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Megawatt-class free electron laser concept for shipboard self-defense

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ABSTRACT

An efficient MW-class free electron laser (FEL) directed energy weapon (DEW) system holds promise for satisfying shipboard self-defense (SSD) requirements on future generations of Navy vessels because of the potential for high-power operation and the accessibility to all IR wavelengths. In order to meet shipboard packaging and prime power constraints, the power efficiency and high real-estate gradient achievable in an FEL driven by a superconducting RF accelerator is attractive. Configuration options and the key development issues for such a system are described.

Keywords: accelerator, defense, FEL, laser, superconducting

1. INTRODUCTION

The recent Naval mission shift from "blue water" to littoral conflict has profoundly affected cruise missile defense requirements. Instead of support defense within a battle group where crossing target engagements predominate, each vessel may be sailing alone at low speed and must now be capable of performing self-defense against a radially incoming threat. Existing low radar-cross-section (RCS), transonic, sea-skimming cruise missiles have compressed the battle space towards the limits of current gun and missile defensive weapon system performance. Meanwhile more capable supersonic and high-g maneuvering missiles are increasingly available.

DEW systems, such as chemical lasers and FELs, maximize the engagement range, duration and keep-out distance, because they deliver their energy to the target at the speed of light. Further, the maneuverability advantage of high-g, high-speed, low-RCS cruise missiles is restricted to limitations inherent in the ship fire control system. DEW systems can thus deliver robust performance even as threat performance increases in the future. Other DEW advantages include the existence a deep magazine and low cost per kill. In the case of an FEL, since electricity is the only consumable, this permits affordable training and leads to a short logistics trail. Navy DEW systems also have the potential to fulfill secondary missions such as anti-satellite (ASAT), theater missile defense (TMD) and low-power deterrence illumination. The ASAT and TMD capabilities arise because, although the laser range may be limited to around 10 km when traversing a horizontal path within a few meters of the ocean surface, the range becomes very extensive as the beam elevation is increased.

The US Navy has developed deuterium fluoride (DF) chemical laser technology to the MW-class level as demonstrated by the MIRACL (mid IR advanced chemical laser) device[1]. However, for point defense in the maritime environment, where the laser beam path to the oncoming missile remains effectively stationary, the DF laser energy deposited in the atmosphere by absorption causes heating that leads to unacceptable levels of thermal blooming, the negative lensing effect that degrades the power density on target. For crossing engagements where the laser path sweeps through the atmosphere, and for environments less stressing than horizontal paths near the sea surface, DF DEW systems remain very attractive. Thus, the US Army Nautilus and US Air Force Space-based Laser (SBL) programs continue to respectively develop DF and HF laser systems for TMD applications. The related US Air Force airborne laser (ABL) TMD project features a chemical oxygen iodine laser (COIL) on a Boeing 747 platform. However, for the Navy SSD application, a high-energy laser weapon system (HELWS) must be developed at a wavelength with less atmospheric absorption in the littoral maritime environment than that of 3.8 micron DF and 1.3 micron COIL devices.

The theoretical advantage of an FEL as a high-power laser centers on the fact that it lases in vacuum and the unconverted drive energy is carried away by the electrons at the ultimate limit of the speed of light. This contrasts with conventional lasers where thermal constraints in the material lasing medium eventually lead to a power limit requiring build-out of the laser system with separate lasers rather than scale-up within the same physical envelope. In practice, the FEL power record has disappointingly remained at around the 11 watts of the Vanderbilt device[2] for some time. However, experiments in preparation should deliver kW-level demonstrations in the very near future[3,4,5]. A second advantage is the broad-band tunability of the FEL which can be achieved by varying the electron energy or the wiggler magnetic field. Since the wavelength is not dependent on particular atomic transition lines as is a conventional high-power laser, the FEL can be designed for operation at any wavelength. Because of this potential for high-power operation and the tunability that permits access to all IR wavelengths, an efficient MW-class FEL DEW system is the laser of choice for the Navy maritime environment, and holds promise for satisfying SSD requirements on future generations of Navy vessels. A third feature of a photocathode-driven FEL, such as we propose, is the picosecond as opposed to the continuous wave (CW) pulse structure of a chemical laser. The resultant intense micropulses are not anticipated to lead to either atmospheric propagation or to target thermal coupling problems. Shorter pulses can actually lead to increased surface absorption and more effective thermal coupling, but the impact on the materials of interest is expected to be comparable to the measured performance of CW beams and will have to await the results of upcoming experiments[5].

