High Energy Lasers: A Sensible Choice for Future Weapon Systems?

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The aim of this article is to explore existing and planned military applications of High Energy Lasers (HELs). These include ballistic missile defence, anti-satellite purposes and counter-artillery missions. Analysing the military advantages and physical limits of HELs for the battlefield, the article raises major security policy questions such as crisis stability, laser countermeasures, proliferation, logistics and the operational use of different projects. Two US projects, the Airborne Laser and the Tactical High Energy Laser are described in detail.

Introduction[1]

In 1916 Albert Einstein postulated the effect of stimulated emission of radiation and thereby laid the theoretical foundations of modern laser technology. However, it was not before 1960 that the first laser, a ruby laser, was built by T.H. Maiman. Today, lasers are widely employed in both civilian and military settings. Examples for civilian applications include CD-players, medical lasers, industrial laser welding and laser induced fusion experiments. Militarily, lasers are used as range finders, communication devices and target designators for laser guided weapons.

The output power of modern day lasers ranges from milliwatts to megawatts (in cases where they deliver continuous output power), or even petawatts (10^{15} W) for short pulse lasers. In military terms, lasers with continuous output powers greater than 20 kW are classified as High Energy Lasers (HEL). Output powers in the range of kilowatts or even megawatts allow the creation of laser beams with potential harmful intensity over distances of up to several hundred kilometres. These beams can be used to heat up targets, which then may lead to structural failure of the target object.

The first military applications of lasers were developed in the mid to late 1960s, and massive financial amounts have been spent on further research and development (R&D) since. Today, a number of research programs focus specifically on laser based directed energy weapons (DEWs). In 2005, more than half a billion US dollars is spent on R&D on DEWs by the United States

[1] This article is based on a paper given by the authors at the Spring Summit 2005 of the Deutsche Physikalische Gesellschaft (German Physical Society) in Berlin. The authors thank Jürgen Altmann, Achim Maas, Björn Michaelsen and the Editor of *Security Challenges*, Christopher Michaelsen, for their helpful comments. We also thank Prof's Emmelmann (Hamburg University of Technology) and Spitzer (University of Hamburg) for their support of experimental work in this field.

(US) alone.[2] Other industrial countries such as France or Germany are conducting research in the field of HELs as well. Others, such as Russia, have done so in the past and might still have significant expertise in this field.

The aim of this article is to explore existing and planned military applications of HELs. In particular, we attempt to answer whether and to what extent investments in these weapons are sensible in the context of contemporary international security. Firstly, we will briefly examine the different military applications of laser technology. We will then introduce the technical characteristics of HELs. This scientific background is necessary in order to be able to address important security policy questions that arise from the development of HELs. These policy questions will be subject to analysis in a following section. Finally, we will survey some current HEL weapon projects. In particular, we will examine two advanced HEL projects in the US, the Airborne Laser and the Tactical High Energy Laser.

Military Applications of Laser Technology

Military laser applications can be usually divided into DEW applications and sensor applications. Some lasers, however, fit into both categories. Laser weapons are termed DEW when the energy of the laser beam is directly responsible for inflicting damage on a target object. Lasers may also be used as active sensors. This means that information is gathered using a laser beam which is emitted and then partly reflected back onto the sensor. In case the intensity of this beam is sufficient to damage a target, a sensor laser could be used as DEW as well. Table 1 summarises important military applications of contemporary laser technology.

Sensor applications	***Example***	***Status***
target illumination	laser-guided bombs	first built 1968
range finding	fire control in tanks	deployed 1976
communications	submarine communications	R&D
LiDAR / LaDAR (laser radar)	verification of chemical WMD	R&D
Directed energy weapons		
blinding lasers	British and Chinese prototypes	Illegal (since 1995),but in use several times before
point defence	defence against artillery	prototype
missile defence	airborne laser	R&D

Table 1: Military Laser Applications.

[2] For further information see table 2 and note (n.) 21.

SENSOR APPLICATIONS

The first laser-guided bombs were built for the US Air Force in 1968.[3] They are the oldest example of military use of laser technology. However, it was not before the Gulf War of 1991 that these weapons became more widely known to the general public. Laser-guided bombs rely on the principle of so-called target illumination. The target is lit up by a laser spot of distinct wavelength and modulation. A detector inside the bomb identifies this signal, and, using control flaps, the bomb is automatically guided to the designated target.

