Australian Government
Department of Defence
Science and Technology

EDTAS
EMERGING DISRUPTIVE TECHNOLOGY
ASSESSMENT SYMPOSIUM

DIRECTED ENERGY TECHNOLOGIES

INSIGHTS PAPER

Noetic GROUP

ABOUT THIS PAPER

Includes information that supports a broad baseline understanding of related technology concepts. These may or may not be directly applicable, in all contexts, to the definition of Directed Energy.

Highlights case studies applicable to, or complementing, Directed Energy.

The author of this paper is Michelle Todd. Michelle is a Director at Noetic Group and a keen advocate for future's thinking techniques which shape Australia's strategic position.

Noetic would like to acknowledge the participation of subject matter experts, across academia, industry and Defence. The insights gained throughout the stakeholder engagement process was critical in the development of this paper and Noetic thanks each individual for dedicating time to support Australia's future in Directed Energy technologies. Noetic would also like to thank Defence Science and Technology and the University of New South Wales, for their contribution to, and review of, this paper.

This Insights Paper was designed by Noetic's creative Design Team and Michelle would like to personally thank the team for their tremendous efforts.

CONTACT AND FURTHER INFORMATION

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www.noeticgroup.com

INTRODUCTION

Defence Science and Technology (DST) is responsible for the development of key Defence technological capabilities. DST delivers valuable scientific advice and innovative solutions for Defence and National Security, and is recognised as a national leader in safeguarding Australia. As part of their role in exploring emerging technologies, DST is seeking to understand the challenges and threats emerging from Directed Energy (DE) technologies.

The themes for the Emerging Disruptive Technology Assessment Symposiums (EDTAS) have been derived from the Next Generation Technology Fund (NGTF), a forward-looking program focussing on research opportunities in emerging and future technologies – providing an investment of AUD 730 million dollars between 2016-2026. The 2016 Defence White Paper outlined that over the next two decades, technological advances such as directed energy weapons (DEW) require a response to develop capabilities which can protect Australia's armed forces[1].

DST, in partnership with Noetic Group and the University of New South Wales (UNSW), will host an EDTAS to explore potential advances in DE technologies up to 2040; conducting immersive activities to understand future possibilities.

EDTAS will explore DE technologies over two separate symposia. The first symposium is an unclassified event, hosting experts from academia, industry and Defence. The second symposium is a classified event held for Defence and select attendees only. The purpose of each symposium is to draw on key insights to support a DST 'Big Picture Analysis Report' provides a pathway for priority research areas into the future.

1. 2016 Defence White Paper §2.43-2.45 page 52 (www.defence.gov.au/WhitePaper/Docs/2016-Defence-White-Paper.pdf)

AIM

This Insights Paper will inform EDTAS by providing a common reference point and understanding of DE technologies. It:

- covers key and emerging trends
- explores challenges and opportunities (including those specific to Australia), and
- supports EDTAS participants' involvement in exploring the future.

SCOPE AND FOCUS

This Insights Paper is neither an exhaustive nor definitive research paper. Rather, this paper explores the history of DE technologies, current and future technology concepts (weaving case studies throughout), drivers and trends and is intended to inform and focus the symposium discussions.

Key insights have been derived through a series of interviews with subject matter experts (SME)[2] as identified by DST, leveraging their experience, expertise and knowledge. Interviews were documented, individually reviewed and subsequently validated by the SMEs. In addition to this, interviews were complemented by extensive desktop research and analysis.

For the purposes of this paper, Directed Energy (DE) has been defined as follows:

"Directed Energy systems are electrically powered, which include high energy laser (HEL) and high-power microwave (HPM)/high-power radio frequency (HPRF)[3] sources that are able to direct electromagnetic energy at the speed of light to damage a target."

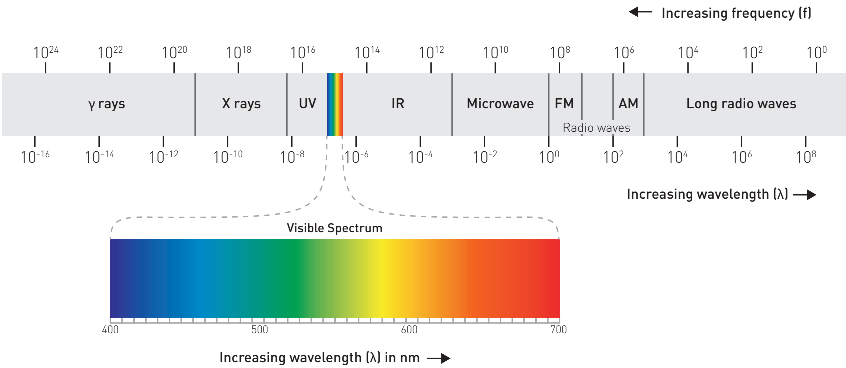
This paper will explore both HEL and HPRF technology (including component technology) drivers and the associated enabling technologies that support DE applications, including offensive or defensive capabilities in a DE technology context.

2. A list of SMEs can be found in Appendix A
3. High power microwave (HPM) is used interchangeably with HPRF within this paper.

GEN ESIS

OVERVIEW

The idea of 'radiotelegraphy' pre-dates the invention of radio, with scientists exploring and researching such concepts since the 1830s. While there are numerous scientists to whom we can attribute the discovery and invention of systems that could detect radio frequencies; James Clerk Maxwell and Heinrich Rudolf Hertz are credited as pioneers in understanding electromagnetism[4].



The electromagnetic spectrum includes frequencies ranging from high-frequency gamma rays to low frequency radio waves. Different forms of electromagnetic (EM) energy are categorised by their wavelengths and frequencies. In this paper (as is standard practice), we refer to frequency when discussing HPRF and HPM, and wavelength when discussing HEL.

For the purposes of this Insights Paper, Directed Energy systems are those employing high energy laser (HEL) and high-powered radio frequency (HPRF) sources, which can direct electromagnetic energy onto a target causing thermal (HEL) or electrical overload (HPRF) damage.

4. National Centre for Biotechnology Information,, Ramsay PS (2013): Heinrich Hertz, The father of frequency (https://www.ncbi.nlm.nih.gov/pubmed/23682537); Harvard University, Heinrich Hertz's Wireless Experimentation 1887 (http://people.seas.harvard.edu/~jones/cscie129/nu_lectures/lecture6/hertz/Hertz_exp.html)

Lasers - Measures of Impact

Laser power is measured in watts, with low power lasers typically in milliwatts, and high-power lasers in tens of watts (DE systems are in the order of tens to hundreds of kilowatts).

The ability of lasers to damage or affect various materials and targets is not due solely to power, but rather power divided by the area of laser spot called 'irradiance' (or sometimes power density, measured in watts/m^2).

The same power focussed in a small spot will have a greater effect than when the laser beam is spread over a large area. Therefore, the angle formed by individual light rays in the laser beam (beam divergence) and also the distance to the target, is crucial. More distant targets are more challenging to destroy as the beam spreads.

Beam divergence is determined by laser design, construction, wavelength and apertures the beam is traveling through.

When referring to the impact of lasers, there is a need to distinguish lasers that produce light continuously (also known as continuous wave or CW) and 'pulsed lasers,' that emit light intermittently, typically in regularly spaced pulses.

The latter would typically have (broadly) similar average power to CW lasers, but extremely high peak powers. As a result of this high peak power, the impact of such pulsed lasers tends to be significantly higher than that of CW lasers.

Name	Prefix	Factor
tera	T	10^{12}
giga	G	10^{9}
mega	M	10^{6}
kilo	k	10^{3}
milli	m	10^{-3}
micro	μ	10^{-6}
nano	n	10^{-9}
pico	p	10^{-12}

The United States Department of Defence (DOD) defines HELs as lasers with a continuous output power greater than 20 kW or a pulsed energy in excess of 1 kJ[5]. Laser wavelengths typically range from 400 nanometres (nm) (visible range) to 2 micron (infrared range), but longer wavelengths (e.g. ~300 micron) are also possible.

Fundamentals of Laser Types

The below list provides additional context on the types of lasers currently in use across a range of applications. Not all laser types listed below are currently used in DE systems.

Chemical (Gas) lasers use a gas or a mixture of gases within a tube. The best-known gas laser uses a mixture of helium and neon (HeNe), with a primary output of red light at 632.8 nanometres (nm) (nm = 10^{-9} metres). Helium-neon lasers can also be made to emit yellow, orange, green, or infrared light; typical powers are in the milliwatt range. Carbon dioxide (CO^2) lasers are used in industry for cutting, emit light at around 10 micron wavelength and their power can reach tens of watts.

Dye lasers use a laser medium that is usually a complex organic dye in liquid solution or suspension. The appropriate choice of the dye (and its concentration) allows the production of laser light over a broad range of wavelengths in or near the visible spectrum. Dye lasers commonly employ optical pumping, although some types have used chemical reaction pumping. The most commonly used dye is Rhodamine 6G, which provides tunability over 200 nm bandwidth in the red portion (620 nm) of the spectrum.

Crystal/Glass/Solid-state lasers involve light from an external source that excites a solid-state material containing atoms known as dopants, which have been added to a host material at low concentrations. Important examples include glasses and crystals doped with the rare-earth element neodymium, and glasses doped with erbium or ytterbium, which can be drawn into fibres for use as fibre-optic lasers or amplifiers.

Semiconductor lasers (sometimes referred to as diode lasers) emit visible or infrared light when an electric current passes through them. The emission occurs at the interface between two regions doped with different materials (*p-n* junction). The wavelength depends on the semiconductor compound. The most common diode laser is the gallium arsenide diode laser with a central emission of around 840 nm

5. US Defense Threat Reduction Agency, 'Section 11: Lasers and Optics Technology', in US Department of Defense, Developing Science and Technologies List, Ft. Belvoir, 2000 (http://www.dtic.mil/mctl/DSTL/Sec11.pdf)

HPM and HPRF are grouped under the same 'umbrella' and are used interchangeably. The EM frequency spectrum for this area ranges from low megahertz (MHz) to high gigahertz (GHz) frequencies (1×10^6 Hz to 1×10^{11} Hz). Invisible to the human eye, these frequencies range from wavelengths of 0.1 centimetres (GHz frequencies) to three metres (MHz frequencies) in length[6].

