High-Energy Laser Weapon Integration with Ground Vehicles

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SUMMARY

There is potential for the near-term development and demonstration of a new ground vehicle based weapon system that integrates an electric solid-state high-energy laser (HEL) as the primary armament. This weapon system promises to provide revolutionary warfighting capabilities with a small logistics footprint. The benefits of this weapon system are significant; however, there are several significant technical and integration challenges to address before such a system can be fielded. The architecture of an electric, solid-state HEL weapon system would likely be based upon a hybrid electric vehicle that provides a common electrical power source for the propulsion and weapon subsystems. The demands of the weapon subsystem on the power source are substantial for a weapon-class HEL. Also, the electro-optical efficiency of the weapon subsystem is inherently low, resulting in significant heat levels that must be effectively removed from the system. Practical solutions to these challenges are further complicated by the severe size and weight constraints imposed upon future-force ground vehicle weapon systems.

1.0 INTRODUCTION

Directed energy weapons such as HEL promise to provide revolutionary capabilities to the warfighter. The US Department of Defense (DoD) is making significant investments in HEL technology due to the transformational capabilities it can provide the warfighter. Currently, chemical lasers are the only technology proven to achieve the power levels required for weapon-class applications. Chemical lasers provide significant output power but come with a huge logistics burden due to the large variety and quantity of chemical fuels required for laser operation. High power solid-state laser (SSL) technology is maturing and has the potential to significantly mitigate or eliminate the logistical burdens associated with chemical lasers.

The US Army has a strong preference for SSL technology for an objective weapon system. This preference is based upon the belief that a SSL is the best option for ground vehicle integration. The US Army has established a near-term investment strategy [1] to leverage weapon-class chemical lasers as test bed demonstrators to address weaponization issues including the definition of HEL concept of operations (CONOPS). The knowledge and lessons learned from these chemical laser demonstrators will transition to future SSL programs for full system development and fielding .

SSL technologies employ the concept of optical pumping; using an intense light source to excite atoms in a lasing medium made up of synthetic or rare earth materials (e.g., ruby, sapphire). Because they rely on electrical power, solid-state lasers will impose less of a logistical burden than chemical lasers for weapon

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applications. Current state-of-the-art SSL systems are relatively inefficient (~10%) resulting in a significant thermal management issue. To date, developmental SSL have managed to demonstrate power output levels in the 10 kW range. Due to recent advances in laser diode technology (optical pumping), adaptive optics, and gain media development, it is projected that SSL will reach weapon-class power levels (>100 kW) within the next three to four years.

Given recent technology advances and interest by the DoD there is a real possibility for integration of a weapon-class solid-state HEL into a ground combat vehicle within the next three to five years. In addition to recent advances in SSL technology, the planned proliferation of electric vehicle platforms such as the Future Combat System (FCS) Manned Ground Vehicles (MGVs) serves as a key enabler for this new type of weapon system.

The integration of a HEL with a ground combat vehicle will present a number of significant technical challenges. The intent of this paper is to examine the feasibility of a ground vehicle based solid-state HEL weapon system with special emphasis on power supply and thermal management impacts.

2.0 HEL CAPABILITIES

A weapon-class HEL is an advanced armament technology that provides an unconventional means of delivering lethal energy to a target. Weaponization of HEL technology promises new and revolutionary capabilities to the warfighter; however limitations due primarily to natural and induced atmospheric conditions will require this weapon be used in a complementary role to conventional kinetic energy weapons. HEL weapons use a focused spot of light to inflict thermal damage at the surface of the target. HEL has unique characteristics [2] not found in other types of weapons systems that include:

- *Speed of light delivery*: The energy is delivered to the target by means of an intense beam of coherent light. The energy appears at the target nearly instantaneously upon emission from the source (weapon system). There is no delay time between launch and interface with the target as with conventional kinetic energy weapons.
- *Not effected by gravity*: Kinematics and aerodynamics that effect conventional kinetic energy weapons have no effect on HEL. Because of this capability HEL can easily engage and neutralize targets that attempt to counter with high-g maneuvers or other evasive measures.
- *Extreme precision*: The HEL is a precision weapon where the laser beam can be focused on a small area (cm^2) of a target to neutralize or destroy it out to ranges of several kilometres As a result collateral damage can be significantly reduced compared to kinetic energy weapons.
- *Lethal and non-lethal capabilities*: The HEL can vary the amount of energy placed on the target as well as where the energy is placed. This control and variability allows a HEL to perform both lethal and non-lethal missions.
- *Low cost-per-kill*: Kinetic energy weapons can cost $1k to $1M per shot depending on the type of munitions. Solid-state HELs require only the fuel supply of the prime power to generate the energy to operate the laser.
- *Deep magazines*: Kinetic energy weapons have limited magazine size and significant logistic issues associated with ammunition re-supply. Conversely, the magazine depth of a solid state HEL is limited only by the capacity of the prime power source.

