

Laser-Based Directed Energy Weapons: Technological Capabilities, Material Interaction, and Strategic Deployment Pathways

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*A version of this article has been formally published in **Defense Science Reviews** (DOI: <https://doi.org/10.37055/pno/216776>). The present version is shared as a preprint to facilitate early dissemination of the research and to support academic discussion. The content remains consistent with the published work, and readers are encouraged to consult the final published version for citation and reference purpose*

Abstract

Objectives: This review aims to evaluate the current capabilities of laser-based Directed Energy Weapons (DEWs), assess their interaction with aerospace and defence-relevant materials, analyse atmospheric propagation constraints, and identify technological barriers and future strategic pathways for deployment across land, air, and naval platforms. **Methods:** A systematic literature survey covering 2005–2025 was conducted using Scopus, Web of Science, and defense technical repositories. Sources were filtered based on relevance to laser technology, material response under laser irradiation, propagation modelling, and platform integration frameworks. Comparative analysis was performed across laser types, power architectures, battlefield roles, and integration strategies within layered air-defence systems. **Results:** Solid-state, fibre, and chemical lasers exhibit varying power levels, efficiencies, and platform suitability, with fibre lasers demonstrating the highest readiness for operational deployment. Material response analysis highlights distinct ablation thresholds, deformation behaviours, and surface degradation patterns for aerospace alloys and composites. Atmospheric propagation remains a primary performance constraint, while mitigation using adaptive optics, beam shaping, and wavelength optimization shows measurable improvement. System-level challenges persist regarding power generation, thermal management, and AI-supported beam control for mobile platforms. **Conclusions:** Laser-based DEWs are transitioning from prototype demonstrations to practical use, yet achieving deployment-ready solutions requires further advances in laser–material coupling models, scalable power architectures, and battlefield-integrated sensor fusion. Future opportunities include AI-driven beam control, compact energy storage, and pathways toward space-based laser platforms. Coordinated progress in materials engineering, power electronics, and autonomous targeting is essential for maturing DEWs into reliable and strategically transformative weapon systems.

Keywords: Direct Energy Weapons (DEWs); High-Energy Lasers; Laser–Material Interaction; Air Defence Systems; Ablation Threshold; Thermal Response of Materials; Beam Propagation; Optical Countermeasures; Target Engagement; Strategic Défense Technologies.

Abbreviation	Full Form
ADITYA	Advanced Directed Infrared Technology for Aerospace
AO	Adaptive Optics
ANN	Artificial Neural Network

CFRP	Carbon Fiber Reinforced Polymer
CHESS	Centre for High Energy Systems and Sciences
CIWS	Close-In Weapon System
CW	Continuous Wave
DEW	Directed Energy Weapon
DRDO	Defence Research and Development Organisation
FEL	Free Electron Laser
HAZ	Heat-Affected Zone
HELIOS	High-Energy Laser and Integrated Optical-dazzler with Surveillance
IDRW	Indian Defence Research Wing
LaWS	Laser Weapon System
LOAC	Law of Armed Conflict
R&D	Research and Development
SAM	Surface-to-Air Missile
SHORAD	Short-Range Air defence
SSL	Solid-State Laser
TRL	Technology Readiness Level
UAV	Unmanned Aerial Vehicle

1.Introduction

Modern conflict environments are increasingly shaped by asymmetric, low-cost aerial threats such as drone swarms, loitering munitions, and rapidly manoeuvring hypersonic vehicles. These emerging systems have exposed the practical limits of conventional kinetic air-defence, where every interception carries a high financial cost, a finite magazine, and delayed reaction time under saturation attacks (Adams & Schallhorn 2016). In contrast, laser-based Directed Energy Weapons (DEWs) are gaining prominence as a transformative solution because they deliver energy at the speed of light, offer scalable destructive and non-destructive effects, and significantly reduce cost-per-engagement (Phipps 2007; Adams & Schallhorn 2016). Their ability to disable or destroy threats without physical ammunition provides a compelling operational advantage, particularly against fast, unpredictable, or swarm-based threats. Recent demonstrations reflect this momentum across multiple countries. The U.S. Navy's LaWS showcased shipborne laser engagement against UAVs and small vessels (US Navy Office of Naval Research 2017), while Israel's Iron Beam entered advanced testing to counter short-range rockets and low-flying threats as part of its layered defence structure (Rafael Advanced Defense Systems 2023). Parallel advances are reported in the United States and China on mobile and airborne laser weapon concepts (Lockheed Martin 2022; NATO Science and Technology Organization 2019). India has also accelerated indigenous developments through DRDO programmes, particularly ADITYA and CHESS, aimed at counter-UAV and short-range laser-based intercept capabilities (Indian Defence Research Wing 2024; High Energy Laser Joint Technology Office 2020). Despite these advancements, current research remains

fragmented, with many publications addressing isolated components such as laser physics, atmospheric optics, or individual nation-level programmes. There is a lack of consolidated, multidisciplinary analysis that connects technology readiness, material effects under laser exposure, atmospheric propagation constraints, and integration challenges within layered defence architectures. Moreover, AI-driven beam control, compact power sources, and feasibility of space-based deployment are emerging topics that require unified treatment rather than single-domain discussion (Hanák et al. 2024). This review responds to these gaps by examining **laser weapon technologies, material interaction mechanisms, propagation challenges, integration in tactical air-defence systems, and future strategic pathways**. By synthesizing engineering, materials science, and operational perspectives, the paper aims to support a clearer understanding of the opportunities, limitations, and research directions shaping the future of laser-directed energy warfare. Figure 1 depicts the integration of high-energy lasers into a layered air defence system. Radar units provide early detection and tracking of UAVs, loitering munitions, and cruise missiles. Missile batteries and CIWS form the kinetic layers, while laser DEWs engage low-altitude, fast-moving targets with near-instant response. The arrangement underscores the complementary role of lasers in short- to medium-range defence, enhancing flexibility and reducing engagement costs. As illustrated in **Figure 1**, laser-based directed energy weapons are integrated within a layered air-defence architecture alongside kinetic interceptors and sensor networks.

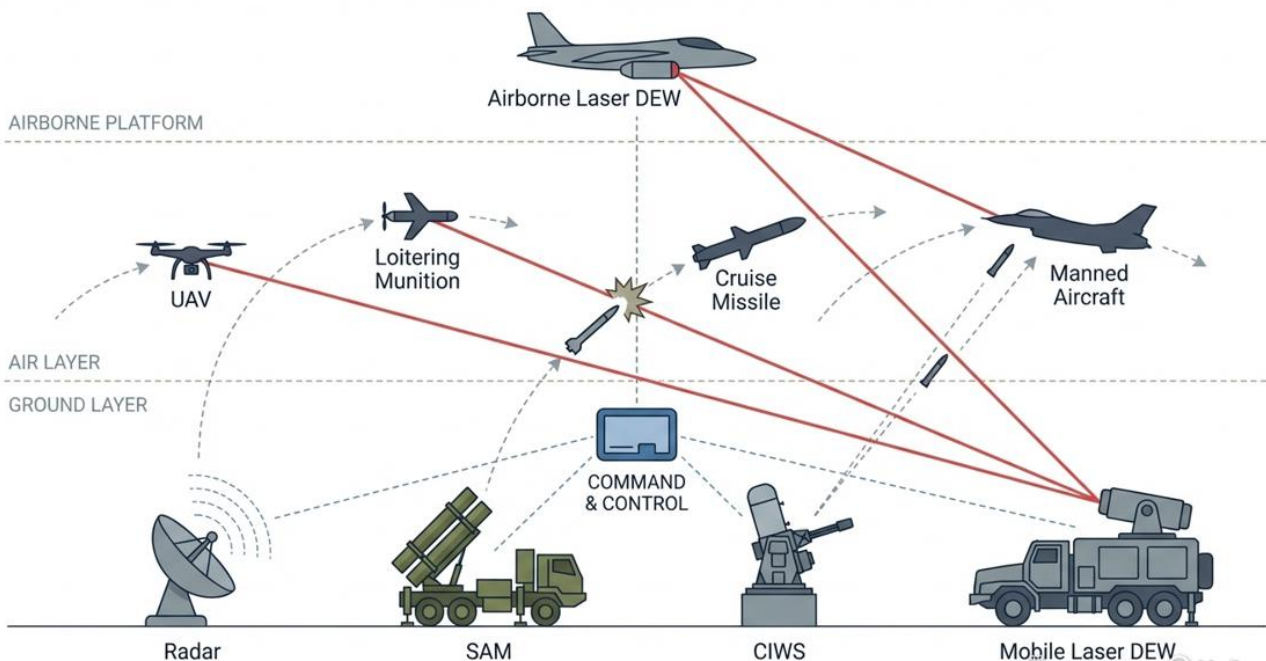


Figure 1. Multi-layered air-defence architecture integrating laser-based directed energy weapons (DEWs) alongside kinetic interceptors and sensor networks. The schematic illustrates the complementary role of naval, land, and airborne laser systems in countering diverse aerial threats including UAVs, loitering munitions, cruise missiles, and manned aircraft through rapid, precision, and cost-efficient engagement within a layered command-and-control framework. *Source: Author’s own conceptual classification.*