HPRF Bands[7]

Narrow-band generates coherent RF radiation by extracting energy from intense relativistic electron beams (IREBs) via a physical coupling mechanism. Typically, GHz frequency range.

Ultra-wide bands generate high-peak power EM pulses by directly exciting an antenna system using high-voltage pulses and a fast switching electrical current. Typically, most of the RF energy is radiated as unipolar (single) or bipolar (dual) type pulses. Although it is possible to generate dumped sinusoidal waveforms[8] of several wave cycles.

Which Door? Which Effect?

There are numerous pathways and entry points through which HPRF emissions can penetrate electronic systems. These entry points are known as the 'front' and 'back' door.

Front Door: EM signals that enter and propagate through the primary sensing circuitry of the target and the paths designed to carry signals into a system. Pathways can be antennae, domes or other sensor 'windows'. This could include the propagation of a signal into a radar via its receiver circuitry.

Back Door: EM signals enter and propagate through circuitry and paths that were not intended for signal entry. Pathways can be cracks, seams or seals.

Continued over...

6. Air University – Maxwell Air Force Base, High Power Microwaves, Strategic and Operational Implications for Warfare, Eileen M. Walling, Colonel, USAF (May 2000)
7. Ibid.
8. The sine or sinusoidal wave is a curve that describes a smooth repetitive oscillation. The sine waveform is defined as the waveforms in which amplitude is always proportional to sine of its displacement angle at every point of time. All waves can be made by adding up sine waves.

Electrical components are extremely sensitive to HPRF emissions, which cause a range of effects including temporary to permanent damage – known as 'upset', 'lock-up' or 'latch-up'.

Upset: Temporary alteration of the electrical state of one or more components, circuits or electrical pathways. When emissions have ceased, the items return to normal with no lasting effects generally seen.

Lock-up: The electrical state of components, circuits or pathways are temporarily altered. However, the items remain altered even after emissions have ceased. To regain functionality, the system must be reset manually.

Latch-up: A severe form of lock-up in which some of the internal components may be degraded by emissions. Even after cycling power through the system, the system may not return to normal function and further maintenance may be required. In some cases, normal function cannot be resumed.

Controversial Beginnings: Light Amplification by Stimulated Emission of Radiation (Laser)[9]

In the early twentieth century, numerous physicists had been working toward emitting electromagnetic waves with ever shorter wavelengths. After radio waves (metres) and radar waves (centimetres, then millimetres), the next logical step was far-infrared waves.

There are three incredibly influential Physicists who could be considered the inventors of the first lasers - Charles Townes, Arthur Schawlow and Gordon Gould.

In 1957, Townes realised it would be easier to amplify radiation with very short wave than with far-infrared waves – moving away from the far-infrared region to the well-known techniques for amplifying light.

Working with Schawlow, the two men determined that atoms could be stimulated more effectively when placed in an optical cavity with mirrors at each end. The light rays in such a cavity move back and forth inside increasing the chances for stimulating atoms to radiate. One of the mirrors is only partly silvered so some of the rays are able to leak out – the Fabry-Pérot etalon arrangement.

Gould who was working on his thesis at the time, called it 'Light Amplification by Stimulated Emission of Radiation' or LASER for short.

Townes and Schawlow, and Gould submitted patents nine months apart, with Townes and Schawlow receiving their patent grant prior to Gould. However, Gould had discussed his theories with Townes in 1957, two years prior to when both patents were filed – as a result Gould sued. Patent battles raged on for over thirty years, with Gould receiving settlements in 1987.

Did you know: the optical techniques and theoretical knowledge to build a laser existed in the 1930s. But the principle of how to build a laser was not realised until the 1950s.

What untapped potential exists in the DE space today?

9. American Institute of Physics: Bright Idea, The First Lasers (https://history.aip.org/exhibits/laser/sections/whoinvented.html)

EVOLUTION

DE technologies, Directed Energy Weapons (DEWs) and related concepts have been part of military warfare for thousands of years. Roman author, Lucian, credited Greek mathematician and scientist Archimedes with inventing the first DEW - using mirrors to focus sunlight on invading ships and setting them on fire during the siege of Syracuse in 214-212 BCE – referred to as 'Archimedes Mirrors'.

Modern applications of DE technologies have seen numerous advancements in the DEW space, including public announcements of research programs designed to employ DE technologies as offensive and defensive capabilities – primarily to support governments in countering complex threats, such as ballistic missiles.

During testing for the first detonation of a nuclear device (the Trinity Nuclear Test), electronics and sensitive equipment were shielded in anticipation of effects causes by an electromagnetic pulse (EMP). Between 1951 and 1953, the British conducted a series of nuclear tests in Australia. At this time, there were numerous observations of electronic instrumentation failures, which the British called 'radioflash'[10].

Nuclear EMPs are caused as a result of the explosion; a variant of this is the High-altitude EMP (HEMP), where an electromagnetic energy field is produced in the atmosphere by the power and radiation of a nuclear explosion. However, there are also EMPs which are produced by non-nuclear sources, such as HPMs.

During the 1970s, the US commenced research into DE technologies. The Defense Advanced Research Projects Agency (DARPA) supported many technological and early system concepts for tactical HELs. This support funded the development of the Baseline Demonstration Laser (BDL) and the US Navy (USN) Chemical Laser (NACL)[11].

10. Reminiscences of High-power Electromagnetics, Carl E Baum, IEEE (http://ece-research.unm.edu/summa/notes/History/BaumReminiscences.pdf)
11. United States, Defense Advanced Research Projects Agency (https://www.darpa.mil/about-us/timeline/miracl)

Strategic Defense Initiative (SDI) – the 'Star Wars' program[12]

On 23 March 1983, in a televised address, US President Ronald Reagan announced his intention to commence research into a national defence system that was intended to make nuclear weapons obsolete. The research took several forms and was collectively known as the Strategic Defense Initiative, or SDI.

At the core of the SDI was a program to develop a space-based missile defence capability that could protect the United States of America from large-scale nuclear attacks. The proposal involved numerous DE technology advancements, including space-based lasers, that could identify and destroy incoming ballistic missiles (at launch, in flight and at approach).

The research program highlighted futuristic capabilities that had only been seen in the famous science fiction movie, Star Wars and was nicknamed the 'Star Wars' program.

While working on the BDL and NACL systems, DARPA funded the 'Special Laser Technology Development Program'. This program of work formed the basis for several developmental laser systems, including the Mid-Infrared Advanced Chemical Laser (MIRACL) – **a massive megawatt device that relied on rocket-engine-like combustion**, first lased in 1980; and the **Chemical Oxygen-Iodine Laser (COIL)**. The latter forming the basis of the US Air Force's (USAF) **Airborne Laser** (ABL)[13].

12. United States, Department of State Archives (https://2001-2009.state.gov/r/pa/ho/time/rd/104253.htm)
13. United States, Defense Advanced Research Projects Agency (https://www.darpa.mil/about-us/timeline/miracl); Northrop Grumman, Laser Firsts (https://www.northropgrumman.com/Capabilities/LaserFirsts/Pages/default.aspx)

SPOTLIGHT ON COLLABORATION

Boeing YAL-1 Airborne Laser: Chemical Oxygen-Iodine Laser (COIL)[14]

In 1999, assembly began on a militarised Boeing 747-400 Freighter to be used as a platform for the USAF's ABL program. In October 2006, the system was rolled-out and designated YAL-1. The ABL was designed to provide a speed-of-light capability to destroy ballistic missiles in their boost flight phase (to mitigate atmospheric limitations suffered by terrestrial lasers). The YAL-1 inaugural flight occurred in 2007.

In February 2010, the flying test bed destroyed a ballistic missile off the coast of Southern California. The program ceased in 2011.

14. Boeing, Historical Snapshot 747 (https://www.boeing.com/history/products/747.page); Northrop Grumman, Laser Firsts (https://www.northropgrumman.com/Capabilities/LaserFirsts/Pages/default.aspx)

While significant research was ongoing in HELs during the 1980s, the USAF was concurrently researching higher frequencies of the high-power microwave frequency spectrum[15]. This research followed significant investment by the US government on EMP and DE technologies as part of the SDI.

In 2007, the US military demonstrated a Raytheon-developed **HPM-based, wide-area counter-personnel** Active Denial System (ADS)[16]. Three years later in 2010, the ADS was deployed to Afghanistan, however, there were complexities regarding the use of the technology in the battlespace and its operational efficacy in complex environments (including the effects of climate and other considerations). The ADS was subsequently returned and was not used during operational activities[17].

The ADS is capable of firing a **high-powered RF beam of 95 GHz, designed to induce physical pain to individuals** through heat and skin irritation. The ADS could also be used as crowd suppression and control. The ADS is currently deployed on US military Hummer and Stryker vehicles, which also carry conventional weapons and other non-lethal weapons (such as the 'sonic cannon' Long Range Audible Device) – highlighting its complementary use to other technologies.

The USAF Special Operations Command decided to pursue ADS II in 2011, a program where the technology would be smaller and more reliable (overcoming some of the challenges identified with the previous ADS). The research was focussed on mounting the ADS II on current airborne platforms, such as the AC-130J Gunship[18].

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15. Air University – Maxwell Air Force Base, High Power Microwaves, Strategic and Operational Implications for Warfare, Eileen M. Walling, Colonel, USAF (May 2000)
16. British Broadcasting Corporation (http://news.bbc.co.uk/2/hi/americas/6297149.stm)
17. AEI Center for Defense Studies (https://web.archive.org/web/20141101231037/http://www.defensestudies.org/cds/an-opportunity-missed/)
18. Strategy Page (https://strategypage.com/htmw/htairw/articles/20150810.aspx); Flight Global (https://www.flightglobal.com/news/articles/us-special-forces-pursuing-ac-130-based-active-denial-415124/)

Broader than Military: Civil Applications[19]

The Los Angeles County Jail deployed an 'Assault Intervention Device' (AID), also known as the 'Silent Defender', in 2010. The AID was designed to lessen assaults occurring within the facility, either between inmates or directed towards guards. The AID, developed by Raytheon, is controlled by a joystick and emits a beam, equivalent to the size of a Compact Disc (CD), over approximately 30 metres.

