

Analysis of the importance of laser-based directed energy devices and their potential dual use: perspectives for a Brazilian solution

Análisis de la importancia de los dispositivos de energía dirigida por láser y el potencial doble uso: perspectivas para una solución brasileña

Abstract: The development and use of dual-use technologies, understood as those capable of being used in civilian applications and typically military missions (with or without minor adaptations), is a historical phenomenon. Among the advanced technologies with dual-use possibilities are those based on directed-energy principles (Directed Energy Weapons – DEW), which have been the subject of research for some time by military powers (the United States, Russia, China, and India), although these projects apparently remain at an essentially theoretical or experimental stage. Since the spread of unmanned aerial vehicle (UAV) technology, or “drones,” as an effective and operational weapon of war, especially since the outbreak of high-intensity conflicts in the early 2020s, the development of laser systems as anti-aircraft vectors specifically aimed at this threat has gained momentum, and has even been announced by several countries as being available in their arsenals, although most scientists in the field of photonics are skeptical as to whether the technical obstacles involved will actually be overcome. In this context, there is potential for DEW technology based on fiber lasers to be developed in Brazil through innovation efforts with dual-use characteristics.

Keywords: Technology; Dual-use; Laser; Drone; Development; Brazil.

Resumen: El desarrollo y uso de tecnologías de doble uso, entendidas como aquellas adecuadas para uso tanto en aplicaciones civiles como en misiones específicamente militares (con pequeñas adaptaciones o sin ellas), es un fenómeno histórico. Entre las tecnologías avanzadas con posibilidades de doble uso están aquellas basadas en principios de energía dirigida (Armas de Energía Dirigida, AED), que desde hace tiempo han sido objeto de investigación por parte de potencias militares (Estados Unidos, Rusia, China e India), aunque aparentemente estos proyectos aún se encuentran en una fase esencialmente teórica o experimental. A partir de la difusión de la tecnología de Vehículos Aéreos no Tripulados (VANT) o “drones” como arma de guerra efectiva y operativa, especialmente a partir del estallido de conflictos de alta intensidad a principios de los años 2020, el desarrollo de sistemas láser como vectores antiaéreos dirigidos a esta amenaza cobró impulso, incluso varios países anunciaron que los tenían disponibles en sus arsenales, aunque la mayoría de los científicos en el campo de la fotónica tienen una opinión escéptica con respecto a la superación efectiva de los obstáculos técnicos involucrados. En este contexto, se observa el potencial que la tecnología de AED basada en láser de fibra puede desarrollarse en Brasil a partir de esfuerzos de innovación con características de doble uso.

Palabras clave: Tecnología; Doble uso; Láser; Dron; Desarrollo; Brasil.

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1 INTRODUCTION

The traditional conceptualization deems dual-use technologies as those fed by a common core technology—defined by its end use rather than by the resources for its development, with civilian, military, or civilian-military users (Gummet; Reppy, 1988). However, these technologies go beyond “artifacts,” including the workforce’s technical knowledge (including the scientific basis, experience, and skills—human capital, know-how, and know why). Moreover, controlling manufacturing and management processes adds to the technological community necessary to produce these artifacts. Knowledge about systems integration exemplifies this (Watkins, 1990).

According to the conceptualization above, the first decade of the 21st century gave rise to dual use technologies related to the control of energy sources for guidance and navigation systems and weapons (Avila *et al.*, 2009), generically referred to as directed-energy weapons (DEW).

According to Deveci (Deveci, 2007), the beginning of the second decade of the 21st century cataloged and considered viable DEW that involve the optical segmentation of energy beams (laser), particle ionization (plasma), or electromagnetic wave (microwaves) modulation.

The word “laser” is the acronym for “light amplification by stimulated emission of radiation.” In practice, we tend to refer to laser when we think of devices that produce electromagnetic radiation, the elementary unit of which is the photon, with its own characteristics. According to quantum physics, photons are simultaneously a wave and a particle. Their electromagnetic spectrum consists of radiation of various wavelengths. However, what we call “light” is the range of radiation that is perceived by the human eye. Unlike sunlight, which is chaotic and emits radiation in all directions within the entire wavelength spectrum, lasers are coherent (remaining in phase in time and space), monochromatic (the same wavelength), collimated (the same direction, parallel, non-divergent, narrow, concentrated, and with one millimeter in diameter), and highly intense. Scientific research, medicine, and industry use laser (the latter to cut materials of great hardness, such as steel) (Catorze, 2009).

The military also commonly uses laser in several different forms of sensors, but its application as DEW results from the concept of projecting a large amount of energy stored in the weapon onto a specific target (for example: a ballistic missile, an aircraft, a satellite, etc.), producing structural or incendiary damage (Correa; Peron; Vergueiro, 2018).

Brazil also uses and produces equipment for industrial, health, agricultural, sanitation, and other purposes (Bagnato, 2008) that take advantage of the same principles of directed energy inherent to DEW, and could, at least hypothetically, take advantage of that equipment and its associated knowledge to develop or adapt such weapons.