3.0 POTENTIAL REQUIREMENTS FOR A HEL SYSTEM

The US Army HEL acquisition strategy [1] includes an effort to analyze and develop an understanding of the military utility of a HEL system. This effort is being addressed concurrently with the development of SSL technology and chemical laser test-bed demonstrator work. These military utility studies will demonstrate and quantify the military benefits and mission requirements for a proposed HEL weapons system. From this information, system requirements can be derived and allocated to subsystem and component requirements, allowing the evaluation of design options and assessment of the value of the HEL technology. The development of requirements for a HEL weapon system creates a special challenge, in part because the driver for a future weapon system acquisition is capabilities–based, and no predecessor weapon system exists from which baseline requirements can be derived.

Some assumptions regarding the key capabilities of a conceptual weapon system can be made for the sake of analysis. Key performance parameters for a future ground-based SSL weapon system are likely to include:

- *100 kW power output*. Several programs [3] with the DoD are focusing on a 100 kW power output as the entry-level capability for a weapon-class SSL. It is anticipated this power level will meet the projected mission area requirements of a SSHEL with limited range of engagement.
- *C130 transportability*. This is a firm requirement for future ground based weapon systems, especially those systems planned for deployment with the FCS Unit of Action. This imposes tight constraints on volume and weight for the total weapon system.
- *Air defense mission*. There is specific interest within the US Army to use HEL technology for tactical air defense [1]. Given the unique characteristics of the HEL, the traditional air defense role of protecting critical assets from enemy aircraft and missiles can be expanded to include engagement of incoming rocket, artillery and mortar (RAM) threats. The ability to engage and defeat RAM-type threats is a revolutionary capability never before achievable until the weaponization of HEL technology. In addition, the HEL can provide an effective means to defeat enemy UAVs and cruise missiles threats.
- *Continuous engagement up to 60 seconds*. The optimum amount of time for continuous, uninterrupted target engagement will be determined based on comprehensive system and force effectiveness analysis. 60 seconds is merely an arbitrary timeframe for purposes of this analysis. This key performance parameter will drive the subsystem requirements for system power and thermal capacity required to effectively engage target(s) prior to a planned system recovery period. The length of recovery time is another factor that will be defined through further system effectiveness analysis.

4.0 HEL SYSTEM DESCRIPTION

For purposes of this analysis, we will refer to the system generically as a “solid-state high-energy laser (SSHEL) weapon system”. The SSHEL consists of an armoured combat vehicle platform such as the FCS MGV with an integrated 100 kW high energy laser mission module. The vehicle is powered by a hybrid electric drive system and meets the physical size and weight constraints required for transport by C130 aircraft. The system’s primary mission is air defense and it includes the requisite fire control, optical conditioning and beam pointing components to support this mission. The C4ISR system provides the required interfaces and capabilities to deploy in the future-force network-centric battlefield environment.

The system architecture selected as an analytical model for the SSHEL defines the power supply and the thermal management subsystems as common elements of the system (Figure 1). Within this architecture the other functional elements of the SSHEL system are defined as loads that interface to these subsystems.