19. Raytheon, Silent Guardian (https://web.archive.org/web/20061214103048/http://www.raytheon.com/products/silent_guardian/); National Broadcasting Corporation, Los Angeles (https://www.nbclosangeles.com/news/local/New-Laser-Weapon-Debuts-in-LA-County-Jail-101230974.html)

In 2011, the USN and Northrop Grumman successfully **demonstrated a high-energy, solid-state laser defence at sea**, by completing a counter-material test of the Maritime Laser Demonstrator (MLD) against small boats[20]. The MLD successfully demonstrated the first naval laser system, installed on a decommissioned Spruance-class destroyer; the first naval system to be integrated with a ship's radar and navigation system, and the first electric laser weapon to be fired at sea from a moving platform.

The following year, Northrop Grumman announced their next generation 'Firestrike' family of high-energy solid-state lasers. The **first product of the 'Firestrike' family was 'Gamma', which could fire short bursts at 13.3 kW over 1.5 hours.** Gamma uses a "slab" architecture (similar to previous Northrop Grumman high-power, solid-state lasers, such as the Joint High-Power Solid-State Laser (JHPSSL) and the MLD). Northrop Grumman testing of Gamma **demonstrated that the laser could burn through the Unmanned Autonomous Vehicle (UAV) skin and critical components of a target drone used to simulate anti-ship cruise missile threats** to USN ships[21].

20. Global Newswire – Northrop Grumman (http://www.globenewswire.com/newsarchive/noc/press/pages/news_releases.html?d=218331)
21. Northrop Grumman, FIRESTRIKE (https://www.northropgrumman.com/Capabilities/SolidStateHighEnergyLaserSystems/Pages/default.aspx)

In 2012, US Air Force Research Lab (AFRL) conducted a weapon flight test in Utah. The test was part of AFRL's counter-electronics high-powered microwave advanced missile project (CHAMP). CHAMP renders electronic targets useless, by using a non-kinetic alternative to traditional explosive weapons, using the radiofrequency energy to defeat a target. During the test, **the CHAMP missile navigated a pre-programmed flight plan and emitted bursts of high-powered energy, effectively knocking out the target's data and electronic sub-systems. CHAMP also allows for selective high-frequency radio wave strikes against numerous targets during a single mission[22].**

Concurrently, Lockheed Martin developed a **10-kW fibre laser** prototype in 2012. The Area Defence Anti-Munitions (ADAM) system, successfully destroyed an unmanned aerial vehicle (UAV) target. The ADAM can destroy two small boats at approximately two kilometres[23].

The following year, Lockheed Martin developed a 30 kW Accelerated Laser Demonstration Initiative (ALADIN), a **spectral beam combining fibre laser demonstrator. ALADIN is a multiple fibre laser modular capability that forms a single, powerful, high-quality beam, aiming to provide efficiency and lethality in a design that is scalable to higher power levels[24].**

In 2014, DARPA, within the research program 'Excalibur', developed **coherent optical phased array technology to enable scalable laser weapons, which were aimed to be 10 times lighter and more compact than existing high-power chemical laser systems. The optical phased array architecture provides electro-optical systems with the same flexibility and performance enhancements that microwave phased arrays provide for RF systems.** A multifunction Excalibur array may also perform laser radar, target designation, laser communications, and airborne-platform self-protection tasks.

22. Boeing, CHAMP – Lights Out, 2012 (https://www.boeing.com/features/2012/10/bds-champ-10-22-12.page)
23. Lockheed Martin, News Release (ATHENA) https://www.lockheedmartin.com/en-us/products/athena.html/
24. Ibid

45 Down: Raytheon's HEL and HPRF capabilities excel in combating UAVs[25]

Raytheon and the AFRL have demonstrated a high-power microwave system which engaged multiple UAV swarms, downing 33 drones, two and three at a time. The DE system emits an adjustable width energy beam that can render UAVs unable to fly.

Raytheon's HEL system identified, tracked, engaged and downed 12 airborne, manoeuvring small (Class I) and medium (Class II) UAVs, and destroyed six stationary mortar projectiles.

25. Raytheon, Press Release (https://www.raytheon.com/news/feature/forty-five-down)

HERE AND NOW

The use of DE technologies has gained significant traction since 2016, with research programs substantially increasing in effort. The current use and application of DE and DEW technologies is primarily explored within a Defence context and numerous countries are now demonstrating their sovereign capabilities in this field.

While the US is currently the world leader in demonstrations of DE technologies, there have been significant advancements globally (with support from Defence Primes involved in collaborative and joint initiatives). Various countries are now actively developing and deploying DEWs into the battlespace.

Increased interest, research and development of DEWs is in response to the evolving global threat environment and 21st Century warfighting demands.

Points of Difference: Directed Energy Weapons vs Electronic Warfare

A common assumption is that DEWs are like Electronic Warfare (EW) systems. The relationship between a DEW, specifically HPRF, and an EW system is that both use the frequency spectrum to work against electronics.

While there is a foundational similarity between systems, EW systems are limited to jamming and generally only affect other systems when the EW system is operating. When an EW system ceases operation, the system being affected returns to normal. EW systems require knowledge of the system being targeted, as EW systems generally target the other system's frequency or modulation. Further, the system needs to be operational for it to be affected (i.e. if the system is turned off or the frequency or modulation is not known, it will have no affect). DEWs in contrast are designed to overwhelm the other system's ability to reject, disperse or withstand energy. There are four major differences between an EW system and a DEW.

DEWs:

1. Do not rely on exact knowledge of other electronic systems
2. Can leave persisting and lasting effects
3. Affect electrical systems even when they are turned off, and
4. The entire affected electrical system needs to be hardened to counter effects, not just individual components or circuits.

DEFENCE APPLICATIONS

Increases in hybrid warfare and contested battlespace scenarios has meant research programs are looking to DEWs to address a range of threats – albeit as complementary measures to conventional weapons systems. One of the most notable threats being the need to counter the increase in use and sophistication of UAVs and Improvised Explosive Devices (IEDs).

Countries are now increasing efforts in DE technology research across all physical warfighting domains - land, air, sea and space. The following provides a snapshot of recent global developments in the Defence domain:

+ The US Army, working with the High Energy Laser Joint Technology Office, initiated the Robust Electric Laser Initiative (RELI) effort in 2010, with the US Army integrating a 50 kW RELI on their HEL Mobile Tactical Truck in 2018.
+ In 2017, Lockheed Martin developed a prototype Advanced Test High Energy Asset (ATHENA) Laser Weapon System (LWS). In tests conducted at White Sands Missile Range in New Mexico, US, ATHENA destroyed five UAVs.
+ In January 2017, Huang Wenhua (Deputy Director of China's Northwest Institute of Nuclear Technology) received a first prize 'National Science and Technology' progress award, for research on DE, specifically a HPM weapon. According to Huang, the technology was initially tested in 2010 in what was referred to as the 'Huahai' exercise. The capabilities of the HPM weapon remain unknown[26].

26. The Diplomat, 'The PLA's potential breakthrough in high-power microwave weapons' (https://thediplomat.com/2017/03/the-plas-potential-breakthrough-in-high-power-microwave-weapons/)

+ The United Kingdom (UK) Ministry of Defence (MOD) publicly announced in 2017, a consortium – 'Dragonfire' – comprising a mix of major defence firms including MBDA and BAE, in addition to science and engineering company QinetiQ to produce a LWS. The capability was intended to be deployed on Royal Navy (RN) ships[27]
+ During a State address in 2018, Russia announced the development of HEL systems for Russian Armed Forces. The 'Peresvet' combat laser entered experimental combat service in late 2018, following the country's ongoing military modernisation program[28].

There have been significant announcements and demonstrations of DEWs globally in 2019, with countries such as the US, United Kingdom, France, Germany, China and Turkey demonstrating their capabilities. The increase of publicly available information suggests numerous countries have intensified efforts into DEWs, with numerous demonstrators, in addition to integration on platforms, gaining media and public attention.

27. Ministry of Defence, Royal Navy, News Release (https://www.royalnavy.mod.uk/news-and-latest-activity/news/2017/january/06/170106-lasers)
28. Business Insider, Briefing (https://www.businessinsider.com.au/russia-deploys-new-laser-weapon-with-russian-armed-forces-2018-12?r=US&IR=T)

COUNTERING THE SWARM: FRENCH ARMY BASTILLE DAY 2019 UNVEILING[29]

While the following technologies highlight electronic warfare capabilities, what possibilities exist from a DE perspective?

In July 2019, the French Army unveiled two new counter-UAV (cUAV) tactical weapons at Bastille Day celebrations. The two technologies are being used to disrupt UAV operating near military or law enforcement personnel and assets.

DroneGun Tactical from DroneShield – Australian technology on the world stage

DroneGun Tactical is manufactured by Australian Company DroneShield. It is designed to mitigate, control and manage UAVs.

The DroneGun is 143 cm long and 20 cm wide, weighing approximately 7.3 kilograms (kg). DroneShield state the DroneGun has a 1 to 2km range and an operating time of approximately two hours, using two rechargeable Lithium-Ion batteries.

29. Army Recognition (https://www.armyrecognition.com/weapons_defence_industry_military_technology_uk/secret_weapons_and_new_military_equipment_unveiled_by_french_army.html)

NEROD F5 Drone Gun from MC2 Technologies

The NEROD F5 is developed and manufactured by French company MC2 Technologies. MC2 states the NEROD F5 is a microwave jammer capable of disrupting and neutralising all communication protocols used by UAVs.

This system uses directional antennas inside the rifle to disrupt UAVs. The user must aim for the drone to neutralise it.

The NEROD F5 has a maximum range of 2.5 km, a total weight of approximately 7kg and 2 hours of operation.

+ Countries such as Germany are also advancing developments in the DE space. Rheinmetall and MBDA Deutschland agreed to collaborate in order to construct, integrate and test a laser demonstrator on a German Navy K130 Braunschweig class (also known as Korvette 130) ship[30].
+ At the US Center for Strategic and Budgetary Assessment (CSBA) Directed Energy Summit in March 2019, USN Director of Surface Warfare, announced plans to integrate a 60 kW HEL and Integrated Optical-dazzler with Surveillance weapon system (HELIOS) aboard a West Coast Arleigh Burke-class Flight IIA destroyer. The HELIOS will serve as an **early test case to integrate a LWS into the 'Aegis' combat system** of the USN's surface fleet. Additionally, the laser system intends to provide a new capability as a sensor, to give more precise targeting data than a ship's current combat system. The USN intends to have HELIOS integrated by 2021[31].
+ Media reporting by Chinese-state owned network CCTV has highlighted China's advancements in HEL technologies, shown in a ground-based, vehicle-mounted application[32].The report suggests China's HEL system beared resemblances to the USN LWS, showing China's rapid progress in developing similar technologies.