From the military point of view, the advent of DEW (lasers and high-power microwaves) tends to generate strategic reflexes in the current international system since,

more than a punctual innovation, the emergence of this new type of weapon would occur under the three macro-transformations characterizing our time: the energy matrix (overcoming fossil fuels), demographic (on the scale of billions), and technological transitions (digitalization and knowledge industry). As these transitions will produce significant effects, although still uncertain from an ecological, economic, political, and other points of view, new strategic weapons could change the distribution of power in the international system even if the vectors of this transformation remain controversial (Avila *et al.*, 2009).

The theory of deterrence acquired more precise scientific content and doctrinal centrality in the emergence of nuclear weapons during the Cold War. This theoretical look at the logic of the strategic relationship between actors that can retaliate—developed by civil strategists, especially in the U.S. (Bernard Brodie, Henry Kissinger, Thomas Schelling, Herman Kahn, Albert Wohlstetter, etc.) but also in Europe (Raymond Aron, Lawrence Freedman, Colin Gray, etc.)—bases the idea of deterrence on the credible threat of an extremely severe punishment to prevent the action of an adversary. It soon acquired a meaning of its own, associated with the destructive potential of nuclear weapons (Avila *et al.*, 2009).

As with tanks and airplanes, laser weapons will abolish neither nuclear weapons and their vectors nor many of the currently predominant conventional weapon systems, but they tend to be more credible deterrent and operational use than nuclear weapons as they enable greater control of the human costs of war. Their lower economic cost and technological barriers to access in relation to thermonuclear arsenals can horizontalize direct laser energy weapons and equalize military competition, resulting in a more balanced multipolar distribution in the international system (Avila *et al.*, 2009).

Laser weapons manipulate several forms of electromagnetic energy depending on their intended objectives: low-power laser diode, high-power chemical laser, millimeter waves, or microwaves. Their first realistic operational applications would be defense against ballistic missiles, including devices in the space orbit of the Earth; with this scope, they have been developed since the 1960s in parallel with a series of scientific discoveries and technological achievements (Correa; Peron; Vergueiro, 2018).

Kinetic weapons cause damage or fire, which can be fatal to the target. Kinetic weapons are based on chemically energetic propellants or explosive warheads that are projected onto a target. On the other hand, DEW project a large amount of energy stored in the weapon onto a target, producing structural or incendiary damage. They differ from kinetic weapons in this respect since they produce effects at the speed of light rather than at supersonic or subsonic speeds, such as projectile weapons (LaPorta; Feller, 2017).

Most of the contemporary literature gathers a range of DEW, including high-energy laser, high-power microwave, and particle beam- and laser-induced plasma weapons. The first two classes can be described as genuine DEW, whereas particle weapons would be better classified as projectile weapons that accelerate atomic or subatomic particles into relativistic speeds (Correa; Peron; Vergueiro, 2018).

Speculation suggests that the U.S. arsenal will widely introduce operational high-powered laser weapons in the next decade. Such weapons will possess unique capabilities to strike targets at the speed of light, considerably reducing the efficiency of many kinetic devices, especially ballistic missiles (LaPorta; Feller, 2017).

However, some scholars show no such enthusiasm about the imminence of the commonplace and large-scale use of DEW, emphasizing the significant barriers to the short-term success of laser weapons, notably the difficulty of transposing laboratory technological solutions for validation based on operational and logical concepts and materials compatible with the security that is expected of weapon systems. It is also necessary to consider the definition of a possible policy for the use of these weapons according to the concepts still in force in international law and customs (Gutheinz, 2006).

2 RESEARCH METHODOLOGY

Technological roadmapping was adopted in this research, a flexible technique widely used in industry to support strategic and long-term planning (Phaal; Farrukh; Probert, 2004). This approach provides structured and often graphical means to explore and describe the relationships between markets, products, and technologies (which evolve over time). Technological roadmapping can find, evaluate, and choose strategic technological alternatives that support the fulfillment of organizational objectives (Camargo et al., 2017).

Data were collected by a systematic bibliographic search on academic databases, including Scopus, Web of Science, IEEE Xplore, and Google Scholar, for publications from 2000 to 2023. The following keywords were used: “directed energy weapons,” “high power laser,” “fiber laser,” “dual-use technology,” and “UAV defense systems.” A documentary analysis of government technical reports, defense agency white papers, and specialized media articles on the development of directed-energy weapons in the major military powers (U.S., Russia, China, and India) was also carried out. Source selection prioritized peer-reviewed articles, official reports, and primary sources, emphasizing publications on technical data from the last 10 years (despite the inclusion of historical sources for contextualization).

To map the technological evolution and find opportunities for development in Brazil, the roadmapping architecture in Phaal, Farrukh, and Probert (2004)—which integrates commercial and technological perspectives along a time axis—was applied. This method can find gaps, anticipate future needs, and align resources with strategic objectives. Roadmapping involved three main phases: 1) preliminary activities (including definition of scope and time horizon); 2) development of the technological map (identification of critical system requirements, specification of the main technological areas, and identification of technological alternatives); and 3) follow-up activities (including periodic reviews and updating of the map).

This study recognizes the methodological limitations inherent to the sensitive nature of military technical information, which has restricted access to accurate operational

data and hindered the independent validation of government statements about operating systems. Moreover, its exploratory analysis of the Brazilian technical capacity is based on public information and consultations with specialists without exhaustively surveying the available national infrastructure. Still, technological roadmapping proved appropriate to prospectively analyze emerging technologies in environments with uncertainties and technical complexity, systematically integrating multiple sources of information and finding viable technological trajectories for Brazil.