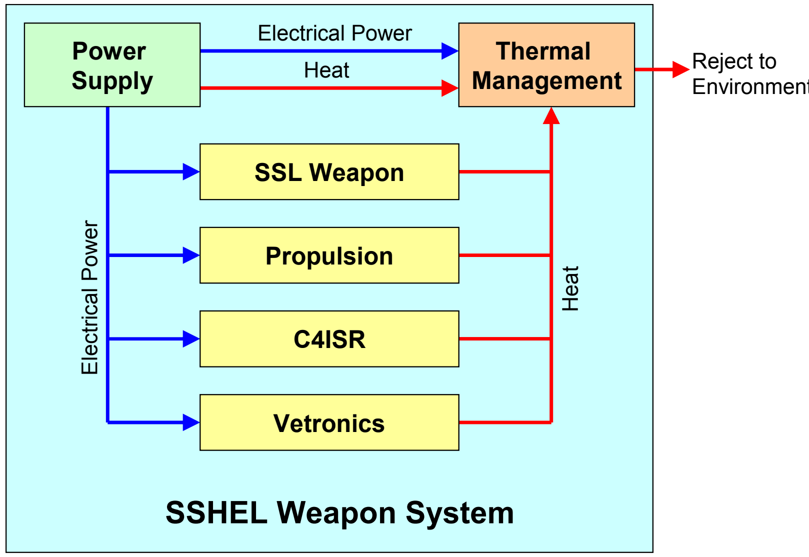

Figure 1: SSHEL System Model Architecture

Operationally, power is provided to each of the subsystem elements to achieve the desired function. Each subsystem has an inherent efficiency resulting in heat that must be rejected from the subsystem via the thermal management subsystem. Table 1 defines estimates for the SSHEL system electrical and thermal characteristics as a basis for analysis. Balancing power supply and thermal management performance with mission engagement and mobility requirements are critical design parameters for the system.

Subsystem	Power Required (Watts Average)	Waste Heat (Watts)
Power Supply	----	26 – 70 kW
Thermal Management	100 kW	30 kW
SSL Weapon	1.0 MW	900 kW
Propulsion	200 kW	30 kW
C4ISR	5 kW	5 kW
Vetronics	75 kW	50 kW

Table 1: SSHEL Subsystem Electrical and Thermal Characteristics

The power requirements of the SSHEL system will vary based upon the operational states. For this analysis three states will be defined.

- *Idle* –The SSHEL is stationary with only the C4ISR and required components of the automotive, SSL fire control and propulsion systems operational.
- *Mobile* –The SSHEL combat system is moving on the battlefield.
- *Engagement* – The SSHEL is stationary with the laser operational.

5.0 SSL WEAPON

This analysis is not intended to define in detail the implementation of a specific laser technology, but rather, to understand the integration challenges of a weapon-class SSL that are common to all SSL laser technologies. There are several critical SSL weapon integration challenges, with two being power supply and thermal management.

Using existing models which characterize a 100 kW SSL weapon module [4] and assuming the SSL weapon module will be a self-contained unit, a weight and volume of 600 kg and 1.5m³ (without a beam director) is selected for purposes of this study. The module includes gain media, laser diode optical pumps and the associated optics bench. Power will be provided to the module from the vehicle platform power supply. An interface is provided from the module to the thermal management subsystem from which heat can be extracted.

6.0 POWER SUPPLY

The architecture of an objective SSHEL weapon system will likely utilize a single power source that is common to all subsystems. Conceptually, a shared power source for an electric weapon and propulsion will provide a significant logistical advantage. The components of this power system include a prime power source, generator, batteries, control system, and power distribution to the weapon, propulsion and other loads on the vehicle platform.

Given all identified subsystem loads, the SSL weapon itself will place the greatest demand on the power supply. During lasing, a 100 kW SSHEL weapon system with an electro-optical efficiency of 10% will require 1 MW of power from the power supply subsystem. The power for this load will be supplied primarily from the battery and be replenished by the generator during a recovery period. For a 60 second engagement cycle, the weapon system will require the battery to provide a minimum capacity of 60MJ. Li-Ion batteries are well suited to meet the demands of this application. This battery technology provides a high energy density (220 kJ/kg) and a high power density (8 kW/kg), and it is expected that this technology will advance in the next few years to provide even greater densities. For the SSHEL, current analysis shows that Li-Ion technology will meet energy storage and power requirements in a package less than 500 kg. The on-board generator will supplement the SSL power requirements during lasing and provide power to recharge the batteries during recovery. The generator for this application will range in size from 350 to 400 kW.

The power supply design for the SSHEL application will need to balance performance and transportability requirements. The generator and battery components must meet engagement and mobility requirements while achieving the weight and volume objectives that allow C130 transportability. The design must also minimize the recovery time for the system by optimizing battery recharge and thermal management (which will be the design driver) cycle times.. A key operational issue for the power system design is to ensure that the system does not expend all stored energy for weapon engagements, but rather, maintains enough reserve energy for required mobility.

Power supply models have been created to provide a basis for system trades. An example simulation (Figure 2) illustrates the results of a multi-state scenario. This simulation is based upon a SSHEL system power supply configuration of Li-Ion batteries with capacity of 179 MJ and power of 10.4 MW with a 400 kW generator.