Table 1. FEL HELWS top-level performance goals

Engage threat of 4 simultaneously arriving supersonic cruise missiles
360 degree coverage over a 20 second engagement time
Hard thermal kill (aerodynamic destruction or high explosive detonation)
System recycle time ≤ 20 minutes
1 MW laser output power
1 - 2 micron wavelength (nominally 1.6 micron)
Availability ≥ 95%
Power throttling for alternate missions
Packagable inside 5"/54 gun envelope (weight ≤ 100 tonnes : volume ≤ 500 m^3)

The top-level performance goals selected by the authors to scope the FEL system parameters are shown in Table 1. The four simultaneous arriving supersonic missiles and engagement timeline represent a possible future threat where hard kill follows from the velocity difference of the combatants. The recycle time reflects a balance between the speed of recovery against system size and prime power drain. The MW power level is not based on known experimental data but is rather a rough order of magnitude estimate to size the system, and the wavelength selection is discussed below. The 5"/54 packaging defines the maximum real estate that is likely to be available on future vessels and as such establishes an upper limit target for the system. Additionally, this should not be viewed as implying a direct retrofit to this specific gun volume which represents prime real estate and function on active vessels.

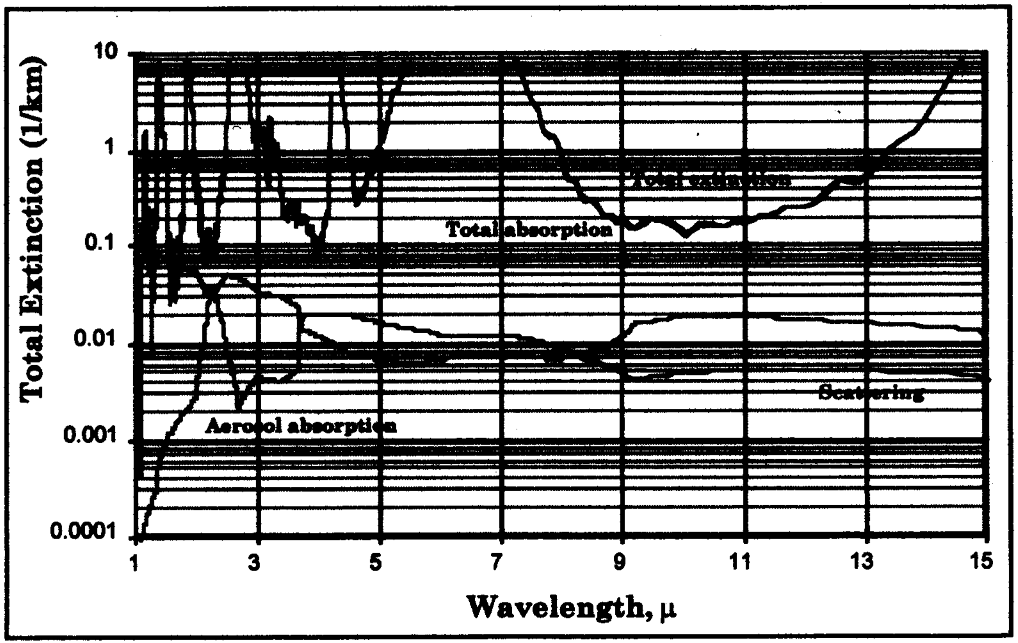

Figure 1. Nominal atmospheric extinction due to absorption, scattering, and aerosol absorption[6]

Figure 1 shows the total atmospheric extinction composed of atmospheric absorption, scattering and aerosol absorption, for typical benign maritime atmospheric conditions. The scattering curve moves up and down significantly with varying conditions, while the atmospheric absorption remains sensibly constant. This figure illustrates that the desire to push to shorter wavelength for ever more transparent absorption windows conflicts with improved scattering at longer wavelength. It shows that the total extinction remains fairly constant at around 0.1/km in the window regions from one to four microns. However, the additional nonlinear effects of atmospheric turbulence and thermal blooming, which degrade the delivered power density by increasing the achievable spot size on target, must also be taken into effect. Thermal blooming depends on the energy absorbed and resultant heating along the laser path, and is a complex function of absorption, wind speed and direction, and the various engagement velocity vectors. For point defense, when thermal blooming is included, there is a clear drive to the low absorption windows between one and two microns, although there is some degree of prejudice against the lowest wavelengths because of issues related to eye safety. Subject to further analysis, the propagation window at 1.6 microns has been identified as the wavelength of choice. Operation within the window further requires that the laser have less than 4 Angstrom wander and a better than 40 Angstrom full-width half-max (FWHM) bandwidth. The reason why the 3.8 micron DF and 1.3 micron COIL systems are not adequate for the Navy mission is clear from this figure. As aerosol and other atmospheric conditions worsen, the performance effectiveness of the 1.6 micron FEL system will degrade gracefully.