1.1. Literature Review and Novelty Justification

Research on Directed Energy Weapons (DEWs) has expanded significantly over the past two decades, progressing from laboratory-scale demonstrations to early-stage operational deployment. Early foundational texts such as **Phipps (2007)** established the physics of laser ablation and the conditions that govern material removal, while **Adams and Schallhorn (2016)** outlined the first broad overview of DEW concepts, system components, and emerging military applications. These works are historically important but were published before recent shifts in combat requirements, particularly the rise of low-cost UAV swarms and the demand for mobile high-energy platforms. Strategic and governmental assessments from **HEL-JTO (2020)**, **NATO STO (2019; 2020)** and the **US National Academies (2008)** examined the military relevance and potential advantages of DEWs. However, these studies largely focused on feasibility and strategic posturing and did not attempt to compare performance across different laser technologies or operational environments. Manufacturer briefs, including those from **Lockheed Martin (2022)** and **Rafael (2023)**, provide updated performance claims but remain platform-specific and commercially selective. A substantial body of literature addresses atmospheric propagation and its challenges (e.g., **Andrews and Phillips, 2005; Weichel, 1990; Roth and Monjardet, 2018; Liu, Chen and Xu, 2022**). More recent work has shifted from theoretical degradation models toward practical compensation techniques, including adaptive optics and predictive control (**Nguyen, Park and Kim, 2023; Lin, Chen and Wu, 2023**). Yet, these studies typically examine propagation in isolation and do not incorporate how material behaviour, beam shaping, energy storage or targeting doctrine interact in real operational settings. Research into material survivability and coatings has gained relevance with the adoption of composites and additive manufacturing in defence structures (**Zhang et al., 2025; Voynov et al., 2021**). Power requirements and thermal limits for intercepting missiles and drones have also been quantified (**Benford, Benford and Satori, 2021**), while solutions for energy storage and platform cooling continue to evolve (**Fedorov, Zhang and Wang, 2024; Amini, Zhao and Karimi, 2024**). However, these contributions remain scattered across materials science, thermal engineering, and defence operations leaving decision-makers without a consolidated engineering-to-tactics perspective. The rapid rise of AI-enabled targeting, wavefront correction and autonomous decision-making now represents a major frontier area in DEW development (**Patel and Srinivasan, 2024; Wang, Chen and Luo, 2022; Nickel et al., 2015; Wilcke et al., 2017**). While these works demonstrate promise, they are not yet incorporated into most published DEW reviews, and their implications for real-world deployment are still evolving. Studies that discuss tactical integration and layered air defence (e.g., **Farlik and Tesar, 2018; Roux and Van Vuuren, 2007; Kline, Ahner and Lunday, 2019; Chen et al., 2020; Ho et al., 2022**) highlight gap: traditional modelling frameworks treat weapons as interchangeable interceptors, without accounting for unique DEW factors such as dwell time, coherence losses, or cost-per-engagement dynamics. As a result, the literature provides insights into resource allocation but does not present a unified view of how DEWs reshape tactical doctrine. Finally, while market forecasts and defence briefings (**GAO, 2023; Precedence Research, 2024; Army-Technology, 2025**) confirm increasing investment, there is limited scholarly analysis comparing national strategies or technology maturity. The emerging discussion around **space-based DEW systems (Baccarelli et al., 2023)** suggests a future where laser defence becomes part of orbital deterrence, yet no consolidated framework links current terrestrial capabilities to these longer-term ambitions.

This review advances the state of existing literature in four ways:

- **It connects physics, atmospheric effects, and tactical integration**
Instead of treating ablation, propagation, and platform constraints independently, this review presents a combined model of *how laser energy translates to operational outcomes* under real-world environmental variables.
- **It offers a cross-national capability and roadmap comparison**
Most previous literature focuses on single-nation programs. This review compares approaches across the US, Israel, NATO initiatives, China, and India capturing both divergence and convergence in strategy.
- **It incorporates the newest developments in AI, autonomy, and beam control**
These areas have emerged only in the last few years and are largely absent from earlier reviews.
- **It positions DEWs within modern layered air defense systems, not as standalone weapons**

2. Types of Laser-Based Directed Energy Weapons

Laser-based Directed Energy Weapons (DEWs) are primarily distinguished by their **laser generation mechanism, gain medium, and deployment platform**, each of which governs achievable power levels, beam quality, efficiency, and operational suitability. Different laser technologies exhibit distinct advantages and limitations depending on mission requirements such as engagement range, dwell time, platform mobility, and thermal management capability. The four principal laser approaches currently shaping global DEW development **solid-state, chemical, fibre, and free-electron lasers** are discussed below together with their representative land-, naval-, and airborne applications.

2.1 Solid-State Lasers (SSL)

Solid-state lasers employ crystalline or glass-based gain media, such as Nd: YAG or Yb: YAG, and typically operate in the near-infrared region around **1.06 μm** . These systems are valued for their **compact form factor, mechanical robustness, and relatively simple architecture**, making them well suited for mobile and distributed defence platforms. Advances in diode pumping have significantly improved electrical efficiency and beam stability; however, **thermal management remains a key constraint** under sustained high-power operation. Solid-state laser technology underpins several counter-drone and short-range defence demonstrators, including vehicle-mounted systems such as the U.S. Army's HELMTT program, and remains relevant across land-based, naval, and limited airborne applications.

2.2 Chemical Lasers

Chemical lasers generate laser radiation through highly energetic chemical reactions, such as hydrogen–fluorine (HF), deuterium–fluorine (DF), or chemical oxygen–iodine (COIL) processes, enabling **megawatt-class output power**. The most prominent demonstration of this capability was the YAL-1 Airborne Laser program, which validated boost-phase missile interception. However, reliance on **toxic reactants, bulky fuel storage, complex logistics, and stringent safety requirements** has significantly reduced the attractiveness of chemical lasers for modern operational deployment. Consequently, chemical lasers are now regarded primarily as **legacy or experimental systems**, with current DEW development efforts shifting decisively toward electrically powered laser architectures.

2.3 Fibre Lasers

Fibre lasers utilize rare-earth-doped optical fibres most commonly ytterbium or erbium as the gain medium, producing output wavelengths in the **1.0–1.1 μm range**. They offer **high electrical-to-optical efficiency (35–45%)**, excellent beam quality, and enhanced thermal dissipation owing to their large surface-area-to-volume ratio. Crucially, fibre lasers can be scaled through **coherent beam combining**, enabling substantial power growth without severe degradation in beam quality. These attributes have positioned fibre lasers at the core of contemporary DEW programs, including the U.S. Navy's HELIOS system and the DE M-SHORAD vehicle-mounted platform. Recent advances in multi-core and phase-controlled fibre architectures have pushed

operational power levels beyond the **300-kW class**, establishing fibre lasers as the leading candidates for near-term, multi-platform DEW deployment.

2.4 Free-Electron Lasers (FEL)

Free-electron lasers generate coherent radiation using a relativistic electron beam passing through a magnetic undulator, rather than a conventional solid or gaseous gain medium. This architecture enables **broad wavelength tunability**, ranging from infrared to X-ray regimes, and theoretically allows extremely high output power without traditional material-based thermal constraints. Despite these advantages, FEL systems remain **largely experimental** due to the substantial size, mass, power demand, and complexity of the required particle accelerators, cryogenic subsystems, and beam-control infrastructure. As a result, FEL research has been primarily confined to **naval or fixed experimental facilities**, where power availability and spatial constraints are less restrictive. Current technology readiness levels indicate continued research rather than near-term operational deployment.

2.5 Delivery Platforms

Land-Based Systems: Ground-based DEW platforms are particularly suited to tactical and short-range defence missions, including counter-UAV, loitering munition, and low-altitude threat interception. Vehicle-mounted architectures such as HELMTT (United States) and ADITYA (India) demonstrate the feasibility of mobile laser defence, while Israel’s Iron Beam highlights the effectiveness of ground-based fibre laser systems as cost-efficient complements to missile-based air-defence architectures.

Naval Systems: Naval vessels represent highly favourable DEW platforms due to their **substantial onboard power generation, cooling capacity, and structural volume**. Shipborne systems such as LaWS and HELIOS have demonstrated successful engagement of UAVs and fast-attack craft, integrating laser weapons with electro-optical sensors, radar, and ISR networks for sustained maritime defence operations.

Airborne Systems: Airborne laser platforms offer extended line-of-sight and early-phase interception capability, particularly against missiles and high-value aerial threats. The YAL-1 COIL program marked a major milestone in boost-phase missile defence, while ongoing research focuses on **compact 50–100 kW class electrically powered lasers** deployable on large UAVs and fighter aircraft. Among current technologies, **fibre lasers exhibit the most favourable scalability and efficiency for airborne applications**, as reflected in the platform mapping shown in Figure 2.