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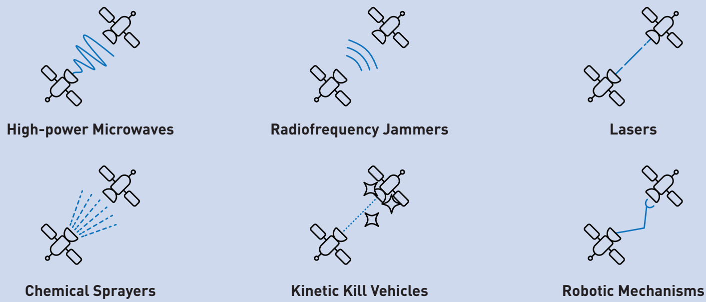
30. MBDA Missile Systems, Press Release (https://newsroom.mbda-systems.com/strongrheinmetall-and-mbda-to-develop-high-energy-laser-effector-system-for-the-german-navy-strongbr-nbsp/)
31. United States Naval Institute, News Release (https://news.usni.org/2019/03/20/navy-ready-burn-boats-2021-laser-installation-destroyer)
32. The Maritime Executive (https://www.maritime-executive.com/article/china-tests-laser-weapon-similar-to-u-s-navy-prototype)

Non-terrestrial focus: DE technologies in Space[33]

While a large focus in recent time has been on the terrestrial application of DEWs, the US Defense Intelligence Agency (DIA) released the 'Challenges to Security in Space' assessment, highlighting that China and Russia are actively developing DEWs in the space domain in addition to other space-based capabilities (see figure below).

DIA assessed that China is likely pursuing laser weapons to disrupt, degrade, or damage satellites and their sensors and possibly already has a limited capability to employ laser systems against satellite sensors. China will likely field a ground-based laser weapon that can counter low-orbit space-based sensors by 2020, and by the mid-to-late 2020s, may field higher power systems that extend the threat to the structures of non-optical satellites.

Further the DIA report outlined that Russia is likely pursuing laser weapons to disrupt, degrade, or damage satellites and their sensors. Prior to July 2018, Russia began delivering a laser weapon system to the Aerospace Forces that likely is intended for an anti-satellite (ASAT) mission. In public statements, President Vladimir Putin called it a "new type of strategic weapon," and the Russian Defense Ministry asserted that it is capable of "fighting satellites in orbit." Russia is also developing an airborne ASAT laser weapon system to use against space-based missile defence sensors.



The application and deployment of DE technologies has progressed, with countries now actively deploying offensive and defensive capabilities within the battlespace, with an emphasis on land and sea applications.

33. US Defense Intelligence Agency, Challenges to Security in Space Assessment 2019

Next Level: Turkish Military shoots down UAV in Syria[34]

In the early 2010s, Turkish company Savtag demonstrated a HEL system which incremented from 1.25 kW up to 50 kW. The systems were created in conjunction with Tubitak, a state research institute. The systems were shown as technology demonstrators, highlighting that the Turkish government were planning to use these developments as weapons.

In 2015, the Turkish government spent USD 450 million on the program, an amount comparable to other global leaders in the HEL space.

In the same year, Aselsan holdings, the largest Turkish military-industrial corporation, took the Turkish laser weapons program "under the wing". On July 7, 2018, the company issued a press release stating that it had successfully tested a combat laser capable of hitting small-sized UAVs from 500 metres, as well as destroying explosive devices from 200 metres. The compact laser gun was installed on the Turkish 'Otokar Cobra' armoured vehicle and was equipped with a guidance system allowing the continuous hold of the laser marker on a target.

In 2019, media reports suggest a new Turkish installation, shot down a United Arab Emirates owned, Chinese made UAV. The LWS is mounted on the chassis of an off-road armoured car. Like the earlier Aselsan model, it is equipped with a Turkish-made optoelectronic guidance system, allowing accurate inspection of the target for firing – enabling the identification of vulnerable points to hold the laser marker on until the target is destroyed. Similar to the previous demonstrator, a continuous radiation mode is provided (without long interruptions to the "pumping" of the laser) generating 50 kW output power. This is currently the most powerful combat laser in the Turkish ground combat vehicle arsenal.

34. Army Recognition (https://www.armyrecognition.com/weapons_defence_industry_military_technology_uk/turkey_uses_laser_weapon_technology_to_shoot_down_chinese_uav_wing_loong_ii_in_libya.html)

Particular efforts to focus on multi-domain[35] use and advancements of DE technologies may be declining, with a push to re-focus efforts on the terrestrial application of DE and DEW capabilities and the consideration of where DE technologies could support future challenges and changes to the battle landscape.

Pentagon Shifts DE Efforts: Terrestrial Focus[36]

In a recent announcement, the US. DOD is prioritising its DEW research on technologies ready to field now, instead of focussing on the creation of more complex space-based technology.

In particular, the Pentagon is exploring the usefulness of DE, specifically on how to increase the power of weapons. This shift highlights the Pentagon's preference to advance technologies ready to deploy in terrestrial domains in the near-term and is shelving plans to develop systems that are years away from initial testing in the space domain.

+ In July 2019, the UK MOD announced plans to focus on HEL beam combination technologies, dedicating GBP 130 million to the research program. The intent is to trial and deploy combined HEL technologies into UK RN ships, in addition to British Army armoured vehicles and UK 'Wildcat' helicopters. This activity is different to the 'Dragonfire' program, as it combines multiple laser beams to produce a weapon more powerful than its predecessors and resistant to the most challenging environmental conditions – one of the ongoing challenges for HEL weapons systems, indicating the need to focus on future requirements. Testing is expected to commence in 2023[37].

These examples highlight a global push to enhance DEWs. Advancements in evolution signify a strategic, future-focussed push by governments to develop DE technologies to solve a range of complex challenges into the future.

35. Covering sea, air, space and land domains
36. United States Naval Institute, News Release (https://news.usni.org/2019/09/05/pentagon-shifts-focus-on-directed-energy-weapons-technology)
37. Royal Navy, News Release (https://www.royalnavy.mod.uk/news-and-latest-activity/news/2019/july/10/190710-mod-130m-lasers)

1830: 'Radiotelegraphy'

1887: Heinrich Hertz 'Wireless Telegraphy'

1951-1953: British Nuclear Testing 'radioflash'
Documented impact of electromagnetic pulse to electronic systems

1957-1959: Light Amplification by Stimulated Emission of Radiation (LASER)
Patent application

1970: DARPA commenced research and development
Technological and early system concepts for tactical HELs

1980: Mid-Infrared Advanced Chemical Laser (MIRACL)
- A massive megawatt device that relied on rocket-engine-like combustion
- First lased

Chemical Oxygen Iodine Laser (COIL)
- Basis of US Air Force's (USAF) Airborne Laser (ABL)

1983: USA Strategic Defense Initiative 'Star Wars Program'
Space-based missile defence capability concept

2007: HPM Active Denial System
- HPM-based, wide-area counter-personnel
- High-powered RF beam of 95 GHz, designed to induce physical pain to individuals

2011: Maritime Laser Demonstrator (MLD) against small boats
- HE solid-state laser (SSL) demonstrator

DIRECTED ENERGY TECHNOLOGIES
TIMELINE

2019: HEL and Integrated Optical-dazzler with Surveillance weapon system (HELIOS)
- 60 kW maritime Laser Weapon System
- Early test case for full integration into a battle management system

2017: Advanced Test High Energy Asset (ATHENA) Laser Weapon System
- ATHENA destroyed five UAVs in tests

'Dragonfire' industry consortium UK capability
- Laser Weapon System intended to be deployed on ships

2014: DARPA 'Excalibur' – coherent optical phased array technology
- Coherent optical phased array technology
- Aimed to be 10 times lighter and more compact than existing high-power chemical laser systems
- Phased array architecture provides electro-optical systems with the same flexibility and performance enhancements of microwave phased arrays

2013: 30 kW Accelerated Laser Demonstration Initiative (ALADIN)
- Spectral beam combining fibre laser demonstrator
- Multiple fibre laser modular capability that forms a single, powerful, high-quality beam that is scalable to higher power levels

2012: 'Firestrike' SSL
- Capable of firing short bursts at 13.3 kW over 1.5 hours
- Demonstration of burning through UAV skin and critical components of a target drone used to simulate anti-ship cruise missile threats

Area Defence Anti-munitions (ADAM) system
- 10 kW fibre laser prototype

US AFRL Counter-electronics high-power microwave advanced missile (CHAMP) project
- Missile navigated a pre-programmed flight plan and emitted bursts of high-powered energy, effectively knocking out the target's data and electronic sub-systems
- Allows for selective high-frequency radio wave strikes against numerous targets during a single mission

AUSTRALIA'S CONTRIBUTION

Australia, through DST, has a DE program of effort. However, compared to other partners, Australia's capability is still evolving. Amidst ongoing efforts globally, there is a push for Australia to develop a niche capability to support DE efforts. This includes a focus on Size, Weight and Power (SWaP) developments, particularly miniaturisation of DE-related technologies.

Australia's academic and research cohort is robust, with multiple Australian-based universities involved in research programs that either directly, or indirectly, support DE development efforts. These efforts are complemented by a leading-edge Australian Defence Industry, with multiple Australia-based companies involved in technology within Australia and globally.

Given Australia's potential in the DE space, there are some key (and critical) areas Australia could focus effort towards, or harness, to further support DE programs in collaboration with DST and others.

One critical area, is the development of a sovereign capability, specifically the development of laser diodes, semiconductors and antennae. This is likely to require significant resourcing, investment and facilities in addition to cross-collaboration between government, academia and industry.

Additional areas of focus could include the development of bespoke manufacturing and system design capabilities, access to appropriate testing environments, the development of training pathways to increase understanding of DE and underlying technologies, and importantly, the ability for academia to work with the appropriate tools that enable and support research activities.