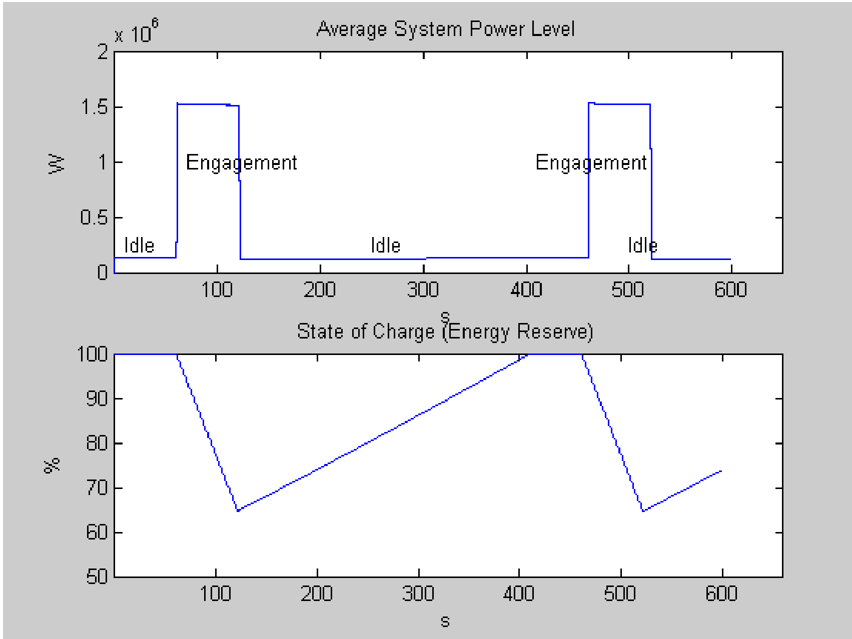

Figure 2: SSHEL Power and Energy Profile for Idle and Engagement States

7.0 THERMAL MANAGEMENT SYSTEM

The SSHEL system will generate large amounts of waste heat (Table 1) that must be rejected from the weapon system. The thermal management system performs this function by collecting waste heat from the subsystems on the SSHEL system and rejecting it from the weapon platform to the environment. The largest contributor to the thermal problem is the SSL weapon subsystem. The SSL weapon has two primary sources of waste heat; the laser diode optical pumps and the gain media. The amount of thermal energy to be expelled to the environment depends upon the operational state of the system. The relative waste heat levels for the SSHEL are illustrated in Table 2.

System State	Waste Heat (Watts)
Idle	55 kW
Mobility	90 kW
Engagement	1025 kW

Table 2: 100 kW SSHEL Waste Heat

It is anticipated that the operation of the SSL weapon system will be cyclic with periods of engagement followed by significant periods of idle time that could be used for recovery of the electrical and thermal subsystems. The cyclic operation of the system allows for implementation of a thermal management system that will temporarily store waste heat and reject it over the recovery period. This approach of heat storage within a phase change medium (PCM) will significantly reduce the volume and weight requirements of the thermal management subsystem [5]. To address the heat rejection requirements of the SSHEL system in real-time would require a thermal management subsystem in excess of 5,000 kg. Studies have shown that implementation of a PCM-type system could reduce the mass of the thermal management subsystem to as low as 400-500 kg [6]. Real-time rejection of waste heat generated by the SSL weapon is impractical given the transportability constraints on the SSHEL system.

8.0 OTHER INTEGRATION CHALLENGES

The SSL subsystem will present other integration challenges due to its physical characteristics and installation requirements. The subsystem is comprised of a collection of fragile optics, sensors and other components that require precise alignment be maintained. The area within the vehicle that houses this subsystem must maintain a clean, dust-free and temperature-controlled environment. The subsystem must also be mechanically isolated with active shock and vibration damping to impede the transfer of vibration from the vehicle during laser operation and to prevent misalignment of the optical chain due to severe cross-country mobility conditions.

9.0 CONCLUSION

The proposed implementation of hybrid-electric technology for future-force combat vehicles provides the enabling capability for directed energy weapons such as the SSHEL. A SSHEL weapon system will provide new and transformational capabilities never before available to the warfighter. Results of the analysis provided in this paper illustrate the relative magnitude of the integration challenges for a solid-state HEL on a ground combat vehicle. The requirements of the thermal management subsystem will likely present the greatest challenges to the integrator as operational requirements for a SSHEL evolve. Although there will be integration challenges, the near-term feasibility of integrating a 100 kW SSL onto a FCS-class ground combat vehicle appear achievable.

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