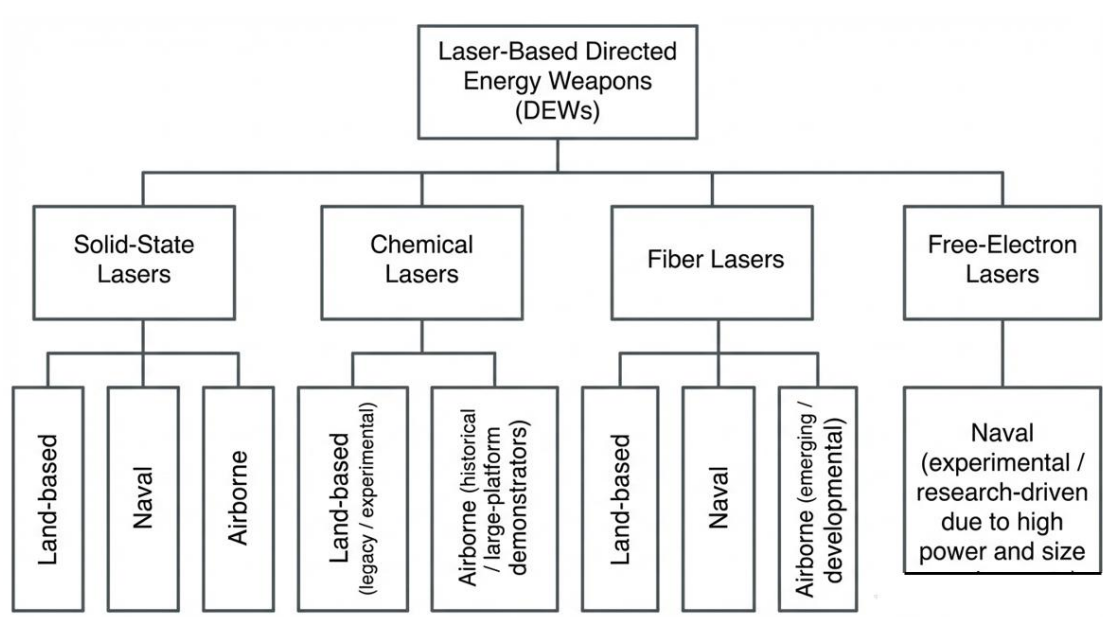


Figure 2. Hierarchical classification of laser-based Directed Energy Weapons (DEWs) according to laser generation mechanism, gain medium, and realistic platform-level deployment. The schematic differentiates solid-state, chemical, fibre, and free-electron laser

technologies and maps their suitability to land-based, naval, and airborne systems based on power scalability, system compactness, thermal management demands, and logistical constraints. Solid-state and fibre lasers exhibit the broadest applicability across multiple platforms, whereas chemical and free-electron lasers are constrained by hazardous reactants or system complexity, confining their use primarily to legacy, experimental, or specialized naval and airborne roles. The classification highlights the key technological and operational trade-offs that influence strategic adoption pathways for DEW architectures. Table 1 provides a comparative summary of the four laser technologies, including wavelength, output power, efficiency, applications, and principal advantages and limitations, serving as a baseline for evaluating platform suitability across diverse defence scenarios. *Source: Author's own conceptual classification based on published literature.*

Table 1. Comparative performance characteristics of major laser weapon types, categorized by wavelength, output power, energy efficiency, operational advantages, and key limitations. The summary highlights the contrasting power scalability, logistical demands, and platform suitability of solid-state, chemical, fibre, and free-electron lasers. Fibre and solid-state lasers demonstrate the most viable pathways for near-term deployment due to compact architectures and electrical operation, whereas chemical and free-electron lasers remain constrained by hazardous reactants, system complexity, and integration challenges for mobile defence platforms. (Source :Author's compilation based on published literature.)

Laser Type	Wavelength (µm)	Power Output	Efficiency (%)	Current/Notable Use	Advantages	Limitations
Solid-State (SSL)	~1.06 (Nd:YAG), 1.03 (Yb:YAG)	10s to 300+ kW	20–30%	HELMITT (US Army), ADITYA (DRDO), Rheinmetall 20kW+	Compact, modular; solid gain medium; scalable	Heat accumulation; limited continuous output
Chemical Lasers	2.7–3.8 (HF/DF), 1.315 (COIL)	Up to 1 MW	~10–15%	YAL-1 ABL (Boeing 747 COIL – retired), MIRACL	High peak power; long-range engagement potential	Toxic fuels, bulky, logistical & handling hazards
Fiber Lasers	1.03–1.08 (Yb-doped)	50 to 300+ kW (scalable via beam combining)	35–45%	HELIOS (US Navy), DE M-SHORAD (US Army), Lockheed ATHENA	High beam quality; high efficiency; compact footprint	Thermal saturation; limited to CW modes at scale
Free Electron Laser (FEL)	Broad tunability: UV–IR–X-ray	Potentially MW-class (experimental)	N/A (electrical + particle beam)	U.S. Navy R&D (ONR, FEL-N)	Tunable wavelength; potentially unlimited power; no traditional gain medium	Very large system size; complex cryogenics; not yet fieldable

3. LASER–MATERIAL INTERACTION AND TARGET RESPONSE

The effectiveness of laser-based Directed Energy Weapons (DEWs) is fundamentally determined by how high-energy beams interact with target materials. These interactions are governed by laser ablation physics, where incident energy induces rapid heating, phase transitions, and progressive structural degradation. A clear understanding of these mechanisms is critical for estimating time-to-kill (TTK), selecting optimal engagement parameters, and evaluating material vulnerability across different classes of defence systems and aerospace structures.

3.1 Laser Ablation Physics

When a focused laser beam impacts a surface, absorbed photon energy is rapidly converted into heat, initiating a sequence of thermophysical events:

1. **Thermal Conduction:** Heat diffuses into the surrounding material within microns of the surface, influenced by thermal diffusivity, beam intensity, and pulse duration.
2. **Melting:** Continued energy deposition raises surface temperature beyond the melting point, resulting in softening, reflow, or deformation of the structure.
3. **Vaporization:** Once vaporization thresholds are exceeded, material is ejected through vapor plumes or melt expulsion, accelerating mass loss.
4. **Plasma Formation:** At sufficiently high-power densities, vaporized material ionizes into plasma, which can either shield the target or destabilize ablation depending on beam parameters.

The dominant damage mechanism—whether melting, cracking, delamination, spallation, or explosive ablation—is determined by a combination of beam characteristics (wavelength, power density, exposure duration) and intrinsic material properties (thermal conductivity, reflectivity, absorptivity, and phase-transition thresholds).

3.2 Effects on Aircraft Skins and Structural Materials

Modern aircraft, UAVs, and munitions employ lightweight structural materials that exhibit varied thermal responses and failure modes under high-energy laser exposure:

- **Aluminium Alloys (e.g., Al-2024, Al-7075):** While initially reflective in the near-infrared spectrum ($\sim 1.06 \mu\text{m}$), absorption increases rapidly with surface heating and oxide formation. Once melting begins at approximately $660 \text{ }^\circ\text{C}$, high thermal conductivity promotes rapid heat spread, leading to softening and perforation within seconds under power densities exceeding 10 kW/cm^2 .
- **Carbon-Fibre Reinforced Polymers (CFRP):** CFRP exhibits high optical absorption but poor thermal conductivity. This leads to localized thermal runaway, matrix decomposition, fibre delamination, and surface spallation—often resulting in structural failure more quickly than metallic alloys exposed to similar laser flux.
- **Titanium Alloys:** Titanium offers higher melting temperature ($\sim 1650 \text{ }^\circ\text{C}$) and lower thermal conductivity compared to aluminium, enabling greater resistance to short

exposures. However, prolonged or high-intensity irradiation eventually induces localized melting, deformation, and conduction-driven failure.

These material-specific responses emphasize the importance of tailoring laser parameters and engagement strategies to the composition and geometry of the target. Composites and thin-walled structures are particularly vulnerable, whereas high-performance metallic alloys exhibit increased resilience but remain susceptible under sustained high-energy exposure. As shown in **Figure 3**, anisotropic fibre orientation contributes to delamination and plume-induced ejection.