Another form of sensor application is laser range-finding. A pulse is emitted by a laser, which is part of a sensor package. The pulse is partly reflected by the target onto the sensor where it is detected. Because the speed of light is finite, there is a certain delay between the emission of the laser pulse and its detection which depends on the respective distance. Measuring this delay, the sensor's built-in electronics are able to calculate the distance to the target. This kind of laser range-finding is used in fire control systems of tanks since 1976, for example.[4] Initially rather narrow, the application of distance measurement has been widened over the years. A notable development is the so-called 'laser radar'. Laser radars employ concepts similar to those of conventional radars. Laser radars are also known as LiDAR or LaDAR. The abbreviations initially stood for Light Detection and Ranging and Laser Detection and Ranging, respectively. This is misleading, however, as the acronym 'LiDAR' is used for several different applications. Generating three-dimensional maps for cruise missiles navigation using a generalized method of range-finding is one example. It is also possible to determine the speed of moving objects using the Doppler frequency shift. Using a multi-spectral signal allows for gathering of information on the atmospheric composition as the amount of back-scattered energy depends on the wavelength of the beam and the composition of the atmosphere. One possible application of a multi-spectral LiDAR is the detection of chemical warfare agents within the atmosphere.[5]

Sensor applications are also used in the field of communication. One interesting development in this regard is the recent attempt to use lasers in submarine communication.[6] Certain wavelengths have only a small

[3] National Museum of the United States Air Force, 'Texas Instruments BOLT-117 Laser Guided Bomb', October 2002, http://www.wpafb.af.mil/museum/arm/arm21.htm – viewed April 2005; GlobalSecurity.org, 'BOLT-117 (BOmb, Laser Terminal-117)', March 2005, http://www.globalsecurity.org/military/systems/munitions/bolt-117.htm – viewed April 2005.

[4] GlobalSecurity.org, 'M1 Abrams Main Battle Tank', March 2004, http://www.globalsecurity.org/military/systems/ground/m1-intro.htm – viewed 30 April 2005.

[5] Further information about LiDAR applications can be found at P S Argall & R J Sica, 'Lidar (Laser Radar)', in T G Brown et al, (eds), *Optics Encyclopedia: Basic Foundations and Practical Applications*, volume 2 G-L , Wiley-VCH, Weinheim, 2003, http://pcl.physics.uwo.ca/pclhtml/pub/LidarPapers/Argall-Encyc-Optics.pdf, pp. 1305-22.

[6] W P Risk, T R Gosnell & A V Nurmikko, *Compact Blue-Green Lasers (Cambridge Studies in Modern Optics)*, Cambridge University Press, Cambridge, 2003, http://www.loc.gov/catdir/

absorption in water. This means that communication could be possible without the submarine having to surface. And even if the submarine has to surface for the technology to work, laser communication would still be advantageous since it would draw less attention and is easier to secure than undirected radio transmissions.

LASERS AS DIRECTED ENERGY WEAPONS

In order to use laser beams as weapons, a certain amount of laser output power is necessary. The output power depends heavily on the actual target. For so-called soft targets, the minimum power to cause harm can be very low. Blinding lasers, for example, are designed to blind the human eye temporarily or permanently.[7] As the eye is very sensitive, these weapons require only a small amount of output power. Blindness can be caused in several ways: Apart from burning the retina, a laser pulse can also rupture blood vessels inside the eye or cause a process of slow decline of the retina. At a distance of a few meters, even an output power of a few milliwatts can damage the eye because the ocular focuses the beam onto the retina. This dramatically increases the intensity of the beam. Blinding lasers were used in the Falklands conflict and in the Iran/Iraq war of the 1980s.[8] However, in 1995, these weapons were officially banned under International Humanitarian Law.[9] If the aim is to destroy hard targets rather than to blind the enemy, however, the laser requires an output power many orders of magnitude higher than that of blinding lasers. As mentioned, this article will focus specifically on HELs. The US Department of Defense (DOD) defines HELs as lasers with a continuous output power greater than 20 kW or a pulse energy in excess of 1 kJ.[10]

Technical Properties of HEL Weapons

HEL weapons are based on the propagation of a high intensity light beam from the weapon to the target. In order to use a laser as weapon, different processes have to be linked. The first is to actually create the laser beam. The beam energy then needs to be sent through the atmosphere. Finally, the beam energy must interact with the target. The target may be damaged or destroyed only if the whole process technology is successful.