Access to directed energy technologies is fast becoming a strategic requirement for all modern militaries – Australia must focus on systems development and sovereign capability or be left behind.

FROM EXPERT INTERVIEW

Bragging Rights: Spotlight on Australia's contributions to photonics

Australian-British father-son team, Sir William Henry Bragg and Sir William Lawrence Bragg, developed the Bragg formulation of X-ray diffraction. Their research paved the way for a deeper understanding of how electro-magnetic waves are scattered from crystalline materials. 'Bragg reflectors' rely on the Braggs' work, and can be used in optical filters (such as optical bandpass filters).

Fibre Bragg gratings have application in telecommunications, where they are used as notch filters, multiplexers and demultiplexers (to filter out, combine or separate beam frequencies). They are highly versatile devices and are used extensively in photonics research and environmental sensing[38].

In recognition of their efforts, the Braggs won the Nobel Prize in Physics 1915 for their services in the analysis of crystal structure by means of X-rays[39]. Sir William Lawrence Bragg remains the youngest ever Science Laureate at 25.

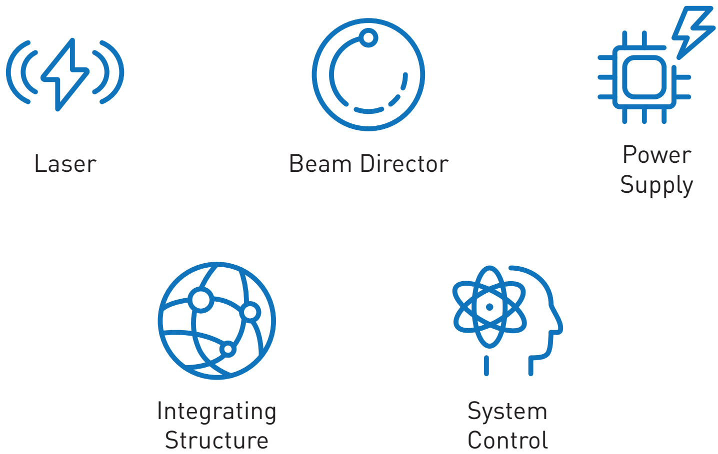
38. Distributed sensing, communications, and power in optical Fibre Smart Sensor networks for structural health monitoring, Graham Wild, 2010, ECU Research Online (https://ro.ecu.edu.au/ecuworks/6361)
39. The Nobel Prize in Physics 1915. NobelPrize.org. Nobel Media AB 2019 (https://www.nobelprize.org/prizes/physics/1915/summary/)

DIRECTED ENERGY SYSTEM: OVERVIEW

DEWs are systems with complex, integrated sub-systems. For example, a HEL system for defence applications consists of several sub-systems:

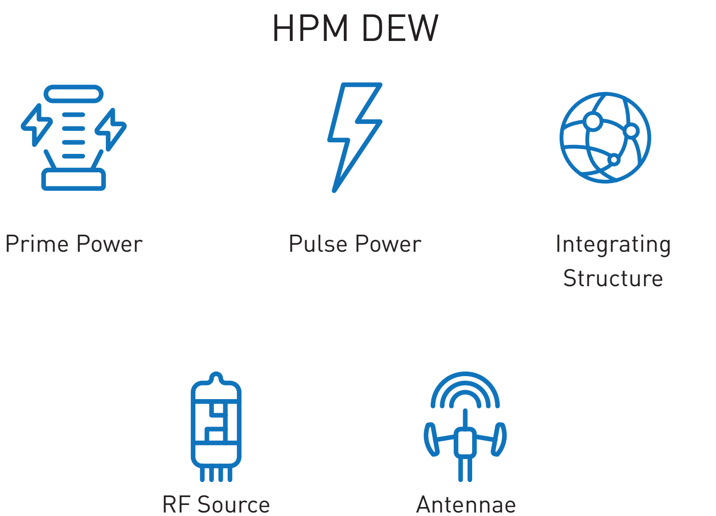
+ **Laser** generates the high-energy beam, either pulsed or continuous wave,
+ **Beam Director** directs and delivers the high-energy beam to the target
+ **Power Supply** generates the power required for the system
+ **Integrating Structure** incorporates the key enabling infrastructure that integrates with platforms
+ **Command and Control sub-system** includes a sensor system for initial target acquisition and contains the command and control system to integrate the laser into a broader operational platform.

Anatomy of a Laser System



From an HPRF perspective, the following typically applies:

+ **Power Supply** generates the power required for the system
+ **Pulse Power & RF Source** generates, amplifies and filters the RF signal
+ **Antennae** transmits the high-power electromagnetic waves (related additional components may be included to direct the waves)
+ **Integrating Structure** incorporates the key enabling infrastructure that integrates with platforms.



ADVANTAGES AND DISADVANTAGES

While DEWs offer advantages compared to conventional weapons systems, there are also disadvantages. DE and conventional weapons are complementary and together are likely to provide the optimal basis for future military roles - with DEWs unlikely to completely replace or displace alternate (or conventional) weapons.

+ Low-cost per engagement/shot
+ Ability to limit, control and target particular localised areas (i.e. discriminate targeting) unlike nuclear, chemical or biological capabilities that result in wide-area effects
+ Near simultaneous engagement across multiple threats/rapid firing (i.e. countering unmanned aerial systems)
+ Ability to be modular and scalable by design
+ Speed of targeting and travel as a defensive strategy (can be redirected and targeted – e.g. intercepting missiles)
+ Not easily tracked – weapons have the potential to emit non-visible light or inaudible sound.

- Weight of system and supporting components
- Vulnerability to atmospheric conditions and distortions (i.e. rain, fog and temperature differential)
- Complex systems (which include cooling, beam control, targeting, power supply etc.)
- HPRF has a risk of electronic fratricide or collateral damage
- High capability and sustainment cost
- Risk of human injury or physical effects on the battlespace (e.g. blinding).

TECH
NOLOGY

With global advancements in DE and DEW technologies and the push to integrate these technologies into existing defence capabilities, there is a need understand today's technologies to identify opportunities for the future. Specifically, identifying what new technologies (including disruptive technologies) could change the DE and DEW landscape in the medium to long term.

For the purposes of this Insights Paper, DE technology has been sub-divided into the following areas and includes both HEL and HPRF-related technologies:

+ **Enabling**
+ **Power Source**
+ **Laser/RF Output (including Amplification)**
+ **Effects and Mitigation/Countering**
+ **Operators and the Human Element**

The following icon table, highlights where there are technology opportunities, considerations or key areas that may provide additional avenues to explore:

Size, Weight and Power	Counter-measures	Power Sources or Electrification	Power Electonics	Autonomy, Artificial Intelligence
Intelligence, Surveillance, Reconnaissance	Materials	Antennae	Survivability	Biological or Physiological Effects
Resilience	Sovereign Capability	Critical Infrastructure	Laser Source or Beam Combination	

ENABLING

Today

Integrating DE and DEW technologies is an ongoing challenge. Different domains provide different opportunities, advantages and requirements. For example, power availability and space on a ship in the maritime domain, is considerably different to the needs of the aerospace domain.

A large portion of focus is on the SWaP of systems, to enable successful integration with existing capabilities in addition to rapid deployment. While the electrical capacity of platforms could increase, this may impact integration into an entire ecosystem (i.e. the system would stand alone, rather than being integrated with and complementing other weapons systems and/or capabilities).

Coherent beam combination technology, specific to HELs, involves 'phasing-up' to deliver the same power with less cooling requirements. It also allows for 'graceful degradation'; allowing replacement of certain components without having to replace an entire capability – replacing one in one thousand components is significantly more reliable and cost-effective than an entire platform. Coherent beam combination technologies have been successfully developed by AFRL. This technique is known as the Locking of Optical Coherence by Single-Detector Electronic Frequency Tagging (LOCSET) – the technology is scalable to a large number of array elements and smaller, therefore more easily deployable.

Photonics uses many examples of metamaterials[40] – these are specific types of composite materials (including nanomaterials[41] that have sub-wavelength features) with properties stemming from the material structure (rather than the properties of the material itself). These can have a variety of useful characteristics (not possible with bulk materials[42]) and can also be homogenous, offering the same capability as bulk materials. Some of these materials are efficient absorbers of laser wavelengths which may include the ability to stop lasers in a few nm – also allowing them to be portable and integrated into equipment.

Tomorrow

Bringing together all ancillary systems to make a true capability will be the focus in the future, as having systems operating in isolation is less feasible. Advancements in integration are already occurring, such as the example where the USN are looking to integrate with the 'Aegis' combat system.

Rapid miniaturisation will support further integration of DE and DEW technologies into a range of different platforms, including autonomous systems in the aviation environment. Advancements in miniaturisation will also reduce potential engineering and maintenance overheads. These developments will support broader utilisation of DE technologies to manage complex threats into the future.

40. Metamaterials are artificially crafted composite materials that derive their properties from internal microstructure, rather than chemical composition found in natural materials.
41. Nanomaterials are defined as the "material with any external dimension in the nanoscale or having internal structure or surface structure in the nanoscale." (ISO/TS 80004). These materials can be engineered, are incidental or natural. Nanoparticles bridge the gap between bulk materials and atomic or molecular structures.
42. A bulk material can have constant physical properties regardless of size, but at the nanoscale this is often not the case.

POWER SOURCE

Today

Over the last decade there have been significant advancements in nano-structured materials, particularly nanoelectronics. For DE technologies, power sources are in-situ, and nano storage advancements will support next steps.

If Moore's Law continues to be achieved, the rapid miniaturisation and developments in capacitors, conductors and magnetics will follow. Specific to power electronics, the current challenge relates to improving the voltage and current densities in a device – in addition to making those devices more compact. The switching of frequency means a more compact design, but there is a parallel need to understand high-frequency circuit boards.

There is a current focus on integrating supercapacitors, which is complementary/parallel to microbatteries. Solid-state microbatteries have ongoing challenges in relation to energy density.

When looking at deploying technology in the field, there are significant logistic chain considerations. Where large power output is required, large numbers of assets are needed to support the infrastructure. Advancements in the miniaturisation of power storage technologies will support more rapidly deployable systems. Additionally, while energy storage has seen incremental advancements since the 1970s, these processes are also costly and require ongoing access to rare-earth materials which may not be easily accessible or available.