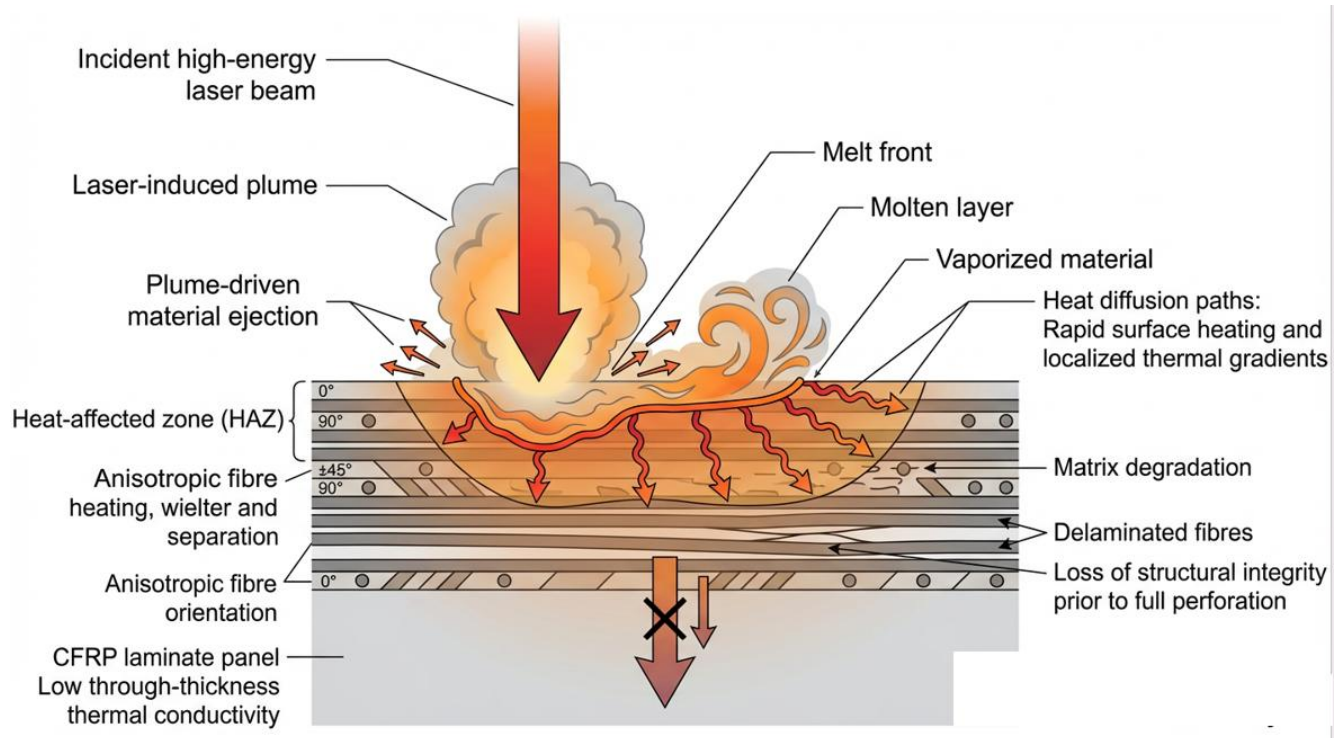


Figure 3. Conceptual schematic of thermal ablation in carbon fibre reinforced polymer (CFRP) composites under high-energy laser irradiation. The model illustrates rapid surface heat absorption, melt-front evolution, matrix degradation, and fibre delamination within the heat-affected zone (HAZ). The inherent layered anisotropy and low through-thickness thermal conductivity of CFRP promote localized thermal runaway and plume-driven material ejection, leading to a progressive loss of structural integrity prior to complete perforation. This schematic highlights the role of material-specific ablation thresholds and failure mechanisms in assessing the vulnerability of aerospace composite structures subjected to directed-energy exposure.

Source: Author's own conceptual illustration based on published literature.

3.3 Effects on Drones, Missiles, and Projectiles

Laser-based Directed Energy Weapons (DEWs) are particularly effective against aerial threats characterized by **thin-walled structures, exposed sensors, and temperature-sensitive electronic subsystems**. Such features reduce the energy and dwell time required to achieve

functional disruption or structural degradation, even in the absence of complete material perforation.

- Mini-UAVs and Commercial Drones:** Miniature UAVs and commercial drones are typically constructed from polymer-based materials, CFRP components, and thin aluminium skins, resulting in **low thermal mass and limited heat dissipation capability**. Continuous-wave laser systems in the **30–50 kW power range** can induce material degradation or localized penetration within a few seconds at engagement ranges below approximately **1 km**, provided adequate beam stabilization. In many cases, **mission kill** occurs prior to full skin perforation due to overheating of onboard electronics, wiring harnesses, battery packs, or electro-optical payloads, leading to loss of propulsion, guidance, or control.
- Mortars and Artillery Projectiles:** Mortars and artillery shells present smaller target cross-sections and shorter engagement windows; however, laser irradiation can still induce functional disruption through **rapid heating of fuzes, casings, or aerodynamic surfaces**. Sustained dwell time is typically required to produce sufficient thermal gradients for casing deformation, fuze malfunction, or destabilization of the projectile’s flight path, which may compromise tracking stability and terminal accuracy without necessarily initiating the explosive fill.
- Cruise Missiles:** Although cruise missiles are generally more robustly constructed, many designs incorporate **aluminium alloys or composite radomes** and external control surfaces that remain vulnerable to laser-induced ablation. Effective engagement against **high-speed and manoeuvring targets** requires precise beam pointing, real-time stabilization, and predictive tracking algorithms to maintain sufficient dwell time on critical subsystems. Localized heating of guidance sensors, radomes, or control surfaces can lead to degraded navigation performance or loss of aerodynamic stability.

Representative material damage thresholds and estimated time-to-kill (TTK) values for commonly encountered aerospace materials are summarized in **Table 2**. These values are derived from controlled experimental studies or simulation-based analyses and should be interpreted as **order-of-magnitude estimates**. Actual operational performance will vary significantly with atmospheric attenuation, beam divergence, target motion, engagement geometry, and laser beam stabilization capability.

Table 2. Ablation thresholds and estimated time-to-kill (TTK) for representative aerospace materials under high-energy laser exposure. (Author’s synthesis and order-of-magnitude estimates based on published experimental and simulation studies.)

Material	Thickness	Ablation Threshold (W/cm² or J/cm²)	Estimated Time to Kill (at 50–100 kW)	Dominant Failure Mode
Al 7075 Alloy	3 mm	~10–12 J/cm ² (CW); ~2,000–2,500 W/cm ²	3–7 sec	Melting, structural softening

CFRP (Epoxy Matrix)	2 mm	~5–7 J/cm ² ; ~1,500–1,800 W/cm ²	2–4 sec	Delamination, thermal spallation
ABS Plastic (Drone Skin)	1.5 mm	~2–4 J/cm ² ; ~1,000 W/cm ²	<2 sec	Charring, surface melting
Titanium Ti-6Al-4V	2 mm	~15–20 J/cm ² ; ~3,000–4,000 W/cm ²	6–10 sec	Surface melting, conduction-driven failure
Borosilicate Glass (Radome)	4 mm	~18 J/cm ² ; ~2,500–3,000 W/cm ²	5–8 sec	Cracking, explosive ablation

Note: Actual lethality outcomes depend on beam diameter, dwell duration, pointing precision, atmospheric loss, and target manoeuvrability. These figures should be interpreted as indicative ranges for design and modelling purposes rather than fixed operational performance.

3.4 Atmospheric and Beam Parameter Considerations

Laser–material interaction is influenced not only by intrinsic thermal and optical properties of the target but also by environmental and beam-specific parameters. Humidity, airborne particulates, and precipitation reduce delivered energy through absorption and scattering, while beam spot size, coherence, jitter, and focal stability govern how effectively energy is deposited on target surfaces. Thermal blooming, produced by localized air heating along the beam path, can defocus or distort high-power continuous-wave lasers, necessitating compensation through adaptive optics or power modulation. Furthermore, rapidly moving or rotating targets require precise beam steering and predictive control to sustain effective dwell time. Lightweight and low-conductivity materials such as CFRP degrade more rapidly under thermal loading, whereas high-performance alloys exhibit delayed but eventual failure under sustained exposure. Accurate modelling of heat transfer, phase transitions, and plume dynamics remains essential for both weapon development and countermeasure planning.

4. ENVIRONMENTAL PROPAGATION AND COUNTERMEASURES

The real-world performance of laser-based DEWs is strongly influenced by atmospheric propagation. Unlike kinetic projectiles, which travel independently of medium clarity, laser beams are affected by water vapor, dust, aerosols, and thermal gradients that alter the amount and distribution of energy arriving at the target.

4.1 Atmospheric Attenuation Mechanisms

Infrared laser systems (1.03–1.06 μm), typically employed in solid-state and fibre architectures, experience attenuation through multiple mechanisms:

- **Aerosol and Dust Scattering:** Smoke, dust, and pollution scatter laser energy (Mie scattering) depending on particle size and concentration.

- **Fog and Rain Absorption:** Water droplets significantly absorb and scatter energy; dense fog may reduce transmission by over 90%, while rain produces moderate yet disruptive loss.
- **Thermal Blooming:** Localized air heating changes the refractive index, causing beam defocus and reduced spot intensity.
- **Turbulence and Beam Wander:** Temperature gradients, wind shear, and battlefield effects induce phase distortion and pointing instability.

These factors reduce effective range and highlight the need for dynamic compensation strategies such as adaptive optics, wavelength optimization, and pulsed-beam operation. As illustrated in **Figure 4**, aerosol scattering disrupts beam coherence even at moderate concentrations.