Section 2 discusses the individual FEL subsystems which are then integrated into two principal configuration concepts in section 3. Section 4 identifies and discusses the key physics, engineering and systems technology development issues. Finally, section 5 provides a summary of the FEL HELWS concept.

2. SUBSYSTEM REQUIREMENTS

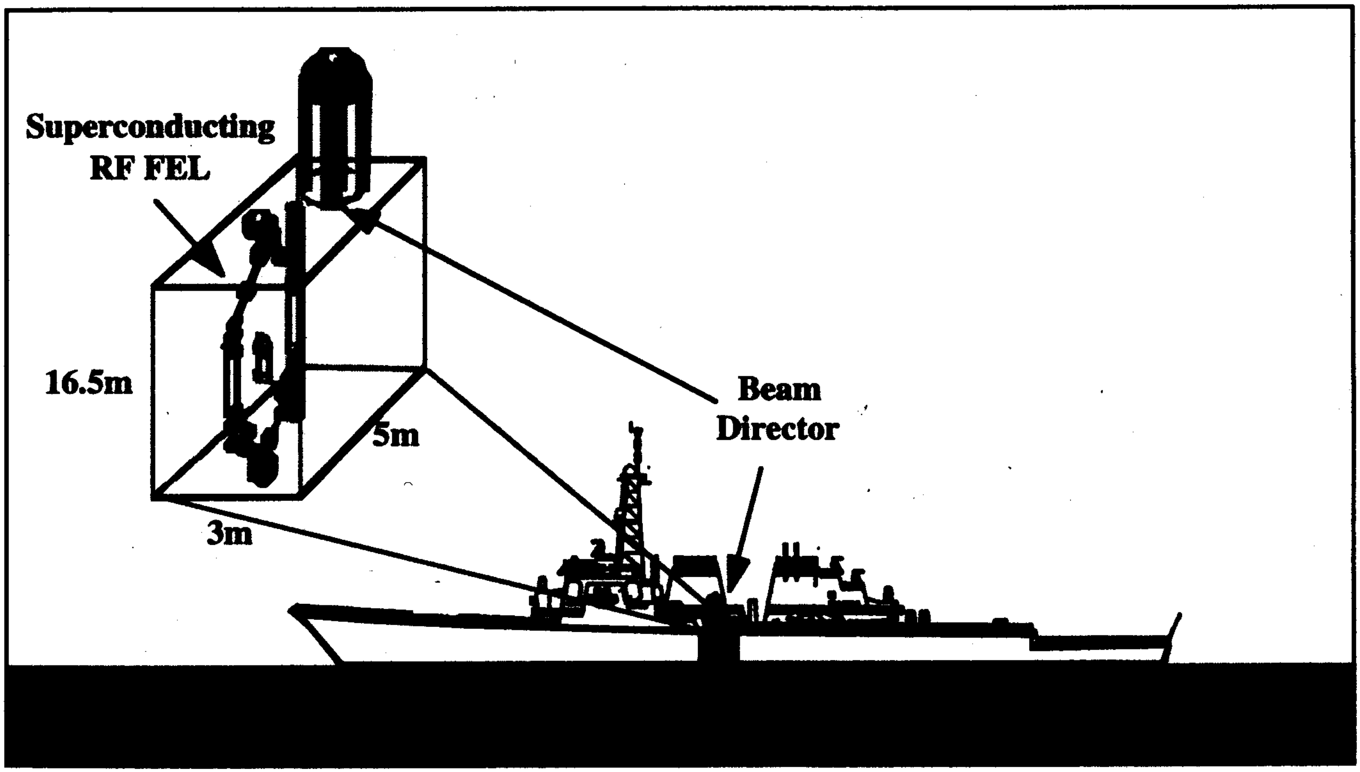

Figure 2. Conceptual Shipboard FEL HELWS Configuration

An FEL HELWS concept is illustrated schematically in figure 2. It features superconducting RF acceleration for the FEL and two midship beam directors to provide the required 360° coverage with vessel lockout. The Navy Sea Lite Beam Director (SLBD) has already demonstrated the performance needed for an SSD system at 3.8 microns[1], although there are aspects of operation in the nautical environment that still require confirmation. Such beam directors, perhaps with reduced aperture (1 - 1.5 meters) because of the shorter wavelength proposed, would be utilized. To avoid bulkhead penetration and overspecialization of the vessel design to the FEL, the system should be mounted vertically and should have a maximum dimension of less than 20 meters to remain below deck. In fact a horizontal orientation would be preferable for FEL subsystem packaging and would enhance the ability to use fuel and the ocean for radiation shielding. The HELWS must utilize the onboard acquisition radar system to provide hand-off to the beam director tracking and pointing, and be fully integrated with the overall fire control system. Given this relative maturity of the balance of the system, we concentrate here on the FEL components and support system requirements to meet the top level goals.

