engineering*, SPIE, Los Angles, CA. January 17, 1989

[27] ASSET, Advanced Surface Ship Evaluation Tool, System User Manual, Vol. 1, May 1990

[28] S. Fish et al, "Initial Impact Assessment of El ectro-Thermal Chemical Gun Outfit Aboard the DDG-51 with Mechanical Drive," DTRC-PAS-91-53, David Talyor Research Center, February 1992

[29] D. Small, "FEL with Short Rayleigh Length," *Proceedings of the 18th International FEL Conference*, Rome, Italy, August 26-31, 1996

INITIAL DISTRIBUTION LIST

1.	Defense Technical Information Center 8725 John J. Kingman Rd., STE 0944 Ft. Belvoir, VA 22060-6218	2
2.	Dudley Knox Library Naval Postgraduate School 411 Dyer Rd. Monterey, CA 93943-5101	2
3.	Chairman, Code ME Department of Mechanical Engineering Naval Postgraduate School Monterey, CA 93943-5002	1
4.	Professor C. N. Calvano, Code ME/Ca Department of Mechanical Engineering Naval Postgraduate School Monterey, CA 93943-5002	2
5.	Professor W. B. Colson, Code PH/Cw Naval Postgraduate School Monterey, CA 93943-5117	6
6.	Naval Engineering Curricular Office, Code 34 Naval Postgraduate School Monterey, CA 93943-5002	1
7.	CAPT Dennis Mahoney AEGIS Program Manager PMS 400 DX 2531 Jefferson Davis Highway Arlington, VA 22244-5104	1

8.	CAPT Mike Gouge Fusion Energy Division Oak Ridge National Laboratory P.O. Box 2009 Oak Ridge, TN 37831-8071	1
9.	John Albertine Code 332, Division Director Directed Energy Division Space and Naval Warfare Systems Command 2541 Crystal Dr. Arlington, VA 22245-5200	1
10.	Dr. George Neil Thomas Jefferson National Accelerator Facility 12000 Jefferson Ave. Newport News, VA 23606	1
11.	Alan Todd Northrup Grumman Corporation 4 Independence Way Princeton, N.J. 08540	1
12.	LT Eric J. Anderson 8 Breezy Dr. Erwinna, PA 18920	2