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samples/cam034/2003268603.pdf , pp. 8 - 12.

[7] A Peters, 'Blinding Laser Weapons: The Need to Ban a Cruel and Inhumane Weapon', *Human Rights Watch Arms Project*, vol. 7, no. 1, September 1995, pp. 1–49.

[8] J H McCall, Jr, 'Blinded by the Light: International Law and the Legality of Anti-Optic Laser Weapons', *Cornell International Law Journal*, vol. 30, no. 1, 1997, pp. 1–44 here: pp. 5 – 6; Peters (as in n. 7), p. 3.

[9] For further discussion see below.

[10] US Defense Threat Reduction Agency, 'Section 11: Lasers and Optics Technology', in US Department of Defense, *Devloping Science and Technologies List*, Ft. Belvoir, 2000, http://www.dtic.mil/mctl/DSTL/Sec11.pdf.

From a military point of view, the use of HEL weapons has both advantages and disadvantages.[11] Some advantages from a military point of view include the following:

- The laser beam travels with the speed of light, i.e. 300 000 kilometres per second. In the vacuum of outer space the beam travels in a straight line. In favourable approximation this is also true for the propagation in the atmosphere. Compared with projectile weapons, targeting is simpler and evasion more difficult.
- Laser beams can be deflected by mirrors. Because mirrors are lighter than heavy gun towers, targeting is easier and quicker.
- The use of optical apertures with sizable diameters leads to collimated (nearly parallel) beams over distances from several hundreds to even thousands of kilometres. It has been suggested to combine this ability with space-based mirrors so that large parts of the world can be covered by only a few HELs.
- 'Ammunition' is only needed for certain laser types, e.g. chemical lasers. Many lasers only need electrical energy to operate. No further ammunition is needed if sufficient electrical energy is provided by a vehicle on which the laser is mounted.
- An attack with HELs does not leave fragments of weapons or ammunition. This makes it more difficult to identify the attacker.

Some potential disadvantages of the military use of HEL applications include the following:

- The target has to be in the line of sight of the laser if no further mirrors are used.
- Every optical aperture causes diffraction effects to the beam. As a consequence, the beam has a divergence. The beam diameter expands with distance and the intensity (power per area) decreases. This means that every laser weapon has range limits. This is true even in the vacuum of space, as the beam still has to leave the laser through an aperture and has to start off with a finite size.
- Interactions between the beam and the atmosphere further reduce the beam's range. Absorption and scattering lead to reduced intensity. Additionally, the beam heats up its own path in the atmosphere. This means that the air's index of refraction is changed depending on the beam intensity. If the temperature difference between the centre and the outer parts of the beam is sufficient, the result is so-called thermal blooming, also known as thermal lens. This leads to higher beam divergences, compared to an ideal, so called diffraction-limited beam divergence, which is caused only by diffraction. Turbulence induces similar effects. Also, for long distances, there is an upper intensity limit for beams propagating within the atmosphere. Above a critical intensity, additional non-linear effects set in and the degrees of absorption and diffraction become a function of intensity. In other words, the higher the intensity, the higher the portion of the energy is absorbed and the less the damage that is inflicted upon a prospective target.[12]

[11] G Neuneck, 'Physik und Abrüstung - Neue Waffentechniken und Rüstungskontrolle', *Physik in unserer Zeit*, vol. 32, no. 1, 2001, pp. 10–17; K Tsipis, 'Laser Weapons', *Scientific American*, vol. 245, no. 6, 1981, pp. 51–57.

[12] US Department of Defense, *Defense Science Board Task Force on High Energy Laser Weapon Systems Applications (SuDoc D 1.107:2002017434)*, Office of the Under Secretary of Defense for Acquisition, Technology and Logistics, 2001, http://www.acq.osd.mil/dsb/reports/

- Today's high power lasers have low energy efficiency and require large and costly energy sources. Small batteries can not store sufficient energy yet.

- The damage mechanism is highly dependent on the physical properties of the target. Compared to conventional explosives, it takes relatively long to destroy the target. The exact timeframe depends, among other things, on the target's reflectivity. If it is too high, the target might not be destroyed at all because most of the energy is then deflected.