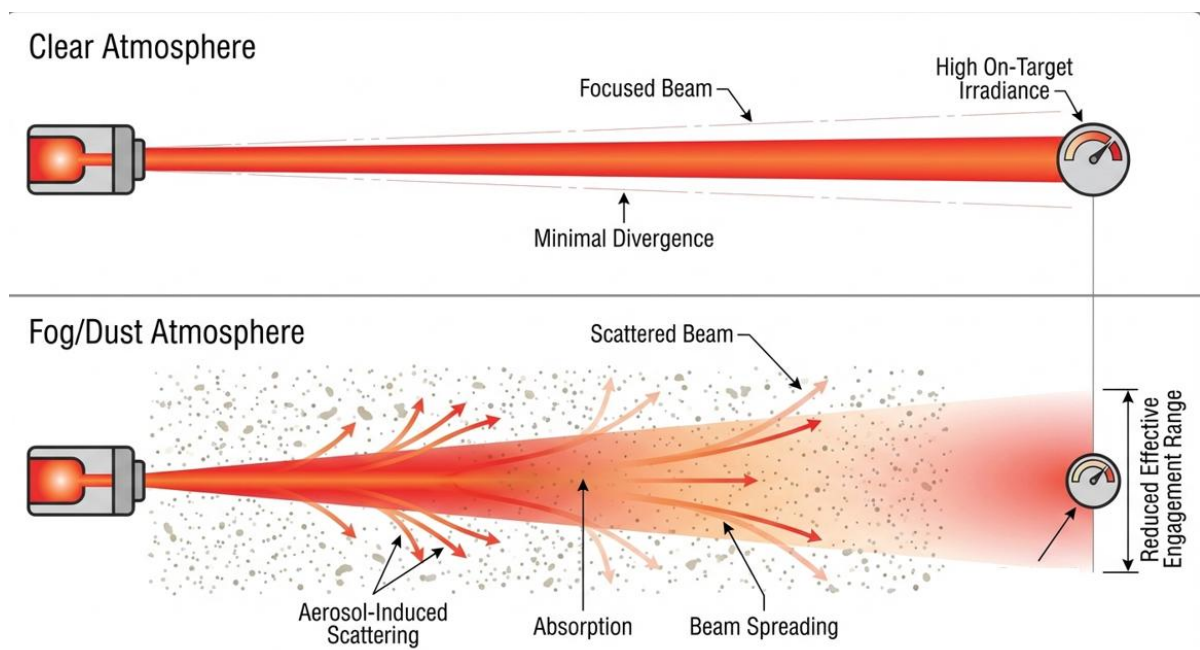


Figure 4. Comparative depiction of laser beam propagation under clear and degraded atmospheric conditions. In clear air, high-energy lasers maintain beam coherence and power density, enabling precise long-range engagement. In fog, smoke, or dust-laden environments, aerosol scattering and absorption disperse the beam, reducing on-target irradiance and effective lethality. Reported attenuation in dense fog and battlefield smoke can exceed 30 dB/km, significantly limiting engagement range unless mitigated through adaptive optics, wavelength selection, or beam-combining strategies. *Source: Author's own conceptual illustration.*

4.2 Countermeasures and Beam Control Techniques

A range of countermeasures has been developed to sustain DEW effectiveness in challenging atmospheric environments where scattering, absorption, and turbulence degrade beam quality. Key approaches include:

- **Adaptive Optics (AO):** Real-time wavefront sensing combined with deformable mirror correction enables compensation for turbulence-induced distortion, enhancing focus and long-range energy delivery. Originally developed for astronomical imaging, AO is now being adapted for naval and land-based laser weapon systems.

- **Beam Shaping and Combining:** Coherent beam combining and phase locking merge multiple lower-power lasers into a single, high-quality beam, improving resilience against phase noise and atmospheric perturbation. This approach extends engagement range and reduces the impact of single-beam divergence.
- **Wavelength Tuning:** Different atmospheric conditions exhibit unique absorption and scattering profiles. Fibre-based lasers operating in the 1.03–1.08 μm band demonstrate improved propagation in fog and haze compared to mid-IR chemical systems. Free-electron lasers offer future potential through real-time tunability to atmospheric transmission windows.
- **Pulsed vs Continuous-Wave Operation:** Pulsed laser operation produces intense, short bursts of energy that limit cumulative heating of air molecules and mitigate thermal blooming. This can be particularly advantageous against moving or rotating targets where continuous dwell is difficult to maintain.

The performance benefits of these countermeasures under representative field conditions are summarized in **Table 3**.

Table 3. Atmospheric attenuation levels and associated countermeasure effectiveness for representative battlefield conditions. (Author’s synthesis based on published atmospheric propagation models and experimental studies.)

Environmental Condition	Typical Attenuation (dB/km)	Countermeasure Efficiency (AO / Beam Shaping)
Clear Air (Standard Atmosphere)	~0.1–0.3	>95% (beam maintains full effectiveness)
Light Rain	~1.0–3.0	80–90% (AO supplemented by pulse operation)
Heavy Rain	~5.0–10.0	60–75% (effective primarily at shorter ranges)
Moderate Fog	~10–20	40–60% (fibre lasers exhibit improved performance)
Dense Fog / Battlefield Smoke	>30	<30% (operational range typically <500 m)
Dust Storm / Desert Winds	~10–15	50–65% (CBC and shielding recommended)
High Turbulence (Desert/Urban Ops)	Phase distortion not measured in dB	70–85% (adaptive optics critical)

Countermeasure efficiency values represent generalised estimates based on controlled testing and simulations; real-world performance may vary.

Achieving sustained line-of-sight engagement remains a key operational challenge in complex environments. Urban structures, uneven terrain, and target manoeuvrability restrict beam accessibility. Turbulence from thermal gradients, explosions, or wind shear further degrade

beam coherence, contributing to phenomena such as thermal blooming and beam wander. Consequently, modern DEW systems must incorporate high-speed beam control, environmental sensing, and predictive tracking to maintain lethality under non-ideal conditions.

4.3 Operational Implications

Atmospheric effects represent one of the most significant constraints on the operational reliability of laser weapons. Nonetheless, ongoing advancements in adaptive optics, atmospheric compensation algorithms, and real-time wavelength optimization are increasing resilience across diverse combat environments. Naval platforms benefit from relatively stable marine microclimates and abundant power and cooling capacity, whereas land-based systems must accommodate greater variability in dust, humidity, and terrain-driven line-of-sight restrictions. Future DEW deployments will rely heavily on environment-aware targeting solutions, integrated sensor fusion, and predictive engagement models to ensure consistent performance across changing battlefield conditions.

5. TACTICAL INTEGRATION INTO AIR DEFENCE SYSTEMS

Laser-based DEWs are emerging as essential components of short-range and point-defence architectures, especially against low-cost, expendable aerial threats such as UAVs, loitering munitions, and RAM projectiles. Their near-zero cost-per-shot, instantaneous engagement, and large effective magazine size complement traditional missile interceptors and extend the capacity of layered defence systems.

5.1 Role in SHORAD

- **UAVs and Drones:** High-energy lasers can disable Class I–III drones by targeting propulsion systems, guidance electronics, or structural components. Systems including the U.S. DE M-SHORAD and Israel’s Iron Beam demonstrate cost-efficient neutralization of UAV swarms.
- **Loitering Munitions:** Directed energy offers precise defeat mechanisms with reduced collateral effects critical in urban or infrastructure-sensitive environments.
- **RAM Threats:** High-power DEWs show promise against mortar shells and slow-moving projectiles within 1–3 km, serving as a complementary layer to kinetic intercept systems.

5.2 Integration with C4ISR

Effective deployment of DEWs requires seamless integration into command, control, communications, computers, intelligence, surveillance, and reconnaissance (C4ISR) frameworks:

- **Radar Systems:** AESA and 3D radars provide initial detection, tracking, and engagement cueing.
- **EO/IR Sensors:** Enable multi-spectral target confirmation, beam alignment, and damage assessment.

- **AI-Based Fire Control:** Enhances threat prioritization and closed-loop tracking, enabling concurrent coordination with surface-to-air missiles and close-in weapon systems within layered defence networks. The layered defence network (Image 6) demonstrates the operational value of distributed intercept systems.

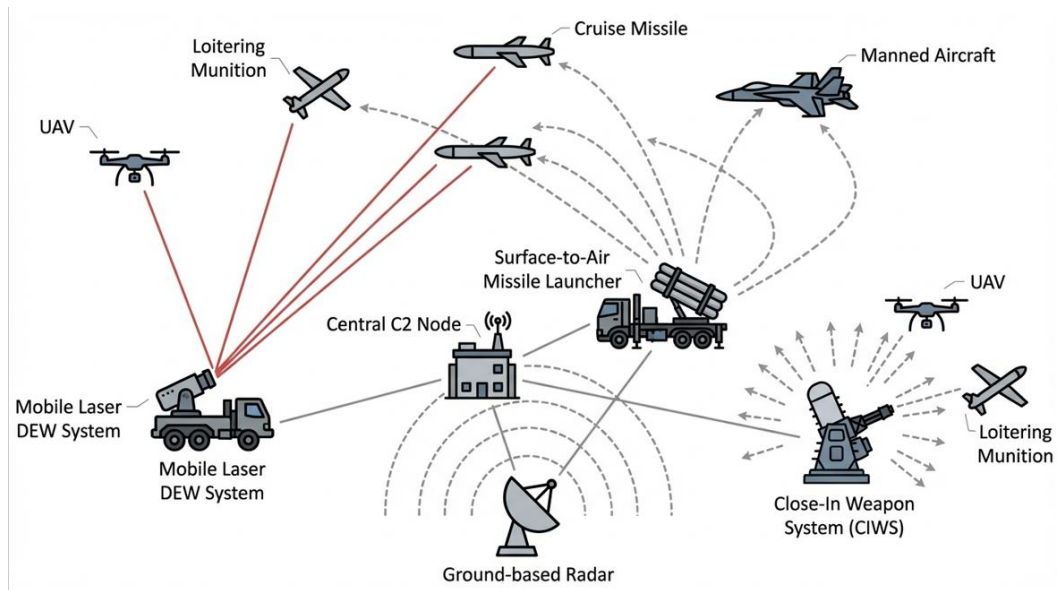


Figure 5. Layered air defence architecture integrating Directed Energy Weapons (DEWs), Surface-to-Air Missiles (SAM), Close-In Weapon Systems (CIWS), and radar-based command and control. *Source: Author's own conceptual illustration .*

Figure 5 illustrates a modern multi-layered air defence system. A central radar unit provides situational awareness and real-time tracking to all defence nodes. The Directed Energy Weapon (DEW) neutralizes UAVs and loitering munitions with precise laser engagement. Surface-to-Air Missiles (SAM) are deployed to intercept cruise missiles at medium-to-long range, while Close-In Weapon Systems (CIWS) represent the last line of defence against close-proximity threats. The red dashed connections denote integrated targeting and sensor communication links, highlighting coordinated response capability and layered coverage for airspace security.