3 CURRENT STATE OF LASER USE ON MILITARY PLATFORMS

In addition to the U.S., the Russian Federation, the People's Republic of China, and the Republic of India have similar advanced programs (Feickert, 2018), but the U.S. was the first to develop experiments with realistic military potential. By the early 1970s, it was already clear to the U.S. Department of Defense that an airborne laser weapon system using available technology would be viable, an idea that physicist Edward Teller (one of the creators of the hydrogen bomb) actively propagated in the 1960s. In 1973, the air force shot down an unmanned aerial vehicle (UAV) in the state of New Mexico using a gas dynamic laser (GDL). In 1976, the army destroyed some unmanned vehicles with high-energy laser in Alabama; and, in 1978, the navy shot down an army tube-launched, optically tracked, wire-guided missile with a chemical laser in California. Thus, the three U.S. armed forces have DEW programs for aerospace, naval, and land use.

To better understand the technical characteristics of the main military high-power laser technologies, a comparative analysis between GDL, chemical oxygen iodine laser (COIL), and fiber laser systems is described below (Table 1).

Table 1 – Comparison between high-power laser technologies

Characteristic	GDL	COIL	Fiber Laser
Wavelength	10.6 μm (CO_2)	1.315 μm	$\sim 1.0 \mu\text{m}$
Typical power	High (MW class)	Very high (MW class)	Medium-high (50-300 kW)
Energy efficiency	High ($\sim 30\%$)	Moderate ($\sim 20\%$)	High (30-40%)
Current status	Obsolete (1970s-1980s)	Discontinued (2014)	In active development
Power supply	Fuel	Chemical reaction	Electrical (diode lasers)
Key advantages	High power, good efficiency	Very high power, electrical independence	Compact, efficient, modular, good beam quality
Disadvantages	Large optics, high atmospheric absorption	Complex logistics, toxic products, high cost	Limited power, propagation challenges
Notable applications	Airborne Laser Laboratory (ALL) – 1980s	Airborne Laser (ABL) – Boeing 747	Directed energy maneuver-short range air defense, High energy laser with integrated optical-dazzler and surveillance, Iron beam, anti-drone systems

Source: Prepared by the author based on Olson (2012) and Al-Aish (2015).

As in Table 1, the evolution of laser technologies for military applications shows a clear development trajectory. COIL progressively replaced GDL (pioneered in the 1970s) in the 1990s due to its higher power and shorter wavelength. However, both technologies faced significant limitations related to logistics complexity and operational costs. Currently, fiber laser-based systems represent the state of the art, offering an optimized balance between power, efficiency, compactness, and operational feasibility that explain their widespread adoption in contemporary military programs.

In aerospace, as early as 1976, the U.S. Air Force launched the airborne laser laboratory program ALL, installing a GDL device on a modified transport aircraft that could track and destroy air targets. Although experimental, it aimed to destroy ballistic missiles under the “peace through light” motto. The same technology was the theoretical mainstay of the Reagan administration’s (1981-1989) “Star Wars” missile defense program, to be used with the support of a complex system of adaptive mirrors and sensors in the orbit of the Earth (Olson, 2012).

Using the lessons learned in its ALL program, the U.S. Air Force launched another similar initiative in 1996, simply called airborne laser (ABL), this time installing high-energy COIL emitters on a Boeing 747 aircraft (Olson, 2012).

The concept of missile defense prevailed, with the ABL being designed for crises, patrolling the airspace neighboring that of a country that threatened to fire ballistic missiles with nuclear warheads and other weapons of mass destruction in such a way that, if fired, they would be shot down in their initial phase (tropopause), ensuring that the debris and warheads fell on the territory of the launching country. A second application was soon considered: an effective anti-satellite weapon to destroy or disable satellites or reconnaissance space vehicles in low orbit. Based on ABL technology, the Advanced Tactical Laser Initiative was launched in 2006, integrated by smaller and cheaper high-energy COIL emitter systems on Hercules AC-130 Spectre transport platforms for ground attack in close support missions. The system would have been used experimentally and successfully against targets on land in tests in New Mexico (Olson, 2012).

In Russia, still during the Soviet period, the Almaz/Beriev A-60 program began, with the first prototype of an Ilyushin Il-76 Candid transport aircraft equipped with high-power laser emitters in 1981 and another in 1991. The technology of the Russian emitters is only partially known. However, considering the Almaz research on GDL (the same from the U.S. ALL program) in ground combat systems, analysts estimate that such technology constitute the basis of the Russian platform, which would be consistent with the theoretical line of Earth-3, conceived to develop ballistic missile defenses since its beginning (Zarubin; Pol’skikh, [20-?]). Analysts also draw attention to the fact that, due to exposure in Russia at least 20 years earlier, the issuers of the 2006 U.S. ABL system seem to have adopted the same configuration.

In 2016, research and development by Almaz would have reportedly modernized the A-60 program. The Ministry of Defense of the Russian Federation published an official note via Deputy Defense Minister Yuri Borisov stating that the country had laser weapons based on a well-known and reliable technology no longer in the experimental stage, being

ready for operational start on air platforms from 2020 to 2022 (Russia [...], 2017), a fact apparently reaffirmed by the 2018 report from the U.S. Director of National Intelligence to the Congress (Coats, 2018).