Tomorrow

Energy storage is key when considering miniaturisation from large to small systems, specifically prime power systems. The challenge when looking at miniaturisation is scaling with volume. To miniaturise, there is a need to develop an understanding of nanoscale interface mechanisms to greatly enhance storage. Battery advancements, such as using lithium-sulphur or sodium-sulphur may provide further opportunities – however, the pressure on the resource sector to maintain an ongoing and consistent supply could be a challenge.

From a power electronics perspective, moving away from a traditional design philosophy for printed circuit boards towards the high-frequency design philosophy of boards will provide advantages. Focussing on power handling capability, in addition to high density, will provide opportunities for the future. Advancements in supercapacitors could also provide opportunities, combining the power density of capacitors with energy storage, to approach that of batteries (particularly when they are hybridised with pseudo capacitance (non-faradaic redox) and/or lithium-ion battery technology.

LASER/RF OUTPUT (INCLUDING AMPLIFICATION)

Today

Maintaining advancements in semiconductor technology will have a direct effect on the development of DE and DEW technologies. The use of silicon carbide, gallium nitride semiconductors are ongoing – research has resulted in an understanding that wafers have the ability to operate at 400 degrees Celsius.

Graphene is a promising material for beam scanning and as a conformal antenna, because it can be manufactured to be very thin and can have tuneable parameters. Research into reconfigurable and conformal antennae is ongoing

There is benefit for conformal antennae for commercial aircraft. For example, a Boeing 747 has more than 20 antennae mounted on the outside of the aircraft. There is only one inside the aircraft nose (for radar). The mounting of antennae (radomes) also increases maintenance costs for aircraft. As the radar antenna sits in the middle of the aircraft's nose, there is limited physical space for other antennae.

There are several technical limitations to antennae research. Firstly, it is difficult to get high gain antennae to scan an area. If antennae have a very broad beam (physically), then this is distributed over a very large area - which significantly decreases energy on a particular target/target area.

Secondly, mechanical rotation of antennae is used (now) to manually change direction and therefore affect a different target area – these move slowly and are cumbersome. Lastly, using conformal antennae is critical, particularly in the aviation environment, as systems are not wholly land based and need to be integrated to support aerodynamics and reduce maintenance costs.

From a HEL perspective, there has been a range of research into coherent and beam combination technologies. While research is ongoing, the current challenge centres around combining low-power units to achieve a 100 kW unit overall. For example, there is the ability to make a tens of GHz linewidth with multi-kW (2-5) output power, single frequency linear polarised beams – but combining this technology is a challenge, in addition to addressing SWaP constraints.

Laser diode developments will continue, although these will be incremental and will generally focus on more efficient gain mediums for optical amplifiers and energy. More broadly for HEL, beam quality and beam termination are key. There is a need to direct the maximum power onto the right area and using the appropriate wavelength (depending on the intended effect). Concurrently there is a need to understand what happens to a beam should the target be missed. Current diode limitations set the context for what can be achieved currently.

Tomorrow

While not specific to DE technologies, advancements in materials and microsystems, specifically nano and other materials will increase over the next 10-20 years. The advancements will be important, particularly in the miniaturisation of these materials. Next generation materials could be flexible, strong, non-corrosive, tailor made (from a conductivity perspective), noise and fire retardant.

Focussing on the interfaces and materials is critical as it is likely that interfaces will be key moving forward. When graphene is used in a system, it influences the material. Past focus was on the intrinsic material qualities, whereas a focus on the integration strategy will determine the interface - and will have the strongest implications for the use of the material into the future.

There could be additional focus on the interfaces, typically focus has been on volume properties alone, when emphasis could be placed on the interfaces themselves – specifically ion transfer (i.e. the reversibility of the system).

On considering 2D materials, such as graphene, there is the possibility to look at whether it can be coated (i.e. produced to conform to a shape), as well as its EM properties – whether it conducts electrical signals, and whether it is possible to shift the material's frequency band and realise beam scanning. Additionally, whether a material/system is compact and lightweight is not necessarily dependent on graphene – this depends on the dielectric constant of the material – providing the ability to pattern particular metal shapes (metamaterial) to change the material's dielectric constant from which could achieve the benefits of being compact and lightweight.

When considering antennae, designing high-gain antennae to be the pattern of a needle (physical beam pattern) is likely to occur in the future. This needle target can then be pointed to a particular area and would increase an antenna's effectiveness, and would also make it highly efficient (i.e. through the combination of needle focussing and high-speed targeting). Another consideration is the development of conformal antennae, which can be part of the outside skin of an aircraft or UAV (and can be any shape). This will increase aerodynamic performance and protect antennae (particularly on smaller devices where the antennae are being used, such as UAVs).

For semiconductors, the next phase of activity, including gallium nitride for RF platforms, related to high-power and frequency, are likely to occur. Gallium oxide and possibly diamond, may present opportunities. These advancements are also likely to support energy distribution technologies. Fundamentally, these technologies are based on ways power can be distributed.

Fibre advancements are ongoing, areas of future consideration could include Diode Pumped Alkali Laser (DPAL). The alkali-vapor laser's intrinsically high efficiency and its compatibility with today's commercially available diode arrays, enables fast-track development paths to tactical systems and power-to-mass ratios that may exceed what is possible compared to other laser.

EFFECTS & MITIGATION/COUNTERING

Today

State and non-state actors are using technologies to cause significant damage to critical infrastructure, conduct hybrid warfare and organised criminal activities. Events such as the Gatwick Airport shutdown, attacks on a Saudi Arabian oil refinery, and the transportation of illicit drugs across borders, highlights the utility of UAVs, as low-cost asymmetric tools. To counter these threats, there is a need to look to current detection, tracking and targeting technologies.

New Threats: Attacks on Saudi Arabian oil infrastructure[43]

With the complexity of threats increasing, where could DE technologies support the protection of critical infrastructure, now and into the future?

In September 2019, a Saudi Arabian oil processing facility was attacked by a 'wave of projectiles,' suspected to be UAVs.

The attacks resulted in a stop in the production of almost of 5.7 million barrels of oil over several days and caused global spikes in oil prices.

The attack on Saudi Arabian infrastructure highlights the presence of new and emerging challenges facing countries, particularly critical infrastructure, causing wide-spread effects around the world. While infrastructure is well protected from the ground, there are challenges with protecting assets from air-based attacks.

DE and DEW technologies provide an opportunity to counter multiple challenges, from smaller-scale illicit drug trafficking (through UAV use) activities to countering ballistic missiles in flight. DE technologies could be capable of limiting swarm-based attacks and attacks involving explosive payloads.

Advancements in optical, acoustic and conventional radar for tracking and targeting technologies provide the ability to target and rapidly destroy small to medium UAVs. Continued developments, specifically regarding the way to direct and control HEL or HPRF systems are ongoing – particularly with the increased use of small and agile UAVs. One of the challenges is the ability to direct DE and DEW technologies that are dynamic enough to stay on target (tracking, precision arming and engagement), for the right amount of time, particularly when the target is evasive and highly manoeuvrable.

43. Washington Post, 'Saudi Arabia oil output takes major hit after apparent drone attacks claimed by Yemen rebels (https://www.washingtonpost.com/world/drone-attacks-on-saudi-oil-facilities-spark-explosions-and-fires/2019/09/14/b6fab6d0-d6b9-11e9-ab26-e6dbebac45d3_story.html); Washington Post 'Who buys Saudi Arabia's Oil' (https://www.washingtonpost.com/world/2019/09/16/who-buys-saudi-arabias-oil/)

There is currently a conventional mindset (in the Defence context) when looking at the UAV challenge (i.e. defeating a UAV out to 1 kilometre). However, DE/DEW technologies may not be able to achieve this, instead targeting and disrupting multiple threats at a closer range is more likely as the technology provides the opportunity to control the effect and level of damage tightly, in order to avoid and counter numerous threats all at once.

There are two parts to this challenge, one is the quality of the beam (in the case of HEL systems) at the target, the second is the level of accuracy required – both are complex issues.

Research efforts to support the hardening of electronic components are already underway. These efforts include radiation-hardened architecture that protects electronics or electronic componentry in high-radiation environments, such as space. These advancements support the ongoing development of satellite instrumentation. While these are specific to the space domain, the hardening of electronics or electronic components has relevance to terrestrial DE and DEW technologies, including protection (i.e. the use of DE technologies and effects to surrounding or nearby electrical components) and countering DE and DEW technologies.

If components are used in an offensive manner, focus may also need to pivot towards protection as the same challenges will apply should DEWs be used against assets. In parallel, there needs to be an improved understanding of the effects of radiation on components.

The amount of radiation in an environment requires the design of specific component technology with dedicated radiation hardened architecture. The use of sensitive and high-performance electronics in space and Defence applications, particularly satellites and aviation (where exposure to higher amounts of radiation occurs), must consider the design of dedicated hardened technologies, that support the ability for components to withstand such harsh conditions.

Hardening for Failure: Starfish Prime[44]

In July 1962 the Atomic Energy Commission (AEC) and the Defence Atomic Support Agency (DASA) conducted a high-altitude nuclear test called Starfish Prime, the largest nuclear test conducted in space.

The test created an electromagnetic pulse (EMP) that caused widespread effects in Hawaii, disrupting a telephone company's microwave link.

In the months that followed the man-made radiation belts caused six satellites to fail, primarily due to the damaging effects of radiation on electrical components and solar arrays.

Advancements in the semiconductor industry are seeing the development and manufacture of highly sophisticated electronics components, based on transistors which are nanoscale objects made up of hundreds of atoms. The new generation of transistors are extremely sensitive to radiation damage, and damage to those may result in the complete failure of electronic systems. These technologies are being used in both the Defence and civilian context and have broad implications if targeted.

Artificial coatings can counter specific types of lasers; however, different types of lasers may match the coatings absorption spectrum – which may be enough to transfer damaging amounts of energy.

Dielectric mirrors, ablative coatings, thermal transport delay and obscurants (such as the use of smoke and smog) in additional to atmospheric and environmental conditions may be effective in reducing the effects of DE technologies.

Tomorrow

With increases in the development of high-speed, precision weapons (such as hypersonics), there are opportunities to look at ways to counter these emerging challenges. As these technologies are developed (and miniaturised), there are likely to be significant impacts on defensive response times.