5.3 Reaction Time and Kill Chain Compression

Laser Directed Energy Weapons (DEWs) significantly reduce engagement timelines and close the kill chain faster than kinetic interceptors:

- **No Reloading:** Laser systems require no physical ammunition, resulting in zero reload cycles and providing uninterrupted engagement capability against massed or swarm attacks.
- **Instant Engagement:** Light-speed beam delivery produces effects within milliseconds, making DEWs highly effective in short-range, time-critical, and saturation scenarios.
- **Compressed Kill Chain:** Integration with radar and electro-optical (EO) sensors, combined with automated target tracking, streamlines the *Detect–Engage–Assess* loop and reduces human-induced response latency.

The comparative performance of Laser DEWs, Surface-to-Air Missiles (SAMs), and Close-In Weapon Systems (CIWS) is summarized in **Table 4**.

Table 4. Comparative Performance of Laser DEWs, SAMs, and CIWS (Author’s own synthesis based on published defence system studies and operational reports.)

Metric	Laser DEW	Surface-to-Air Missile (SAM)	Close-In Weapon System (CIWS)
Engagement Range	1–5 km (tactical systems)	5–100+ km (system-dependent)	0.5–2.5 km
Reaction Time	<1–2 seconds (light-speed + auto-tracking)	5–15 seconds (radar lock + missile launch)	2–5 seconds (cueing + barrel spin-up)
Cost Per Shot	<\$5–10 (electrical energy only)	\$30,000 to >\$1 million	~\$2,000–\$4,000 per burst
Magazine Depth	Virtually unlimited	Finite (launcher capacity)	Limited (ammo belt/drum)
Effect on Target	Thermal ablation, ignition, sensor damage	Blast-fragmentation, kinetic hit	Kinetic fragmentation
Collateral Damage	Minimal (localized energy)	High (blast radius)	Moderate (overshoot/stray rounds)
Weather Sensitivity	High (fog, dust, rain)	Low (all-weather capable)	Low
Maintenance	Moderate (optics and cooling)	High (fuel, storage, missiles)	High (barrel and electronics)

UAV Swarm Neutralization

In short-range conflicts, swarming UAVs are designed to overwhelm kinetic defenses through numerical saturation. Unlike SAM or CIWS platforms constrained by reload time and magazine limits, high-energy lasers with radar/EO tracking engage multiple UAVs at light-speed. By burning electronics and structural components, DEWs deliver precise, low-collateral kills. Demonstrated by systems such as **DE M-SHORAD** and **Iron Beam**, this capability underscores the operational value of DEWs for sustained counter-UAV and base-defense missions in layered air defense architectures.

5.4 Operational Deployments and Examples

Several integrated air defense systems incorporating DEWs are already in field trials or limited deployment:

- **Israel – Iron Beam (Rafael):** Complements Iron Dome with a ~100 kW-class laser for short-range intercepts.

- **United States Army – DE M-SHORAD:** A 50-kW laser mounted on Stryker vehicles to counter UAVs and RAM threats.
- **India – ADITYA DEW Program:** DRDO initiative for laser-based defense against drones and low-altitude missiles.
- **U.S. Navy – LaWS (Laser Weapon System):** Demonstrated shipborne integration with radar and EO targeting to defeat drones and small boats.

Laser DEWs provide a critical layer in modern air defense by enabling **low-cost-per-shot, low-collateral, and rapid-response engagement**. Their integration with radar-guided, EO-enhanced, and AI-augmented fire-control networks ensures synergy with SAM and CIWS, enabling scalable, multi-domain protection against evolving aerial threats.

6. Challenges and Technological Bottlenecks

Despite rapid progress, the operational deployment of laser-based Directed Energy Weapons (DEWs) remains constrained by several **interdependent engineering and system-level challenges**, primarily associated with power generation, thermal management, beam control, and safety. These bottlenecks collectively limit scalability, platform integration, and sustained operational availability.

6.1 Power Generation and Storage

High-energy laser systems typically require **tens to hundreds of kilowatts of continuous electrical power**, with additional overhead for cooling and beam-control subsystems. While fixed land-based installations may draw power directly from the electrical grid, **naval and airborne platforms impose strict constraints on mass, volume, and power density**. Current lithium-ion batteries and supercapacitors provide limited endurance for sustained engagements, particularly under pulsed or burst-power demands. Emerging alternatives including hydrogen fuel cells, solid-state batteries, and compact nuclear or hybrid power sources offer improved energy density but introduce **significant challenges related to cost, safety certification, thermal integration, and platform compatibility**, delaying near-term adoption.

6.2 Thermal Management

Owing to electrical-to-optical conversion efficiencies typically in the range of **20–35% at the system level**, a substantial fraction of input energy is dissipated as waste heat during laser operation. Accumulated thermal loading can degrade optical components, induce beam distortion, and reduce system reliability. Active liquid-cooling architectures, phase-change materials, and heat exchangers are therefore essential but add considerable **mass, volume, and mechanical complexity**. Advanced solutions such as **microchannel heat exchangers, nanofluid coolants, and two-phase cooling loops** show promise; however, their long-term performance and robustness under **high-vibration, shock, and extreme-climate conditions** remain key concerns for defense deployment.

6.3 Beam Control and Target Tracking

Maintaining precise beam focus and dwell time on **high-speed, manoeuvring targets** is challenged by atmospheric turbulence, platform vibration, pointing jitter, and countermeasures

such as reflective or ablative coatings. Adaptive optics, inertial stabilization, and multi-spectral sensing architectures can partially mitigate these effects, yet **scaling beam-control systems to higher power levels without introducing latency or instability remains a critical limitation**. Effective engagement further depends on ultra-fast fire-control integration and predictive tracking algorithms capable of compensating for target motion and environmental uncertainty in real time.

6.4 Safety, Compliance, and Scalability

The deployment of high-energy laser systems introduces significant **human-safety, platform-protection, and legal considerations**, including eye-safety hazards, collateral damage risks, and compliance with international regulatory frameworks such as **CCW Protocol IV**. While demonstrator systems such as HELIOS and Iron Beam have validated operational feasibility, **widespread adoption will require modular, ruggedized architectures** that can be adapted across land, naval, and airborne platforms while maintaining safety assurance and interoperability. Extending DEW concepts toward space-based or multi-domain applications remains largely **long-term and speculative**, constrained by power availability, thermal rejection, and governance considerations. As illustrated in **Figure 6**, electrical energy in high-energy laser DEW systems is converted into optical output through multiple power-conditioning and beam-forming stages, with a substantial fraction of the input energy dissipated as waste heat.