The People's Republic of China would have directed-energy weapons programs mainly based on COIL and free-electron laser technologies in addition to another series of initiatives using laser in different modalities (mainly terrestrial and low intensity) that are irrelevant for this study. The first experiments in the 1960s were conducted with low-power solid-state lasers.

The Chinese Academy of Engineering and Physics was to develop free-electron laser technology, activating an SG-1 device in 1993. On the other hand, the COIL technology would have been assigned to the Dalian Institute of Chemistry and Physics since the 1980s, leading to the first test of a device with a 140-kilometer range in 1993.

China seems to focus on attack platforms at large land bases, with emitters towards targets in low Earth orbit, that is, with a primary anti-satellite objective. A scientific article from 2013 showed a successful experiment in 2005, damaging a satellite in orbit at about 600 kilometers by a laser with 50–100 kilowatts of power in the province of Xinjiang (Gao; Zhou; Wang, 2013). This is in line with the Chinese strategy of basing other long-range systems on land, such as hypersonic anti-ship missiles.

On the other hand, this strategy could indicate the Chinese difficulty in miniaturizing the structures to package chemical elements and generate the large amounts of energy necessary for directed-energy systems, that is, they could be one step short of the U.S. ALL/ABL and Russian A-60 programs. Still, other reports state that, at a military event in October 2009, a successful test of a four-engine aircraft using a laser device to attack a satellite was conducted based on a previously announced platform device produced by the Xian Aircraft Corporation. Speculation suggests that China may have an airborne COIL laser program but that, unlike the Russian and U.S. systems aimed at anti-missile use, the Chinese platform would be primarily designed for anti-satellite use (Fisher Jr., 2017).

The Republic of India entered the DEW development scene relatively recently, apparently in response to the Chinese threat to its space program, going hand in hand with the ballistic missile development effort and nuclear program of India. The Indian space program began in the 1960s (with support from the U.S., France, and Germany), mainly in satellites. Its launch vehicle program ran in parallel with the unstated goal of developing the Agni-V intercontinental ballistic missile system.

The Indian geostrategic situation is conditioned by the perennial threat of neighboring countries, especially China and Pakistan, with which it has fought wars in the 20th century and constant friction in its borders. Much like India, China and Pakistan have nuclear arsenals and ballistic missiles. Thus, Indians must maintain offensive and defensive systems in aerospace to react against aggressions from opposing nations.

India may have increased military investments in space from 2008 onward (Sarti, 2015). For this, its Defence Research & Development Organisation may have started to develop an anti-missile and anti-satellite DEW system in 2014. Thus, they may be exploring strategic COIL and high-power fiber laser technologies (Bose, 2014).

In December 2017, the Defence Research & Development Organisation announced the successful testing of a one-kilowatt laser platform installed on a truck in Chitadruga in the presence of Defense Minister Arun Jaitley. It is unclear what principle the device in this test used, but reports state that the Laser Science & Technology Centre had been working on a project with the same characteristics based on COIL technology. They would also be designing a system based on GDL technology (the same principle in the American ALL and Russian A-60) called “Aditya” (Gurung, 2017).

Still no forecast exists for the installation of an equivalent system for testing on board aircraft. However, studies would exist for an airborne version of the Kilo Ampere Linear Injector microwave system (another class of directed-energy weapons) in an Ilyushin Il-76 aircraft, the same used by the Russian A-60 project. Considering size, the type of sensors for target acquisition, and the characteristics of microwave-directed energy devices, it is realistic to imagine that that platform can also use laser systems.

In Brazil, the development of laser research and the training of the corresponding human resources primarily occur at the Technological Institute of Aeronautics and the Institute of Advanced Studies (branches of the Department of Aerospace Science and Technology, which has been part of the structure of the Air Force Command for about 30 years), which have obtained advances in high-power laser. Despite the dual-use nature of these research projects, the Brazilian Air Force has focused on developing laser weapons since 2000. These projects consider COIL the most suitable technology for laser-directed energy weapon designs due to its tactical advantages in energy needs and the transport of chemical “cartridges” of dimensions appropriate to the possible available vectors (Roso; Moreira; Oliveira, 2014).

The Center for Lasers and Applications at the Institute for Energy and Nuclear Research (a civil research institute linked to the Secretariat of Economic Development, Science, Technology, and Innovation of the Government of the State of São Paulo that primarily targets health, materials processing, environmental monitoring, and nuclear applications) has developed relevant studies on laser technologies, including high-power ones (Marciotto, 2017).

The analysis of the various laser programs shows that, despite great expectations regarding the use of DEW on this principle, in the aerospace and space domains—the limits of which seem to disappear in the face of the possible range of these emissions (Ellis, 2015)—the reality of operational systems (or those close to operationality) indicates two current uses: ballistic missile defense and anti-satellite use.

The Chinese and Indian initiatives, mostly focused on large land-based complexes, ostensibly target these ends, and no realistic prospect exist that airborne systems will be available to these countries in the short or medium term.