44. Charles N. Vittitoe, Sandia National Laboratories (1989): Did high-altitude EMP cause Hawaiian streetlight incident (http://ece-research.unm.edu/summa/notes/SDAN/0031.pdf); Michio Kaku; Daniel Axelrod, To Win a Nuclear War, the Pentagon's Secret War Plans (1987).

Advancements in quantum computing, computational (processing) power, artificial intelligence, machine learning and augmented reality tools, may provide opportunities to explore how detection, tracking and targeting sub-systems can support DE and DEW technologies more broadly.

Advancements in both hardening and shielding technologies will be important in the use and countering of HEL or HPRF DEWs.

Understanding the radiation tolerance of critical electronics and infrastructure requires the ability to develop and build a new generation of electronics that can withstand possible radiation attacks. This includes the possibility of attacks against critical infrastructure and assets, including wide-scale adoption and use of autonomous vehicles.

Furthermore, understanding these tolerance levels is likely to support future advancements in space travel, where electronics will be exposed to large amounts of cosmic radiation for long periods of time.

Next generation electronics and semiconductors may include two categories; the first being soft – where components are damaged but continue to work (while there is data loss, corrective action could be applied); the second being hard damage (where radiation has completely affected components), for which there will need to be advancements in the development of shielding materials. These shielding materials could also have relevance when considering personnel and assets (in either the Defence or civilian context).

Shielding technologies could provide broader utility than mitigating DE or DEWs. Focussing on shielding technologies that could counter DEWs, protect personnel and 'jam' communications - while maintaining communications that are unaffected by EM Interference (EMI)/ EM Congestion (EMC) – providing the ability to protect, maintain communications and at the same time cause adverse effects against an adversary.

Additionally, the development of assets that include geometrical features, may provide additional opportunities to deflect HEL threats.

The more these types, or similar types, of technologies are available in a commercial context, the cheaper they will become over the next decade – which has a flow-on effect for Defence Industry and generates new manufacturing capabilities more broadly.

FROM EXPERT INTERVIEW

OPERATORS & SAFETY

Today

The physiological effects of DE technologies are another important consideration. While there have been efforts to understand the long-term exposure of low-level radiation on the human body, these activities have generally been for shorter amounts of time (i.e. 45 minutes at a time). Further, they do not consider side-lobe, high-power, high-frequency effects over long-term. As the technology develops, there is a need to focus on the physiological effects, to prevent harm and to support early detection.

There has been information suggesting an increase in cancers (including brain tumours), autism and inflammatory disorders due to short-term low-level RF emissions, but longer-term exposure may be a different matter. When looking at high power or HF technology, there are likely to be broad ranging effects. Even short-term studies of high-level use have indicated damage is occurring within 10 seconds. However, research has not focussed on the molecular and cellular effects – which would provide greater detail on the physiological effects. As there is the ability to sequence the genome, there may be the capability to look at physiological effects in further detail.

Current research is also exploring low-level effects by exposing bacteria to EM frequencies – showing that changes occur to the bacteria through EM radiation exposure. There needs to be strong biological infrastructure to understand what the use of high-power technologies will do to humans.

Technology has advanced, with 3D-bio-printing capabilities becoming available within the last year, allowing researchers to determine the effects of DE to cells in a 3D space – with printing being key to this process. In addition, sequencing at a single cell level is required – but there is specialist equipment required to undertake these activities. Ribonucleic Acid (RNA) sequencing at the single cell level started in 2018, which will support and advance our understanding of physiological effects, particularly in the DE space.

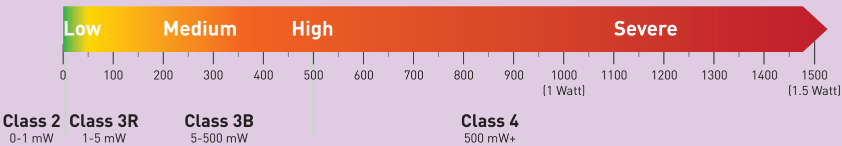
Eye-safety is another important factor. Different classes of lasers affect the human eye in different ways. The dangers of 1 micron lasers arise from the risk of scattered light being reflected into the eye during a laser's operation. Scattered light from a 100 kW laser operating at 1 micron can significantly damage the retina and lead to blindness. If lasers operate at wavelengths beyond 1.4 micron, the danger from scattered light is reduced.

Classes of Laser[45]

Lasers are classified for safety purposes according to their potential for causing injury to eyes and skin.

Most laser products are required, by law, to have a label listing the Class, which is classified as 1, 2, 3R, 3B and 4 (or I, II, IIIa, IIIb and IV).

For visible-beam consumer lasers, there are four main classes: Class 2, 3R, 3B or 4. The first two Classes are relatively safe for eye exposure; the last two are hazardous.



HELs sit within Class 4, however, their power levels are significantly greater than levels that cause eye injuries.

Tomorrow

While there are physiological challenges with DE technologies, there are also considerable opportunities – particularly in medicinal advancements; specifically imaging and diagnostics.

New diseases may emerge in the future as a result of mutations caused by exposure to these frequencies. Exploring the effects of high-level frequency to bacteria (mutations, resistance to antibiotics and emergence of new mutant bacteria) and to human cells in vitro (mutations at the cellular and molecular level) is required. Humans are only part of the challenge as this is likely to affect micro-organisms too.

45. Laser Safety Facts: https://www.lasersafetyfacts.com/resources/FAA---visible-laser-hazard-calcs-for-LSF-v02.png

Similar to electronic and electrical component hardening, there are opportunities to consider in shielding technologies, including cosmic protection, which would support space travel (including long-term space travel). Which includes, understanding the effects on the human body, and what shielding will need to be developed to support human beings exposed to, or operating within, harsh conditions.

Advancements in personal protective equipment (PPE), such as goggles that can be used for certain wavelengths, may provide additional safety to the human eye. However, understanding what wavelengths are and will be used (in offensive or defensive circumstances) is critical for this to be effective.

Additionally, exploring Virtual Reality (VR) or Augmented Reality-related technologies, to enable personnel to be removed from the battlespace entirely or be replaced with autonomous systems and capabilities that interact and perform tasks in theatre (such as autonomous firing). For example, creating a 'heads-up display' (HUD) could allow remote connection to the battlespace, where decision-making and operations are performed remotely, using technologies which cannot be affected by dangerous wavelengths (such as 1 micron).

NON-TECHNICAL

STRATEGY

Sovereign Capability

A range of DE component technology and developments requires Australia to rely heavily on international supply chains. Currently, Australia has a limited sovereign development and manufacturing capability, specifically semiconductors, semiconductor lasers and laser diodes. These challenges present a range of issues, including the ability to rapidly acquire necessary components or tools to enable and support the development of DE and DEW technologies. Although these challenges exist, there are also opportunities to develop Australia's sovereign capability to support future advancements in these technologies.

Australia has unique expertise in the development of fibre technologies, which are core to DE technologies, specifically HEL. Leveraging this expertise may be critical to support HEL developments into the future.

Broader Challenges for Defence & National Security

The advancement of DEWs, will result in significant changes to the battlespace, requiring the need to consider Rules of Engagement (ROE), doctrine, policies and procedures – in both an offensive and defensive context, in light of possibly blinding, burning or RF exposure. This may result in a shift away from conventional weapons, which will mean an increase in training (to understand the technology, terminology, safe use and maintenance) – which are likely to have flow-on effects to industry and academia (and vice-versa).

Additionally, using (either offensively or defensively) DE and DEW technologies will create additional challenges within the National Security space. This includes the protection of critical infrastructure and the use of DE technologies by policing/law enforcement bodies.

Exploring opportunities in the current legislative and policy environment will support possible adaptation or amendments into the future.

FUNDING & RESOURCES

Funding

Funding for DEWs in Australia has been limited, with industry and Defence Primes providing support through joint efforts, typically internationally.

While efforts are ongoing, the NGTF may provide additional opportunities for funding developments and priorities within Australia. The ability to fund research programs which enable and/or support the development of DE technologies, specifically with DST in Australia, will not only support Defence and National Security applications, but may also provide the basis for additional advancements in complementary fields.

Resources, Skills & Attributes

The Comprehensive Nuclear Test-Ban Treaty (CTBT) ended research to understand the EM effects from nuclear testing and associated activities. This resulted in disbanding of modelling and simulation capabilities, causing an overall loss of knowledge which has applicability across DE technology areas.

These challenges are broader than HRPF, including developing a workforce with specialised knowledge. There has been a loss and an ongoing degradation of knowledge in these fields. Therefore, developing training pathways that support ongoing research dedicated to DE technologies will be critical for the future.

There is some overlap with developments in the telecommunications industry, which could facilitate and support taking students/academics who don't have specific HPRF expertise and exposing them to concepts. But there will be limitations to this approach.

Access to appropriate testing facilities will remain an ongoing challenge. However, Australia's access to wide-open spaces and its geographic location may present some opportunities in the future. Increasingly, governments are supporting the development of unique facilities, such as Queensland's UAV/UAS testing facility. While these might support DE technology development and testing, they are multi-purpose and will increase in use and popularity across the broader UAV community.

Australia's Electromagnetic Informatics Lab (EIL)

The University of Technology Sydney's Global Big Data Technologies Centre, Electromagnetic Informatics Lab (EIL) is one of the strongest antenna research laboratories in the world.

The EIL has established well-equipped measurement laboratories that provide and support cutting-edge RF, mm-wave and terahertz (THz) testing facilities including a mini compact range anechoic chamber that is certified up to 90 GHz (the only chamber of its kind in Australia and New Zealand). In April 2018, the EIL also commenced hosting the largest near-field antenna anechoic chamber in the Australian research community, operating from 750 MHz to 50 GHz[46].

Testing Facilities: Where Next

With increasing development of HEL systems, international companies are pursuing suitable testing facilities. In early 2019, MBDA and ALPhANOV inaugurated a Vulnerability Test Facility (VTF) in Bordeaux, France.

The VTF aims to test the effects of lasers on materials - utilising laser power adjustable from 1 to 10 kW and multiple measurement means, including fast, visible and infrared imaging, pyrometers, and thermocouples.