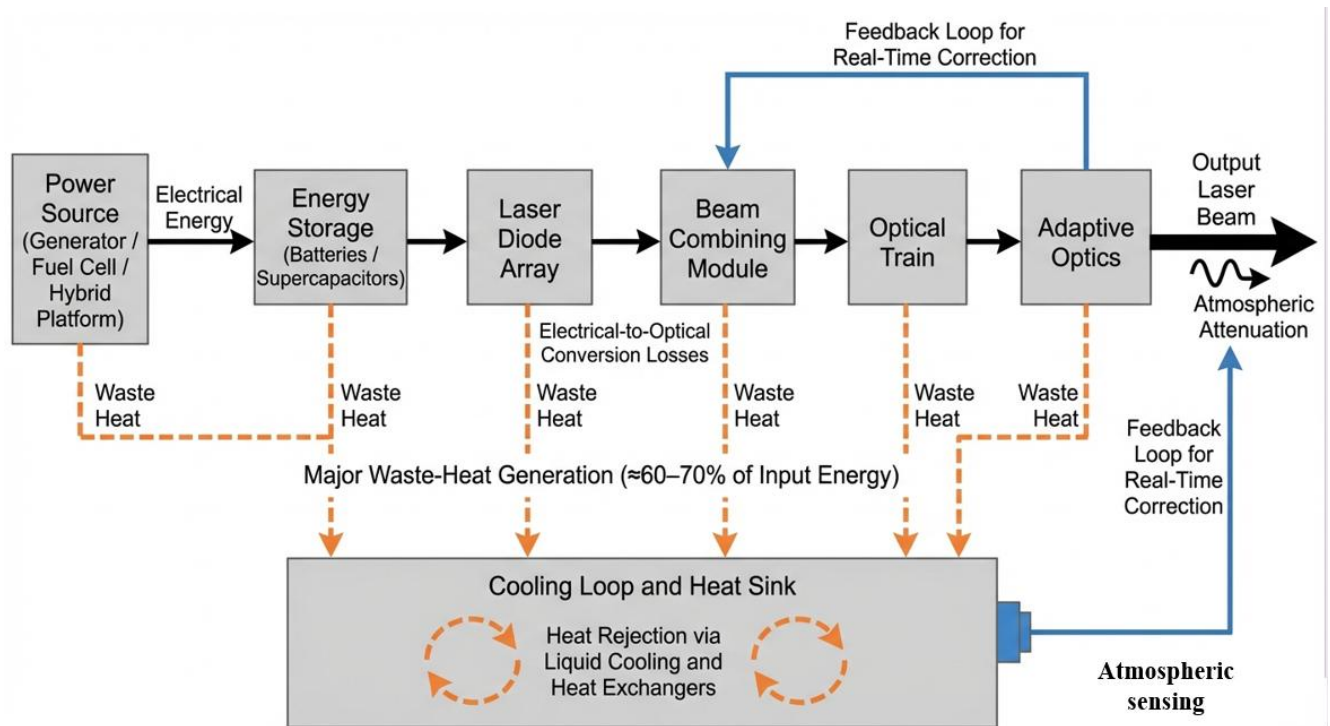


Figure 6. Conceptual energy-flow architecture and thermal loss pathways in a high-energy laser-based directed energy weapon (DEW) system. The schematic illustrates key subsystems, including power generation, energy storage, laser diode arrays, beam-combining optics, optical train, and adaptive optics for dynamic beam correction. Electrical power from generators, fuel cells, or hybrid platforms is conditioned and stored in high-discharge batteries or supercapacitors before driving the laser source. Due to electrical-to-optical conversion inefficiencies, approximately 60–70% of the input energy is dissipated as waste heat,

necessitating closed-loop liquid cooling and heat-exchanger systems to maintain optical stability. Atmospheric attenuation and thermal blooming during beam propagation are mitigated through feedback from wavefront and atmospheric sensors to the adaptive optics module, enabling real-time correction and improved engagement precision. Recent demonstrations, such as DRDO's ADITYA high-energy laser prototype, validate the feasibility of this architecture while highlighting ongoing challenges related to thermal management, compact power integration, and optical stability under high-ambient-temperature conditions. *Source: Author's own conceptual schematic based on published high-energy laser system architectures.*

7. STRATEGIC FUTURE & INDIAN ROADMAP

Laser-based Directed Energy Weapons (DEWs) are poised to reshape future warfare, extending their role from conventional air defense to space-based engagements and autonomous combat systems. For India, developing an indigenous DEW ecosystem is strategically essential for securing technological sovereignty, deterrence, and leadership in next-generation defense domains.

7.1 DRDO and ISRO Prospects

India has initiated multiple DEW programs spanning tactical and strategic applications. DRDO's **ADITYA** (25–50 kW class for UAV/artillery interception) and **CHESS** (100 kW-class for layered air defense) represent significant milestones in ground-based laser weapon development. Parallel advancements by ISRO in **laser communication** and optical tracking (e.g., GSAT payload programs) establish a foundational capability for future **space-based DEWs** and potential **anti-satellite (ASAT) systems**, supported by the Defence Space Agency's evolving role.

7.2 Role in Space Warfare

DEWs offer near-instantaneous engagement, a virtually unlimited magazine, and minimal logistical burden attributes ideally suited for countering satellites, manoeuvring debris, and hypersonic threats. However, challenges persist in **power generation, beam quality maintenance, thermal dissipation, and adherence to the Outer Space Treaty**. India's roadmap requires balancing technological ambition with regulatory alignment, responsible power projection, and coalition-driven norms.

7.3 Ethical, Legal, and Geopolitical Concerns

The proliferation of DEWs intersects with **CCW Protocol IV, Geneva Convention humanitarian provisions, and Laws of Armed Conflict (LOAC)**. New doctrines must define escalation thresholds, proportionality rules, human oversight, and autonomous decision boundaries. Regional dynamics particularly Indo-Pacific deterrence may accelerate development through diversified supply chains, **Quad-based collaboration**, and interoperable standards.

7.4 Interoperability with AI and Autonomous Systems

Future DEW systems will be deeply integrated with **AI-driven warfare architectures**. Machine learning enhances predictive beam control, threat classification, and prioritization through real-time sensor fusion. Autonomous UAV/USV swarms may form distributed defense

networks, while quantum-enhanced computing could transform adaptive optics and targeting precision. As shown in **Table 5** India’s DEW programs remain at lower Technology Readiness Levels (TRLs) relative to global leaders.

Table 5. India vs Global DEW Programs Status, Readiness, Scope (Author’s compilation and assessment based on open-source defence reports and published literature.)

Country	Program/Project	Power Class	Readiness Level (TRL)	Platform Focus	Strategic Scope
USA	HELIOS	60–150 kW (to 300 kW)	TRL 8–9	Naval, land, air	Theater defense, cruise missile, satellite security
USA	DE M-SHORAD	50 kW	TRL 7–8	Wheeled vehicles	Counter-UAV & artillery
Israel	Iron Beam	~100 kW	TRL 8	Ground	Rocket/artillery/UAV interception
China	Silent Hunter	30–100 kW	TRL 7–8	Mobile ground	ASAT & air roles
Russia	Peresvet	Classified	TRL 7–8	Mobile ground	Strategic asset protection
India	ADITYA, CHESS, MK-II(A)	2–30 kW (exp. 50–100 kW)	TRL 5–6	Ground, naval, future ASAT	Short-range UAV/air defense

India stands at a **critical inflection point** in DEW development. With a strong national research base and alignment with global best practices, India can establish leadership in both terrestrial and orbital DEW capabilities. Achieving strategic autonomy by the mid-2030s will require **synergizing power systems, advanced materials, AI-based targeting, manufacturing scale, and regulatory frameworks**. Artificial intelligence is emerging as a primary enabler of autonomous DEW engagement. Machine learning supports **real-time target classification**, distinguishes drones from missiles, and applies **predictive energy allocation** for swarms based on threat velocity and proximity. AI also stabilizes beams, automates retargeting, and modulates power levels to ensure resilience in contested electromagnetic environments. Projected subsystem readiness is outlined in **Table 6**.

Table 6. Projected Technology Readiness Levels (TRLs) for Key Laser-DEW Subsystems (2025–2035) (Author’s projected assessment based on current literature trends and technology readiness analyses.)

Subsystem/Feature	Current TRL (2025)	Projected TRL (2030)	Notes

High-Energy Lasers	Fiber	6–7	9	Near maturity in HELIOS/Iron Beam
Compact Energy Storage		5	8	Li-Air and supercaps advancing
Adaptive Optics		6	8–9	Deployment-ready in labs
AI-Based Prioritization	Threat	4–5	8	DARPA trials ongoing
Space-Based DEWs		3	6	Multiple conceptual demos

8. Discussion: Opportunities, Constraints, and Emerging Risks

The development of laser-based Directed Energy Weapons (DEWs) is the result of parallel advances in photonics, semiconductor electronics, power systems, and computational intelligence. Improvements in laser diode drivers and high-speed switching electronics (Meghelli et al., 1997; Schneibel et al., 1999; Knochenhauer et al., 2009; Moto et al., 2013; Reyaz et al., 2015) have enabled more compact and efficient laser generation, supporting the transition of DEWs from experimental demonstrators to deployable prototypes. However, scaling these components for sustained, high-power engagement introduces ongoing challenges related to thermal stability, conversion efficiency, and pulsed power reliability, particularly for mobile platforms. At the operational level, decision support and weapon–target assignment remain active areas of research. Existing optimisation models largely evolved from kinetic missile defence paradigms (Ahuja, Kumar and Jha, 2007; Lloyd and Witsenhausen, 1986; Kolitz, 1988; Roux and Van Vuuren, 2007; Bogdanowicz et al., 2012; Kline, Ahner and Lunday, 2019; Lu and Chen, 2021). While these frameworks are valuable, they do not fully reflect the unique characteristics of laser engagement such as continuous dwell requirements, sensitivity to atmospheric variation, non-linear time-to-kill behaviour, or swarm-based asynchronous threat patterns. Newer research incorporating artificial intelligence and knowledge-graph–based reasoning (Nickel et al., 2015; Wilcke et al., 2017) points toward more adaptive and predictive engagement models, though practical validation in multi-threat, electronic warfare, or GPS-denied environments remains limited. AI Reliability and Fail-Safe Governance The integration of AI-driven beam control and autonomous target evaluation introduces both opportunity and risk. Current research trends emphasize human-on-loop supervision; however, for strategic applications, a human-in-loop architecture remains critical to ensure accountability, prevent misidentification, and maintain cybersecurity resilience. AI-enabled predictive models must be transparently trained, auditable, and robust against spoofing or deceptive sensor inputs. Establishing fail-safe override logic, traceable decision logging, and ethical engagement protocols is therefore as essential as improving accuracy or reaction time. From a strategic and procurement perspective, industry and market predictions (Precedence Research, 2024; National Defense Magazine, 2025) position DEWs as cost-effective solutions for defending against low-cost, high-volume threats. These expectations are promising; however, they may overestimate near-term readiness by underplaying the logistical realities of power generation, cooling, maintenance, crew training, and lifecycle cost. The U.S. GAO

(2023) has noted that many reported performance metrics are highly scenario-dependent and may not reflect operational durability across diverse theatres. Additionally, while interest in space-based DEWs is increasing (Baccarelli et al., 2023), the supporting policy and regulatory frameworks remain emergent, particularly regarding escalation control, attribution, and rules of engagement for non-kinetic space conflict. Space-Based DEW Feasibility While space-based laser systems offer theoretical advantages in persistence, global coverage, and boost-phase interception, their feasibility is constrained by unresolved engineering barriers. Power generation and rapid discharge, heat rejection in a vacuum, radiation hardening, and orbital servicing impose significant mass and cost penalties. These challenges underscore that space-based DEWs remain a long-term prospect requiring breakthroughs in compact energy storage, thermal management, reusable launch systems, and international governance. Overall, the literature reflects a technology in transition: operationally relevant and strategically attractive, yet still maturing in terms of resilience, maintainability, and system integration within broader C4ISR architectures. The strength of DEWs lies not in replacing kinetic systems outright, but in complementing them—particularly where cost-per-shot asymmetry, collateral sensitivity, and high-volume aerial threats challenge conventional interception.