The Russian programs, which are more advanced and, according to the available evidence, in a state of operational readiness (or imminently so), include the concrete possibility of laser-directed energy weapon systems based on GDL technology in airborne vectors. However, the Russian deployment doctrine points equally towards anti-missile and anti-satellite use.

On the other hand, the U.S. programs show the greater use of laser weapons in the aerospace domain, be it on airborne platforms or in combined systems of ground emitters with devices in orbit. Even so, no sure indications exist that the tactical use of the Advanced Tactical Laser Initiative is operational or close to it.

Much more ambitious projects to establish orbital platforms with laser-directed energy emitters for anti-satellite, anti-missile, and even tactical use against targets on the surface of the Earth have been theorized and estimated for the 2040s (Friedman, 2009). A decisive step by the U.S. in this direction was the creation of an independent Space Force within the Air Force with its own personnel and equipment in 2019 (Sanders, 2022).

3.1 Laser systems for use against UAVs

The introduction of a relatively new and much cheaper technology in the 2010s, which has caused an unimagined disruptive effect on recent battlefields, finds in laser devices a seemingly more effective response than other used or imagined alternatives.

This refers to the introduction of UAVs, or, more popularly, drones. In October 2002, a Hellfire missile launched from a Predator UAV hit the vehicle carrying one of those responsible for the attacks to the American ship USS Cole two years prior, starting a new counterterrorism strategy based on drone strikes. President Obama's two terms carried out 563 strikes, 10 times the number of strikes by his predecessor George W. Bush. Since then, several countries have woken up to the possibilities of adding this type of equipment to their arsenals (Nascimento, 2019).

A UAV can be defined as "a flying machine that does not contain a human being. It is distinct from a guided weapon, such as a laser-guided bomb or cruise missile because it is not a single-use warhead delivery vehicle. A UAV may be remotely piloted or it could be autonomous" (Killeen; Jordan, 2013, p. 13). The main benefit of UAVs is that they require no humans on board. Not only the political aspect of the human casualties but also the absence of fatigue and hunger, their ability to hide the use of force from public opinion, and the fact that they are relatively cheap make them such an attractive element (Nascimento, 2019).

The two traditional conflagrations in the early 2020s heavily used drones, inflicting damage beyond what was expected, including against more powerful and supposedly more advanced adversaries as in the more recent Russian-Ukrainian conflict.

From September 27, 2020, onward, the Armenian Armed Forces began a frontline offensive in the disputed Nagorno-Karabakh region, provoking a counteroffensive by Azerbaijani forces and giving rise to the “44-day war.” During it, about 1,500 Armenian air defense positions, artillery systems, armored vehicles, and other vehicles were destroyed, mainly via Turkish-made UAVs from the Azerbaijani forces, resulting in their victory and the reconquest of a region they had claimed for years (Iskandarov; Gawliczek, 2021).

Although scientific articles offering a more objective view of the Russian-Ukrainian conflict (which began on February 24, 2022) remain rare, major damage to Russian positions and combat assets by mainly Turkish-made UAVs used by the Ukrainians in the early stages of the conflict has been publicized despite the availability of high-power microwave systems for the Russian forces that would supposedly be able to neutralize this equipment (Burdon, 2017). However, more recently, realizing the lethality and flexibility of these platforms, Russian forces have also significantly deployed drones against Ukrainian forces and infrastructure, reportedly using Iranian-made unmanned systems (Meaker, 2022).

Both cases show the general inefficiency of traditional detection systems and anti-aircraft artillery due to the low altitude and relatively small dimensions of UAVs, which can also be launched in an improvised way from small quickly-moving platforms.

The threat becomes even greater under the tactical concept of “drone swarms.” UAVs are small, highly maneuverable, and cheap to produce. They also offer the possibility for a single operator to simultaneously control several drones, although they may be semi- or fully autonomous. Together, these characteristics make plausible the emergence of offensive strategies based on massive multi-unit attacks or, in other words, “drone swarm” attacks (Guitton, 2021).

Several countries, pressured by the emergence of these combat vectors that caused disruptive innovations on the battlefield and by the apparent ineffectiveness of high-power microwave systems that could theoretically stop them, also began to accelerate high-power laser programs for tactical and anti-aircraft use from smaller platforms with more restricted range.

More reliable data on the effective functionality of the systems are restricted and surrounded by secrecy. Moreover, the dissemination of inaccurate news about military capabilities also serves to exert influence, configuring psychological warfare strategies.

Still, news have reported relatively reliable repositories with credible news of laser anti-aircraft systems.

In mid-2022, the Ministry of Defense of the State of Israel released news of the operation of a fully functional prototype after 20 years of research, generically called “Iron Beam,” an evident parallel with the air defense missile system “Iron Dome” (which successfully protects Israel against rockets launched from Palestinian territories).

The apparatus supposedly consists of a laser with a 100-kilowatt output, capable of reaching a UAV up to 20 kilometers. Evidence suggests a chemical laser (Saluja, 2022).

Figure 1 – Iron Beam System Testing

Source: Rafael Defense Systems/Israeli Ministry of Defense.