46. University of Technology Sydney, GBDTC EIL (https://www.uts.edu.au/research-and-teaching/our-research/global-big-data-technologies-centre/our-research/mobile-0)

The VTF can simulate real-world conditions of laser firing, including the inaccuracies inherent in pointing a dynamic beam, employment against crossing and spinning targets, and the complex interactions between the laser and target materials. This allows the requirements to be defined for all the individual components of a laser weapon (laser source, aiming accuracy, beam focus etc.) and the optimisation of future laser system architectures against the various types of targets they may engage (i.e. aircraft, missiles, drones, shells, optical sensors, vehicles, naval vessels etc.)[45]. In addition to physical testing facilities, there is a need to look at facilities within universities and the tools which enable students to apply research concepts.

There are a limited range of facilities in universities across Australia, particularly where students are researching areas that have either direct or indirect relevance to DE technologies. Approaching these challenges in a collaborative manner, through cross-promotional activities, use and access may support ongoing development within Australia (in additional to internationally) supporting sovereign capability developments.

Collaboration

Cross-collaboration is critical for DE and DEW technologies. Research programs are typically isolated, whereas the ability to bring together individuals across government, industry and academia will be critical to support future developments.

This should not only comprise of individuals who have specific technical expertise in HEL or HPRF, but also other fields, such as biological sciences, and complementary activities such as research in developing antennae, semiconductors, supercapacitors, optics, EM field behaviour (propagation) etc.

47. MBDA Missile Systems, Press Release (https://newsroom.mbda-systems.com/strongmbda-and-alphanov-inaugurate-a-test-lab-for-laser-weapons-in-bordeauxnbsp-strong/).

ETHICS & PERCEPTION

Conventions, Treaties and Regulations

There are a range of United Nations (UN), World Health Organisation (WHO), and Australian/New Zealand standards (AS/NZS) which need to be considered when developing and deploying DEWs.

UN Convention: Protocol on Blinding Laser Weapons[48]

In 1995, the UN issued a protocol on Blinding Laser Weapons. The protocol sits within Article IV of the Convention of Certain Conventional Weapons. The Article contains four main points on the use of laser weapons, which include:

The prohibition to employ laser weapons specifically designed, as their sole combat function or as one of their combat functions, to cause permanent blindness to unenhanced, that is to the naked eye, or to the eye with corrective eyesight devices.

In the employment of laser systems, the High Contracting Parties shall take *all feasible precautions to avoid the incidence of permanent blindness to unenhanced vision.* Such precautions shall include training of their armed forces and other practical measures.

Blinding as an incidental or collateral effect of the legitimate military employment of laser systems, including laser systems used against optical equipment, is not covered by the prohibition of the protocol.

For the purpose of this protocol "permanent blindness" means irreversible and un-correctable loss of vision which is seriously disabling with no prospect of recovery. Serious disability is equivalent to visual acuity of less than 20/200 Snellen measured using both eyes.

48. United Nations Treaty Collection (https://treaties.un.org/pages/ViewDetails.aspx?src=TREATY&mtdsg_no=XXVI-2-a&chapter=26&lang=en); International Committee of the Red Cross, Vienna Diplomatic Conference Achieves New Prohibition on Blinding Laser Weapons and Deadlock on Landmines (https://www.icrc.org/en/doc/resources/documents/misc/57jmlc.htm)

While these cover the use of HEL in the battlespace, additional considerations regarding the monitoring of EM frequencies[49] and safety considerations around the class of lasers require consideration (in the current landscape).

Developments of DE and DEW technologies are likely to require the adaptation, amendment, and in some cases, the creation of new governing bodies, architecture and processes to support technology advancements as they occur. These largely fall realm of government, but may also impact industry and academia.

In addition to the above, the International Traffic in Arms Regulations (ITAR) creates challenges in cross-collaboration, information exchange and the development of DE and DEW technologies. While these regulations are critical and required, they can be ambiguous and add additional challenges for government, academia and industry to support future technology developments.

49. The Australian Radiation Protection and Nuclear Safety Agency (ARPANSA), in collaboration with other government agencies such as the Australia Communications and Media Authority (ACMA) support the monitoring and use of the EM spectrum within Australia.

If there is an increase in the use of directed energy technologies, then it is a good opportunity to work with the technology - particularly shields/shielding, protection and the effects on people.

FROM EXPERT INTERVIEW

Public Perception

Changing the approach to public perception of DEWs will remain a challenge. The SDI experience highlights a need to ensure the public understand these technologies appropriately and are not misinformed or misled. This will require a directed and strategic approach to communicating where DE and DEW technologies support Defence and National Security, but where broader developments in the DE space can support other technology advancements.

This includes the employment of DE technology for civilian uses and commercialisation of protective measures against DEW, such as advancements in medical technology, including imaging and diagnostics for the identification and treatment of cancers; the treatment and sterilisation of water; manufacturing and engineering advancements, including welding and smelting applications. Further enhancements include the hardening of sensitive electronics to make them resistant to harsh environments (enabling space travel and protecting critical assets/infrastructure such as autonomous systems) and developing technologies which protect human physiology against the effect of DE technologies.

It is important to recognise that advancements in the DE and DEW technology space will enable broad societal developments and through the application of appropriate messaging and broader understanding of the technology, may result in increased positive public perception.

ACRONYMS

ABL	Airborne Laser
ACMA	Australian Communications and Media Authority
ADAM	Area Defence Anti-Munitions
ADS	Active Denial System
AEC	Atomic Energy Commission
AFRL	Air Force Research Laboratory (United States)
AI	Artificial Intelligence
AID	Assault Intervention Device
ALADIN	Accelerated Laser Demonstration Initiative
AR	Augmented Reality
ARPANSA	Australian Radiation Protection and Nuclear Safety Agency
AS/NZS	Standards Australia and Standards New Zealand
ASAT	Anti-Satellite
ATHENA	Advanced Test High Energy Asset
BDL	Baseline Demonstration Laser
CHAMP	Counter-electronics High-powered microwave Advanced Missile Project
cIED	counter Improvised Explosive Device
COIL	Chemical Oxygen Iodine Laser
CSBA	Center for Strategic Budgetary Assessment
CTBT	Comprehensive Nuclear Test-Ban Treaty
cUAV	counter Unmanned Aerial Vehicle
CW	Continuous Wave

DARPA	Defense Advanced Research Projects Agency
DE	Directed Energy
DEW	Directed Energy Weapon
DIA	Defense Intelligence Agency
DOD	Department of Defense (US)
DPAL	Diode Pumped Alkali Laser
DST	Defence Science and Technology
EDTAS	Emerging Disruptive Technology Assessment Symposium
EIL	Electromagnetic Informatics Lab
EMC	Electromagnetic Congestion
EM	Electromagnetic
EMI	Electromagnetic Interference
EMP	Electromagnetic Pulse
EW	Electronic Warfare
GHz	Gigahertz
HEL	High Energy Laser
HELIOS	HEL Integrated Optical-dazzler with Surveillance weapon system
HEMP	High-altitude Electromagnetic Pulse
HeNe	Helium and Neon
HPM	High Power Microwave
HPRF	High Power Radio Frequency
HUD	Heads-up Display
Hz	Hertz

IED	Improvised Explosive Device
IREB	Intense Relativistic Electron Beams
ISO	International Organization for Standardization
ITAR	International Traffic in Arms Regulations
JHPSSL	Joint High-power Solid-State Laser
kJ	Kilojoule
kW	Kilowatt
LASER	Light Amplification by Stimulated Emission of Radiation
LD	Laser Diode
LOCSET	Locking of Optical Coherence by Single-Detector Electronic Frequency Tagging
LWS	Laser Weapon System
MHz	Megahertz
MIRACL	Mid-infrared Advanced Chemical Laser
MLD	Maritime Laser Demonstrator
MOD	Ministry of Defence (UK)
NACL	Navy Chemical Laser
NASA	National Aeronautics Space Administration
NGTF	Next Generation Technology Fund
NM	Nanometre
RELI	Robust Electric Laser Initiative
RF	Radio Frequency
RNA	Ribonucleic Acid
RN	Royal Navy
ROE	Rules of Engagement

SDI	Strategic Defense Initiative
SME	Subject Matter Expert
SWaP	Size, Weight and Power
THz	Terahertz
UAV	Unmanned Aerial Vehicle
UK	United Kingdom
UNSW	University of New South Wales
UN	United Nations
USAF	United States Air Force
USN	United States Navy
US	United States
VR	Virtual Reality
VTF	Vulnerability Test Facility
WHO	World Health Organization

APPENDIX A: SME INTERVIEWS

Organisation	Name	Role
Aether Photonics	Jae Daniel, with Michael Holzer	Founder and CEO
Australian National University	Dr Lyle Roberts	Postdoctoral Fellow, Department of Quantum Science
Coherent Nufern	Adrian Carter	Chief Technology Officer
DefendTex	Damien Cahill	Program Manager
Macquarie University	Professor Richard Mildren	Department of Physics and Astronomy, BioFocus Research Centre
Mirragin Unmanned Systems	Rob Sutton	Founder and CEO
Northrop Grumman Corporation and Northrop Grumman Australia	Josh Rothenberg, Matt McDonald & Andrew Neumann	Various
Ocular Robotics	Mark Bishop	Founder and CEO
QinetiQ	Lindsay Pears & Ian Gregory	Various
Silanna Group	Dr Petar Atanackovic	Chief Scientist
University of Melbourne	Jafar Shojaii	Postdoctoral Researcher
University of New South Wales	Professor John Fletcher	School of Engineering and Electrical Systems

Organisation	Name	Role
University of New South Wales, Australian Defence Force Academy	Professor Scott Tyo	Professor and Head of School, School of Engineering and Information Technology
University of Technology Sydney	Francesca Iacopi	Head of Discipline, SEDE Communications and Electronics, School of Electrical and Data Engineering
University of Technology Sydney	Dr Peiyuan Qin	Senior Lecturer, School of Electrical and Data Engineering
Victoria University	Daniel Lai	Electronics Engineer
Victoria University	Professor Vasso Apostolopoulos	Interim Deputy Vice-Chancellor, Research

NOTES

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EDTAS
EMERGING DISRUPTIVE TECHNOLOGY
ASSESSMENT SYMPOSIUM

Noetic
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