Limitations, Policy Considerations, and Responsible Adoption

While DEWs offer compelling operational benefits, their deployment raises questions extending beyond engineering performance. There are currently no universally accepted international norms governing non-kinetic engagement, and risks related to sensor blinding, misidentification in autonomous targeting, or escalation through pre-emptive laser use remain insufficiently regulated. The regulatory framework for laser-based DEWs remains fragmented, particularly with respect to the blinding prohibition outlined under the 1995 UN CCW Protocol IV. Although high-energy DEWs are not explicitly classified under existing treaties, their potential to damage sensors, satellites, and crewed assets raises similar humanitarian and compliance concerns. As DEWs transition toward wider operational integration, coordinated legal standards, rules of engagement, real-time incident attribution, and transparency mechanisms will become essential to avoid escalation, misinterpretation, or unintended harm. Addressing these challenges requires collaboration across defence engineering, international policy, humanitarian law, and emerging autonomy governance to ensure capability development does not outpace responsible oversight. Key Directed Energy Weapon (DEW) Challenges, Current Mitigations, and Future Research Directions are shown in Table 7.

Table 7. Key Directed Energy Weapon (DEW) Challenges, Current Mitigations, and Future Research Directions (Author’s own conceptual synthesis based on literature review.)

Challenge	Current Mitigation / Technologies	Future Research Need
Atmospheric attenuation (fog, dust, turbulence)	Adaptive optics, beam shaping, wavelength selection	Real-time atmospheric sensing and AI-based predictive correction
High energy demand for sustained firing	Shipborne power systems, hybrid capacitors, vehicle-integrated power modules	Compact energy storage, rapid discharge architectures, high-density batteries

Thermal management during continuous engagement	Liquid cooling, phase-change plates, heat exchangers	Nano-fluidic cooling, closed-loop vapor chambers, lightweight radiative systems
Tracking fast-moving or swarming aerial threats	AI-assisted tracking, multi-sensor fusion (EO/IR, radar)	Autonomous target prioritization and resilience against adversarial deception
Countermeasures and reflective coatings on targets	Increased power density, multi-spectral beam tuning	Material-specific laser coupling optimisation and adaptive frequency switching
AI reliability and engagement safety	Human-in-loop supervision and operator override	Formal model verification, auditable algorithms, and failsafe decision logic
Feasibility of space-based DEW platforms	Conceptual models and limited orbital testing	Power generation and heat rejection solutions, orbital policy and governance frameworks

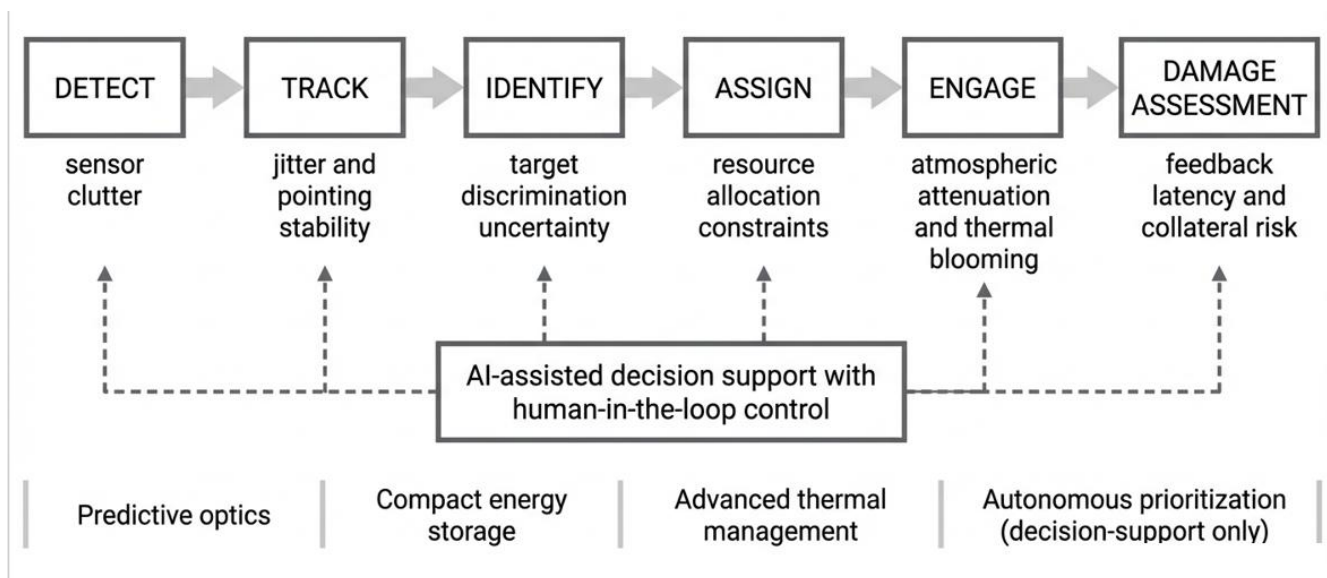


Figure 7. Integrated conceptual model illustrating the Directed Energy Weapon (DEW) kill chain, associated technical bottlenecks, AI-governed control architecture, strategic constraints, and future research pathways. The model highlights the interdependence between operational phases, atmospheric and computational limitations, and the emerging role of ethical and fail-safe governance in next-generation laser weapon systems.

Figure 7 presents an integrated conceptual framework that synthesizes the end-to-end Directed Energy Weapon (DEW) kill chain with the principal technical, computational, and governance constraints influencing system performance. The model links sequential operational phases detection, tracking, identification, engagement, and damage assessment with key engineering bottlenecks such as atmospheric attenuation, beam-control latency, thermal loading, and

power-management limitations. An AI-governed control layer is shown as a decision-support mechanism that enhances sensor fusion, target prioritization, and adaptive beam control while retaining human-in-the-loop oversight to ensure safety and accountability. The framework further incorporates strategic and ethical constraints, including reliability, escalation control, and compliance with international norms, highlighting the need for fail-safe architectures. Collectively, the figure emphasizes that the effectiveness of future laser-based DEW systems will depend not on isolated subsystem advances, but on the coordinated integration of physical, computational, and governance layers across the entire operational lifecycle.

9. CONCLUSION

Laser-based Directed Energy Weapons (DEWs) have progressed from long-standing conceptual studies to **early operational and pre-operational systems**, with platforms such as HELIOS and Iron Beam demonstrating credible defensive utility under constrained engagement scenarios. Nevertheless, **persistent challenges related to power generation, thermal management, atmospheric propagation, beam control, and platform integration** continue to limit widespread deployment and mission flexibility across domains. This review has examined the **classification of laser technologies, platform-specific integration strategies, laser-material interaction mechanisms, atmospheric effects, and system-level bottlenecks**, highlighting the central role of **materials science, thermal engineering, and optical control** in determining DEW performance and reliability. The analysis underscores that operational effectiveness is governed not solely by laser power, but by the coordinated optimization of energy efficiency, heat rejection, beam stability, and engagement geometry. Future DEW development is likely to be shaped by advances in **AI-assisted decision support, adaptive optics, and compact high-energy-density power systems**, which collectively may expand feasible deployment across land, naval, and selected airborne platforms. More speculative applications, including space-based concepts, remain long-term and contingent on substantial breakthroughs in power availability, thermal rejection, and governance frameworks. Within the Indian context, initiatives such as **ADITYA and CHESS** represent important steps toward indigenous high-energy laser capability. However, achieving operational scalability will require **sustained investment in power and thermal subsystems, cross-platform integration, and coordinated collaboration among DRDO, ISRO, academic institutions, and private industry** to accelerate technology maturation. Overall, laser-based DEWs offer the potential for **rapid response, reduced logistical burden, and precision engagement with limited collateral effects** when employed as complementary elements within layered defence architectures. Their future impact will depend on realistic system integration, responsible governance, and continued advances in enabling technologies rather than raw laser output alone.

Declarations

Competing Interests — The author declares no competing financial interests or personal relationships that could have influenced the work reported in this paper.

Ethical Approval — Not applicable; this study does not involve human participants or animal experimentation.

Funding — This research did not receive external funding.

Author Contributions — The author conceptualized the study, conducted the literature review, developed the classification framework, prepared the technical figures and tables, and wrote the manuscript. The author reviewed and approved the final version of the paper.

Data Availability Statement

Since it's a review paper no new data have been generated this paper is based on Existing study in the literature.

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