China also announced (including as a product available for sale) a tactical laser anti-drone system called “Silent Hunter,” produced by Poly Technologies, available in fixed and mobile versions. It consists of a fiber optic laser powered by electrical energy with a maximum power of 30-100 kilowatts and a maximum range of four kilometers. It is said to penetrate five two-millimeter steel plates or a single five-millimeter steel plate at an 800-meter distance, with a secondary capability against ground targets (Malyasov, 2019). According to the description, it uses fiber laser as an offshoot of another system called LW-30 (China Military Drone Alliance, 2022).

Figure 2 – Silent Hunter mobile laser system at the IDEX 2019 arms exhibition in Abu Dhabi

Source: tokyo-dar/Defence Blog.

Among other such systems (with fewer available data), the company Raytheon from the U.S. announced the offer of a mobile device (transported by a utility vehicle) called high-energy laser weapon system. It is said to have a range of three kilometers and be an offshoot of a larger vehicle, transported by an armored Stryker vehicle, called directed-energy maneuver-short range air defense, with higher power (50 kilowatts), the latter with unknown range and performance. Both indicate using a modular high-power laser compatible with chemical or fiber laser technologies.

Figure 3 – High-energy laser weapon system mounted on a Polaris MRZR vehicle (dune buggy)



Source: Raytheon.

Figure 4 – Directed Energy Maneuver-Short Range Air Defense mounted on a Stryker armored vehicle



Source: Raytheon.

The “operational phase” of some laser weapon system programs seems to show the overcoming of some of the technical challenges for this short- or medium-range equipment class (the subject of further comments below), which may also indicate them as viable objectives for development in Brazil as it already has the relevant capacities.

As mentioned, their greatly strategic nature significantly limits the direct access to programs and technologies that have been developed or are under development in Brazil (whether in the military environment or in academia) since, in addition to security, their repercussions to intellectual property (industrial property and copyright) discourage more detailed descriptions.

Aware of these limitations since the beginning of this project, this study adopted a protocol of institutional and professional interactions that aimed to preserve data that, individually considered, may be confidential—even if accessed in this research—and maintain source confidentiality, when requested. Thus, this study references a portion of what it obtained during fieldwork and from interviews in a limited way.

The technology roadmapping (Camargo et al., 2017) adopted in the methodology of this study found several academic programs targeting research with high-power laser—of interest to this study—especially 1) the laser laboratories maintained by the Photonics Division at the Institute of Advanced Studies of the Department of Aerospace Science and Technology and 2) the Center for Lasers and Applications of the Institute for Energy and Nuclear Research.

The former, being linked to the Air Force Command, presumably develop defense applications, per Roso, Moreira, and Oliveira (2014). Attempts to contact them in the fieldwork of this research obtained no responses.

On the one hand, the successful contact with the Center for Lasers and Applications of the Institute for Energy and Nuclear Research contributed to the general and theoretical understanding of the opportunities and challenges regarding the use of high-power lasers as DEW and other ongoing projects, including the one considered more viable for dual development.

On the other hand, this study found information about other ongoing projects at the SENAI Institute for Innovation in Laser Manufacturing and Processing Systems in the state of Santa Catarina, with dual objectives, together with the Army Command (FEDERAÇÃO DAS INDÚSTRIAS DE SANTA CATARINA, 2016). Consultations with this research institute found no defense project in progress, although it has been accredited to receive resources from the Brazilian Company for Industrial Research and Innovation for three industrial areas: 1) laser additive manufacturing, 2) laser surface treatment, and 3) laser welding and cutting, the latter would be more geared toward a dual-use project as it involves the development of a high-power laser.

Under the Army Command, a more immediate interest of the ground force in research involving the development of fiber laser systems was identified, which seems to be consistent with the potential application of high-power laser systems for anti-aircraft (especially anti-drone) purposes, similar to those announced as available for operational use and commercialization.

Fiber lasers are solid-state lasers, i.e., they use solid rather than liquids or gaseous components as their active medium, doping a small percentage of rare earth elements into optical fibers (usually erbium – Er^{68}). Diodes stimulate the generating material, which emits photons at the specific wavelength of the element used for doping. This kind of laser has existed for years at low powers. Its high-power versions (above 40 kilowatts) have only emerged recently (Coelho; Lima; Costa, 2013).

Doping refers to the introduction of a chemical element to change the properties of a material. In this case, the erbium amplifies the light signal propagated generating material across the optical cables as laser. This is fundamental because light travelling through an optical network causes its absorption and the attenuation of its signal. Recovering the amplitude of the original signal requires optical amplifiers along the network, the main component of which is erbium fibers (Vasconcelos, 2005).

Fiber lasers are powered by electricity, which makes them highly mobile and maintainable on the battlefield. Fiber optic lasers use optical fibers as their gain medium. For military purposes, in most cases, the gain medium is a rare-earth-doped fiber, such as erbium, neodymium (Nd^{60}), ytterbium (Yb^{70}), thulium (Tm^{69}), or praseodymium (Pr^{59}), and diodes are used for pumping (Benzoni; Orletsky, 1989). Fiber lasers are robust and require no clean room to operate or maintain like most lasers; overall, they are very efficient. However, they work poorly in some weather conditions.

An example is continuum wave fiber laser, which produces bundles of moderate quality, damaging materials and components via thermal heating and burn-through. This type of laser is easier to assemble due to the flexible fibers.