The FEL device will be considered as accelerator, optical and support subsystems. The electron accelerator consists of an injector, the accelerator proper, the beam transport system and beam dump. Beam recirculation and energy recovery may or may not be employed. The radiation section consists of a wiggler, optical cavity and optical transport to the beam director. Finally, the support subsystem includes the RF power, energy storage, power conditioning from the vessel prime power, cryogenic cooling and safety subsystems.

2.1 Accelerator Subsystem

The accelerator subsystem includes many of the key technology development items. The effective delivery of 1.6 micron radiation requires a beam energy in the wiggler of 80 to 100 MeV. To the extent that neither the wiggler nor the injector technology is additionally stressed, it is desirable to minimize this energy which drives the size of the support systems. 100 MeV has been selected for scoping purposes, at which energy, 1% extraction as 1 MW of IR power requires an average electron current of 1 Amp. The actual range of extraction considered below is 1% to 20%, depending on the outcoupling concept, which implies an average injector current of between 50 mA and 1 A. However, in all cases, simulations indicate a peak current on the order of 600 A is required for lasing[7]. First and foremost then is the need to develop photocathode injector systems capable of reliably delivering such currents for 20 seconds, since thermionic injectors are considered unlikely to provide the required beam brightness. Three possible photocathode concepts are a high-voltage DC gun[5], a room-temperature RF device[4] or a fully superconducting RF gun[8]. The room-temperature RF system has already met the lower current bound but is extremely bulky and power hungry. The other two devices are more efficient, with the superconducting gun being the preferred option, but need significant development to reach the current levels required.

To reach a degree of efficient power utilization and accelerator compactness sufficient for effective shipboard packaging, the FEL electron accelerator must employ high-gradient superconducting RF technology. At the expense of adding a bulky cryogenic refrigeration system, a superconducting accelerator delivers the RF power where it is needed, to the electrons and not to structure, thereby leading to the highest wall-plug efficiency for any selected configuration. The RF, energy storage and upstream power conversion subsystems are major packaging drivers that make high efficiency essential. Additionally, the highest accelerating gradients are achievable in superconducting accelerators, which leads to the shortest accelerating length and thus optimum packaging. We have projected as a system target, a real estate gradient of 12 MV/m, implying a peak cavity field of ~ 50 MV/m. While configurations using room-temperature acceleration can be competitive at much lower powers, they are not realistic for MW-class devices. However, cryogenic acceleration, which can in principle approach superconducting gradients, has not been ruled out as an option, particularly given the uncertainty regarding the required size of the refrigerator system.

The main ring and 1 kW Demonstration FEL accelerators at Jefferson Lab utilize 1.5 GHz. While higher frequencies permit higher accelerating gradients, they also increase the cryomodule high order mode (HOM)[9] power removal problems and increase the sensitivity to beam breakup (BBU)[10] instabilities. It is anticipated that a frequency around 700 MHz will represent the likely compromise between these factors. In addition to the difficulty of delivering a real estate gradient of around 12 MV/m at 700 MHz, there will be problems in coupling the very high power density through the RF windows into the cryomodules within the limited accelerator length.

The beam transport system will be fairly straightforward if recirculation is not employed. However, bending high current beams with little or no emittance growth will not be easy. The relevant parameter here is the peak and not the average current. For present scoping purposes, we have set a 4 meter by 4 meter footprint for a 180° bend. Consider a tiny beam spill of 10^{-6}/m run from such a bend for a 1 A beam at 100 MeV. Such an arc has ~ 10 m run and the beam loss can be imagined to occur vertically over 5 mm. Then the power density over the loss area is 20 kW/m^2 for a total bend power of 1 kW. These numbers clearly indicate why the emittance growth and beam spill in bends at high current is a critical issue.

At first blush, it would seem obvious to recirculate the electron beam back through the accelerator arms as shown in figure 2, in order to recover as much of the unused electron beam energy as possible. However, recirculation imposes additional constraints on the IR extraction that strongly impact overall system parameters. Firstly, energy recovery requires maintaining good beam quality and thus minimizing emittance growth in the beam transport system. It must be rapidly determined if theorized debilitating effects, such as the transport in general of near-kA beams around sharp bends and more specifically coherent synchrotron radiation (CSR)[11], are real problems, and if so, methods of control must be devised. Secondly, the output beam energy spread increases as a strong function of the extracted IR power fraction. Transporting beams with large energy spread around bends for reinsertion 180° off-phase into the accelerators will not be easy. A 2%

energy extraction limit for straight-line energy recovery systems and a 1% limit for fully recirculating systems has therefore been imposed to reflect these constraints. As we will show below, increasing the extracted power fraction in the presence of energy recovery is one of the highest leverage areas for system performance enhancement.