- There are some countermeasures which work especially against lasers. For example, the scattering of the beam in the atmosphere can be raised artificially using a smoke screen; the reflectivity of the target can be improved by special coatings.

Despite these disadvantages and doubts about the feasibility of HEL weapons, several R&D programs are in progress.

Some Policy Questions Regarding Military HELs

MILITARY HELS AS A NEW TECHNOLOGY

Military HELs are relatively new and constitute a new type of weapon. As with any new technology, the first important question is whether and how HELs will proliferate in the future. Since there are a great number of laser applications in material processing, the first impression is that proliferation of HEL weapons might be fueled by the existence of industrial lasers. However, the equipment used in laser material processing is relatively expensive and has to be modified significantly before it can be used in a military setting. In addition, the output power of industrial lasers is usually smaller than ten kilowatts. The availability of these lasers could nonetheless facilitate research for governments keen on obtaining military HELs.

Another key question that needs to be addressed is whether and to what extent a possible future use of HELs may lead to political instabilities or to escalation of an existing conflict. One example of a potentially destabilising event is the deployment of a ground- or space-based laser anti-satellite (ASAT) weapon. In the aftermath of an attack with an ASAT weapon, the country attacked and others may be uncertain as to whether a future satellite failure is due to technical reasons or the result of an attack by a hostile power. In time of crisis, the existence of such a weapon alone might be enough to trigger further military escalation of a conflict. It is interesting to note in this context that the US first tested HELs for use against satellites in October 1997 to examine whether a ground-based HEL can blind satellite optics.[13]

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rephel.pdf, p. 103; P E Nielsen, *Effects of Directed Energy Weapons*, National Defense University Press, Washington D.C., 2003, http://www.ndu.edu/ctnsp/Nielsen-EDEW.pdf, p. 129.

[13] B S Lambeth, *Mastering the Ultimate High Ground: Next Steps in the Military Use of Space*, RAND Project Air Force, Santa Monica CA, 2003, http://www.rand.org/publications/MR/MR1649/MR1649.pdf, p. 102.

Furthermore, it is also important to examine the likelihood of technological arms race. In theory, an arms race may be initiated by the deployment of an HEL missile defence system. Countries that feel threatened by an HEL system could either try to develop such a system themselves or attempt to compensate it with other weapons. Viable options in the latter respect may include the development of technologically advanced missiles that circumvent the system altogether. Another alternative could be the deployment of a high number of missiles with the aim to 'overload' an HEL defence system. It is evident that both efforts have the potential to cause negative spill over effects on other states and to result in an arms race.

ARMS CONTROL AND DISARMAMENT

As briefly mentioned above, the use of blinding laser weapons is illegal under international humanitarian law. In particular, these weapons violate the 1995 Fourth Protocol to the Convention on Prohibitions or Restriction on the Use of Certain Conventional Weapons Which May be Deemed to be Excessively Injurious or to Have Indiscriminate Effects.[14] This protocol outlaws the use and transfer of laser weapons which are intended to cause blindness. Additionally, the signatories are obliged to take the necessary steps to prevent blinding caused by other laser weapon engagements.[15] The protocol is not applicable where collateral blinding occurs as a result of the otherwise legitimate use of military laser applications. As a consequence, the protocol might be applicable to HEL weapons only, if they are especially designed for blinding purposes. Nevertheless, the protocol seems to have had some positive effects so far. Open marketing of blinding lasers has stopped and many laser R&D programs have been aborted after the adoption of the protocol.[16] Indeed, the protocol could constitute the first step towards a comprehensive ban of all laser weapons. This would be a first step toward preventive arms control, a concept which was developed to ban the introduction of new destabilizing weapon systems.[17] Whether and to

[14] For the full text and a list of signatories see ICRC, 'treaty database of the International Comitee of the Red Cross', http://www.icrc.org/ihl.nsf/WebFULL?OpenView – viewed May 2005.