Figure 5 – Continuous-wave fiber laser system



Source: Olson (2012).

Thus, it seems a technology conducive to transport in medium-sized surface (trucks) or armored vehicles by themselves (for example: one truck transports the generators and another the laser system) or mounted on a single structure.

4 LASER DEVELOPMENT PROJECT FOR PROTON THERAPY AT THE INSTITUTE FOR ENERGY AND NUCLEAR RESEARCH

Based on the premise of these fiber laser characteristics, a project at the Institute for Energy and Nuclear Research targeted laser wakefield particle acceleration in partnership with the University of Nebraska, in Lincoln.

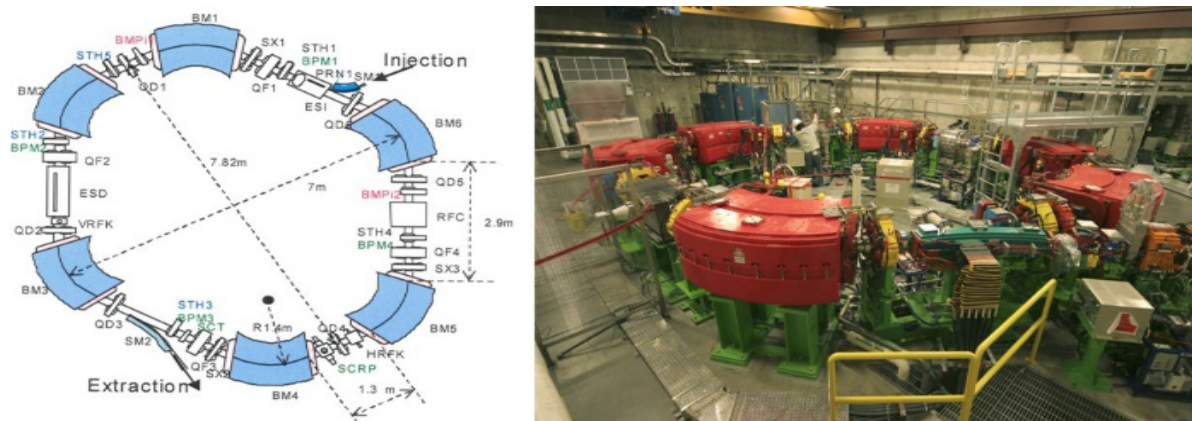
The moment high-intensity laser pulses hit a target, their atoms are ionized and the electrons begin to interact with the electromagnetic field of the laser, being accelerated directly by the luminous field (Lorentz or ponderomotive force). The electrons and ions are separated and a plasma is formed. For solid and thin targets, the pulse passes through the material, followed by a cloud of electrons (sheath) that travels at a relativistic speed. The other ions in the target are attracted to the electrons and repelled against each other, producing a beam of protons and a chain of hadrons. This technique is used in Petawatt systems to produce 100 MeV proton beams. Another powerful method of electron acceleration is laser wakefield plasma acceleration; it produces a longitudinal electric field in plasma to propel electrons (Vieira, 2018).

This project aims to collaborate to the establishment of new particle acceleration regimes for medical purposes, especially for proton therapy for neuro-oncological diseases (brain tumors), in which the proton beam directly reaches the tumor, avoiding healthy brain tissues.

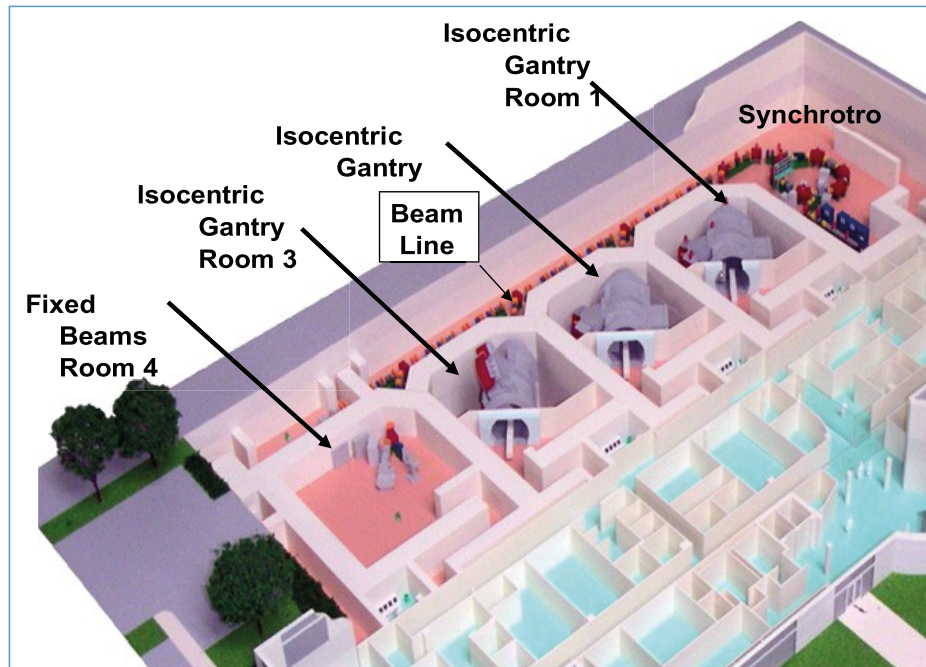
Although it is not a completely new treatment, it is estimated that only 107 units in a few countries use proton therapy since a proton particle accelerator for this purpose is very expensive—about US\$ 40 million per equipment—in addition to the cost of operation and maintenance which is only performed by the few companies that own this technology).