As we have already alluded, the two most promising FEL configurations are a straight system without energy recovery and a fully recirculating system. In addition to potential power savings, there is considerable radiation safety advantage in an energy recovering system which dumps the expended electrons below the key radiation threshold of around 10 MeV. Our target value is 5 MeV, although it may be difficult to fully control the decelerated beam to this low value. In those systems that do not employ energy recovery, dumping the beam at the full energy of 80 to 100 MeV will be a severe problem. An on-board dump would be extremely massive, while the complications of utilizing the ocean directly are significant with respect to vessel architecture.

2.2 Optical Subsystem

The optical subsystem definition is dependent on the optical outcoupling scheme employed. Mirror power loadings of >> 10 kW/cm^2 have been demonstrated[12]. 1-2 micron optical beam transport systems from the resonator to the beam director that do not exceed these values, can be utilized. The key issue here is the choice of outcoupling since both amplifier and oscillator concepts can be accommodated. In either case, the wiggler will likely be very similar to permanent magnet devices in use today[13]. Maintaining FEL optical beam quality better than two times the diffraction limit should not pose a problem. The FEL should have of an order of magnitude power throttling capability to support secondary missions.

An oscillator with a moderate cavity Q and very small Rayleigh range minimizes the mirror loading while preserving reasonable levels of both small signal and saturated gain. In the vibrating and flexing shipboard environment, coupling this oscillator concept with an R-5 resonator cavity[14] has been suggested as being most forgiving with respect to alignment tolerances. Alternately, the Regenerative Amplifier FEL (RAFEL)[3] is a low Q oscillator with very high gain, that offers the theoretical potential of extracting as much as 20% of the electron beam energy in the IR. The cavity Q is low only in saturation, while the high gain at saturation leads to relaxed resonator parameter tolerances and reduced mirror loading. However, in the RAFEL and amplifier concepts, the power density on the first turning mirror of the optical transport system is an issue. The single accelerator master-oscillator power-amplifier (SAMOPA) uses a low extraction efficiency resonator to generate a seed IR beam. The seed is then fed into the main amplifier wiggler to bunch the beam and generate the single-pass high-power IR output. There are many variants of these different schemes and other options include optical klystrons and electron beam outcoupling[15]. Oscillator and amplifier concepts can be mixed and matched with accelerator configurations. Low extraction efficiency leads to high power density in the oscillator cavity and compounds the optical component power density problems. Of particular interest, given the constraints on energy recovery discussed above, are those schemes such as phase-area displacement oscillators that lead to low output energy spread and hence offer the high-leverage potential, in principle, for high extraction together with energy recovery.

2.3 Support Subsystems

The FEL support subsystems dominate the weight and volume of the HELWS package. The two principal support subsystems are the cryogenic refrigerator and RF power. The 4.5°K cryogenic system must be reliable and compact. Today, for ~ 10 MV/m accelerating gradient to 100 MeV, a 2 kW refrigerator would require 0.2 MW active cycle average power to operate and could be as large as 200 m^3. The size of the unit is closely tied to the operating scenario developed and is strongly driven by the cycle time. The present reservoir and refrigerator choice is sized to absorb the temperature rise of the 20 second shot and cool the system back down to the base temperature within 20 minutes. Operational, hot and cold standby modes are envisaged. Cold standby simply maintains the cavity temperature while hot standby would have the injector shot ready.

The vessel prime power must be connected through a power conditioning system to the RF and energy storage subsystems. Our present choice for the energy storage subsystem is composite flywheels. The 20 second operation and 20 minute recharge times are an excellent match to flywheels presently under development. In the time frame that a Navy FEL HELWS would be deployed, these flywheels are projected to achieve 60 kJ/kg and 50 MJ/m^3. When the power electronics and auxilliary components are added, these figures become 30 kJ/kg and 7.5 MJ/m^3. The flywheel output power conversion parameters are assigned to the RF system. When we factor in the nominal 700 MHz RF plug-to-window efficiency of 50%, then we find the energy storage system is sized at 1.3 tonnes/MW and 5.3 m^3/MW, where the number of MWs is sized by the RF system output. RF tubes, modulators and power conditioning are estimated at 2 g/W, 10 m^3/MW and $2/W.

Other support systems that do not pose particular problems and which we do not specifically address here, include diagnostics, instrumentation and control, radiation safety and environmental control, and non-cryogenic cooling. An exception that has not yet been studied in detail is the high energy beam dump if energy recovery is not utilized. Next we consider how to arrange these various components into specific FEL HELWS configurations.

3. HELWS CONFIGURATIONS

The previous section described the various elements that make up a high-power IR FEL system. Although there are many possible system configurations, here we assemble these elements into two distinct concepts that highlight the range of options available, and exhibit very different development issues. The first concept, illustrated schematically in figure 3, is a low extraction efficiency, recirculating device with energy recovery. The second concept of figure 4, denoted the straight-shooter, eschews energy recovery for a straight system with high extraction efficiency. Both systems are sized to deliver 1 MW of IR output at 1.6 microns. They employ superconducting RF acceleration at around 700 MHz with a real estate gradient of 11 MV/m, and require almost equivalent RF power output (6 and 5 MW respectively). The injectors, whose technology is not specified, are required to deliver a 5 MeV input electron beam to the accelerators. The optical cavities should be as long as possible to spread the IR power over the mirrors, but must not be less than 10 meters.

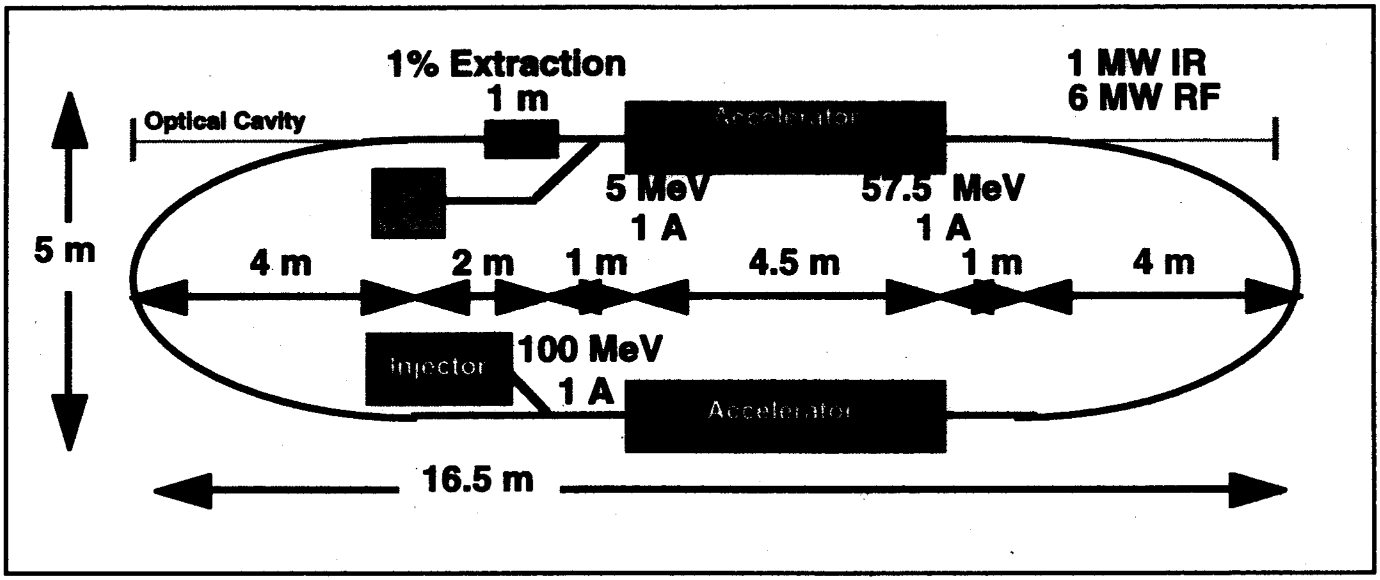

Figure 3. Conceptual Energy Recovery Configuration

The energy recovery system of figure 3 begins with a 5 MeV, 1 A photocathode injector that circulates the beam counterclockwise through two parallel 45 MeV, 700 MHz superconducting accelerator arms and then into a 1% extraction efficiency wiggler within an R-5 optical resonator. The wiggler is placed right after final acceleration to ensure there is no emittance growth due to CSR in a high energy bend and hence optimum entry emittance to the wiggler. If it can be shown that a bend can be negotiated prior to entering the optical cavity, then the wiggler would better be placed after the second bend. The first deceleration leg is then entered with straight beam transport to minimize emittance growth and high energy beam loss in the presence of the bend and because of the significant post-extraction energy spread. This will maximize the energy recovery efficiency. This concept is constrained to low extraction efficiency because of the need to minimize the energy spread introduced if energy recovery is to be successful. The 1 A beam current is set by the 1% extraction efficiency from the 100 MW beam to yield the required 1 MW 1.6 micron IR output. The electron beam then recirculates back through the accelerator arms out of phase, and the residual 5 MW is dumped at 5 MeV following deceleration. At 6 MW RF power, given the proposed flywheel storage, the averaged prime power draw on the ship will be 400 kW split equally between the cooling and flywheel recharge systems. The total electrical system volume will be 92 m^3 and the weight will be 20 tonnes. Table 2 collects rudimentary top-level projections for weight, size and RF cost based on the given