The usual technology for a proton therapy center involves large cyclotrons or synchrotrons accelerating protons and distributing them to rooms in which specialized equipment perform the actual application. The complete set requires a building of its own (Mohan; Grosshans, 2017).

Figure 6 – Synchrotron at the Anderson Proton Therapy Center



Source: Mohan and Grosshans (2017).

Figure 7 – Layout of the Anderson Proton Therapy Center

Source: Mohan and Grosshans (2017).

On the other hand, theoretical and experimental models of particle acceleration by laser beams indicate that, in addition to a substantial decrease in the size of equipment and facilities, they may also substantially decrease associated costs. Laser-driven acceleration offers a highly promising alternative, enabling much higher ionic energies (Hützen et al., 2019) via techniques such as laser-induced relativistic electron vortex in a near-critical-density plasma (Yi, 2019).

The potential for dual use in this case is very high in the civilian environment as the technology can reduce the suffering of an indeterminate number of people afflicted with cancer (including children) and save public resources destined to the cost of radiopharmaceuticals for long periods. Moreover, the medical nature of this technology tends to offer less resistance to access sensitive knowledge and materials and make many financial resources available to the health system, including from abroad and non-refundable ones.

From a military point of view, the technology and its associated scientific knowledge can help to overcome several critical phases in the development of an anti-aircraft directed-energy system, such as those described above.

The energy production and accumulation challenges, such as in fiber laser, can energize electron vortex generators in proton accelerators and high-power laser emitters. The solutions needed for the nanometric computation of neoplastic “targets,” in three dimensions, within cavities in the human body (Samad; Vieira, 2006) can be adapted to calculate the firing of high-power pulses against objects in three-dimensional airspace.

On the other hand, it is necessary to highlight that, despite the public statement from several countries and companies of the operational availability of high-power laser systems, the contacted academic community remains skeptical about the challenges to overcoming a few immutable physical challenges (Stupl; Neunek, 2010).

The biggest challenge seems to lie in atmospheric attenuation—affecting the propagation of laser beams since the water vapor naturally present in the air mixture, clouds, aerosols, and dust particles can absorb or reflect the laser energy (Al-Aish, 2015). Another significant challenge lies in the need for a direct line of sight between emitters and targets since the beams neither describe a ballistic trajectory nor explode close to targets (Roso; Moreira; Oliveira, 2014).

Moreover, applying a high-power laser to a target that only absorbs a portion of that energy tends cause its reflection as intense illumination, which can seriously damage the retina of allied and enemy troops; in the latter case violating the 1995 Additional Protocol to the Convention on Prohibitions or Restrictions on the Use of Certain Conventional Weapons which may be deemed to be Excessively Injurious or to have Indiscriminate Effects (entitled Protocol on Blinding Laser Weapons), thus potentially characterizing a war crime (Petrocínio; Lourenção, 2020).

5 CONCLUSIONS

This research found the theoretical and technical feasibility of high-energy laser weapon systems for tactical applications (mainly against UAVs) based on the development of technologies such as fiber laser via projects involving the triple helix (academia, government, and industry) and the available dual-use knowledge, professionals, and technologies in Brazil.

However, technical challenges still require solutions. The complete control of the production cycle of high-power laser beams in Brazil is yet to be a reality. The strategic and revolutionary character of this weapon class renders unlikely the supply of ready-made systems and the transfer of technology from operators who may have overcome the physical obstacles to laser propagation into the atmosphere and the designation of moving targets on the battlefield (rather than in ideally static conditions of temperature and pressure, such as those in tests made public).

From the point of view of financial and personnel management, linking dual-use laser programs to health constitutes the most appropriate institutional mechanism at this historical moment due to the greater availability of financial, material, and human resources for health than for defense (which can and should still generate knowledge, integration skills, and financial resources that would otherwise be unavailable in the civilian environment alone).

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APPENDIX A – Note on the Use of Artificial Intelligence

To review and adapt this article to the *Coleção Meira Mattos* standards we used the artificial intelligence system Claude (Anthropic) as an auxiliary tool in three activities: 1) complementary bibliographic review (including search for academic references on technology roadmapping and technical data on military laser systems), 2) elaboration of Table 1 (which compares GDL, COIL, and fiber laser technologies by synthesizing the information in specialized sources), and 3) adequacy of the length of the text to the editorial parameters of the journal (including revision of formatting according to the standards of the Brazilian Technical Standards Association). Claude is a large language model by Anthropic. It has been trained in vast corpora of texts to understand and generate a natural language, operating via neural architecture based on transformers. It can process and analyze large volumes of information, find textual patterns, and assist scientific content synthesis, organization, and formatting. The system, rather than replacing the researcher's critical judgment, supported data management and structuring, keeping all decisions on content, analytical interpretation, and argumentation under the author's sole responsibility. Transparency regarding the use of technological tools in academic production is in line with good practices of scientific integrity, enabling the adequate critical evaluation of the methods used to prepare this study.