assumptions. These should be treated with caution and are intended only to identify problem areas such as the cryostat volume. As the blank entries indicate, little cost analysis has been performed to date and the shielding and beam dump volume is uncertain. At least 100 m^3 of the empty central accelerator volume can be used for support subsystems, which explains the reduction of the total volume to 332 m^3 plus the shielding and beam dump volume as indicated by the "*" in table 2. Further sizing detail on some of these systems can be found in reference [16].

Table 2. Top-level parameters for energy recovery configuration

Subsystem	Weight (tonnes)	Volume (m^3)	Cost ($M)
Accelerator (+ 100 m^3 subsystem storage)	32	124 *	-
Optical cavity	2	6	-
RF system	12	60	12
Energy storage & power conditioning	8	32	-
Cryogenic system	20	200	-
Radiation & safety (including beam dump)	-	-	-
Ancillary systems	5	10	-
TOTAL	79+	332+ *	-

An advantage of this concept is that the maximum dimension is nominally 16.5 meters, and hence the 124 m^3 FEL pancake package, with support systems internal to the ring, can be integrated vertically within the vessel as shown in figure 2, without requiring extensive vessel re-configuration. It also dumps the electron beam at 5 MeV, which leads to a manageable beam dump design and acceptable radiation safety. On the other hand, the enforced 1% extraction efficiency not only stresses mirror technology and demands short resonator designs, but also leads to the 1 A current requirement which imposes great stress on injector development and on bend designs for minimal emittance growth.

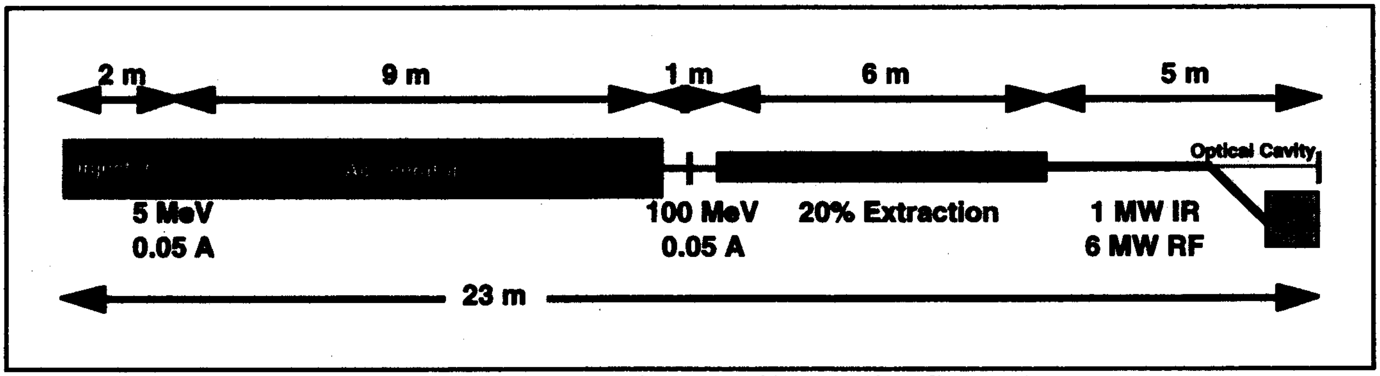

Figure 4. Conceptual Straight-Shooter Configuration

The second concept, shown in figure 4, assumes a completely different approach. Here, a 20% extraction efficiency RAFEL oscillator is coupled with a straight accelerating system. In this case, the required current is only 50 mA for 1 MW of IR output. The 6 meter wiggler is of necessity longer than the 1 meter version required in the low extraction oscillator, and the first turning mirror must be set at least 5 meters beyond the wiggler end in order to reduce the power density on the mirror to an acceptable level. The resultant device is 23 meters long and about one and a half meters in diameter, although additional volume is required for the support systems. In this case, electron beam bends and energy recovery are eliminated, while mirror and injector technology is not particularly stressed. On the other hand, the required wiggler input beam quality is higher, extraction efficiency is stressed and a full energy 5 MW beam dump is needed. It is not clear that such a 100 MeV beam dump can be practically designed for the shipboard environment. Given that it is shown that bending 600 A peak current beams without loss is possible, bending back after the wiggler for separate deceleration to a lower energy is an option that will add to the size and complexity of the configuration, while it is not likely that the RF power can be recovered. A separate table is not shown for this configuration, since given the similarity in RF power level and the specific components themselves, the gross parameters are very similar to those given in table 2 for the recirculating system.

The non-recovering straight configuration becomes relatively more attractive as the required IR output power increases. At 2 MW of IR, the recirculating system needs 2 A from the injector and 12 MW of RF power, while the straight system needs just 100 mA and 10 MW of RF. The leverage that can be obtained from increasing extraction with energy recovery is now clear. With 10% extraction efficiency, the recirculating system requires 100 mA and only 1.5 MW of RF power to deliver 1 MW of IR. The impact of reduced RF power on the weight and volume of the packaging envelope has been identified above, but at $2/W, the cost savings of $9M makes this also a major affordability driver. Hence extraction concepts that can lead to lower energy spread and permit energy recovery should be explored.

Obviously, the ultimate goal of a one-for-one on-deck replacement for the present close-in weapon system (CIWS) or Phalanx gun is not feasible. However, although the projected envelope totals for both concepts meet the 5"/54 targets, a truly attractive HELWS systems would be considerably smaller.

4. TECHNOLOGY DEVELOPMENT ISSUES

Development issues for a MW-class FEL for SSD fall into three categories, physics, engineering and systems. At the systems level, the first order of business is to demonstrate micron wavelength, picosecond pulse structure propagation and power density performance on target in the maritime environment. The high-power FEL and the beam director must be integrated with the shipboard acquisition and fire control systems. The system should be safe, affordable, have an availability exceeding 95% and require minimal crew and maintenance attention. In the evolving Navy, multitasking of the cryogenic and energy storage systems is a strong possibility. High-power, high-efficiency superconducting FELs are dual-use with many known Industrial applications, provided economic targets can be met. Hence, there is a strong synergy with commercial systems that could provide enormous benefit to the affordability and reliability, accessibility, maintainability and inspectability (RAMI) of an FEL HELWS.

On the engineering front, the key issues are the demonstration of up to 100 kW/cm^2 resonator optics power loading, the development of fail-safe, compact 4.5°K cryogenic systems, and the development of high-power superconducting RF components, such as windows, HOM absorbers and tuners, at the chosen frequency. The cryogenic system operating temperature will be studied to find the optimum operating point for the FEL that preserves performance while minimizing system size, weight and cost. Finally, a pervasive problem for both the FEL and optical beam transport and director systems, and the overall system integration, is shipboard vibration and flexing that leads to alignment, jitter and RF cavity microphonics problems. Passive and active alignment and control systems will have to be developed to counter the impact of these motions. However, previous space-based accelerator activities suggest this problem is solvable.

While solutions are projected for the identified engineering and systems issues, the same is not true for certain of the outstanding physics issues. A key item is the development of an effective high-current injector to yield up to one Ampere with good beam quality. The achievable current level may very well downselect the FEL configuration to the lower current options. The next key item is the development of high-gradient superconducting RF cryomodules that can achieve > 10 MV/m real estate gradient at a frequency with tolerable HOM power density and BBU stability. Demonstration of the RAFEL high efficiency wiggler operation with up to 20% extraction efficiency is critical for the straight configurations. For energy recovery configurations, the actual experimental requirements on acceptable wiggler-induced levels of energy spread and bend emittance growth via CSR and other effects, in order that energy recovery can still be successfully effected, need to be identified. It is clear that the actual configuration eventually employed will likely be dependent on the outcome of these physics issues. We again note the high leverage of low energy spread extraction schemes that may permit energy recovery at higher extraction efficiencies.

5. SUMMARY

There is an increasing need for improved Navy SSD against the expanding cruise missile threat. Because of its wavelength selectivity, power efficiency and potential for compact shipboard packaging, a superconducting RF accelerator FEL HELWS is the high-power laser of choice for this mission. Systems that fit within the size and weight envelope of a current Navy 5"/54 gun platform have been considered. Most of the key issues in the development of such a system are physics-based, such as obtaining the required injector current level and brightness, and many are the subject of ongoing experiments[3,4,5]. We plan to continue our initial system configuration studies and begin to introduce costing to our models.

ACKNOWLEDGMENTS

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