[15] The US is a special case. While they took part in the negotiations, they have not signed the protocol. Instead, there has been an unilateral declaration by the US Secretary of Defense which prohibits the use of laser blinding weapons in the US military. This declaration is considered as legally binding by scholars of international law, too; see L Doswald-Beck, 'New Protocol on Blinding Laser Weapons', *International Review of the Red Cross*, no. 310, January-February 1996, p. 285; A Stallard, 'Blinding Laser Weapons. Lethal or Otherwise?', May 2003, http://www.bark.net.au/Globalisation/gloart10.htm – viewed 10 October 2005.

[16] Compare *Ibid*. and W M Arkin & A. Peters, 'US Blinding Laser Weapons', *Human Rights Watch Arms Project*, vol. 7, no. 5, May 1995, http://www.hrw.org/reports/1995/Us2.htm.

[17] Information on the concept of *preventive arms control* can be found in R Mutz & G Neuneck, 'Rüstungsmodernisierung und qualitative Rüstungskontrolle', in E Bahr, G Krell & K von Schubert, (eds), *Friedensgutachten 1989*, Institute for Peace Research and Security Policy at the University of Hamburg, Hamburg, 1989, pp. 129–39; W Liebert & G Neuneck, 'Wissenschaft und Technologie als Faktoren der Rüstungsdynamik', in E Müller & G Neuneck, (eds), *Rüstungsmodernisierung und Rüstungskontrolle: neue Technologien, Rüstungsdynamik und*

what extent a complete ban is realistically achievable is another question, of course.

A first step towards a ban of HEL weapons would be to set limits on some of their technical parameters such as output energy or brilliance. It is also necessary to investigate the differences between laser tools, e.g. in material processing, and laser weapons to write appropriate definitions and guidelines to be able to unambiguously distinguish between them. Braid et al. and Altmann have made some suggestions how to tackle this problem.[18] Restricting HEL tools permanently to the interior of buildings would prohibit their use as offensive weapon.

If agreement on arms control measures was to be reached, the important question of verification remains. As far as long range (several hundred kilometres) laser weapons are concerned a ban appears to be verifiable relatively easily. These weapons need large optical apertures in order to prevent energy dissipation by diffraction. The resulting optical elements would require a diameter of one meter or more and need special coatings. As there is no other field of application for specially coated large diameter optics apart from long range HEL weapons, looking for these optics or indicators of their construction would be a good way to verify a ban.

The detection of a laser engagement or the source of such an engagement is a different problem. The beam itself is not visible on a radar screen and there are no remainders of ammunition after the attack. If the aim is to limit the intensity of laser beams within the atmosphere, verification may be possible by observing the scattered radiation due to interaction with the atmosphere. If the distance to the laser source is known, the beam diameter can also be calculated. Braid et al. and Prilutsky and Fomenkova have demonstrated that the intensity can be estimated using both quantities.[19]

Stabilität, Militär, Rüstung, Sicherheit 69 , Nomos, Baden-Baden, 1991, pp. 45–60; *Idem*, 'Civil-Military Ambivalence of Science and the Problem of Qualitative Arms Control: An Example of Laser Isotope Separation', in H-G Brauch et al., (eds), *Controlling the development and spread of military technology: lessons from the past and challenges for the 1990s*, VU Univ. Press, Amsterdam, 1992, pp. 43–57; T Petermann, M Socher & C Wennrich, *Präventive Rüstungskontrolle bei Neuen Technologien. Utopie oder Notwendigkeit?*, Studien des Büros für Technikfolgen-Abschätzung beim Deutschen Bundestag 3, Edition Sigma, Berlin, 1997.

[18] T H Braid et al., 'Laser Brightness Verification', *Science and Global Security*, vol. 2, no. 1, 1990, http://www.princeton.edu/%7Eglobsec/publications/pdf/2_1Braid.pdf, pp. 59–78;
J Altmann, 'Verifying Limits on Research and Development - Case Studies: Beam Weapons, Electromagnetic Guns', in J Altmann, T Stock & J-P Stroot, (eds), *Verification After the Cold War: Broadening the Process* , V.U. Press, Amsterdam1994, pp. 225–34.

[19] Braid et al. (as in n. 18); O F Prilutsky & M N Fomenkova, 'Laser Beam Scattering in the Atmosphere', *Science and Global Security*, vol. 2, no. 1, 1990, http://www.princeton.edu/%7Eglobsec/publications/pdf/2_1Pilutsky.pdf, pp. 79–86.

HEL Weapon Projects – A Brief Survey[20]

UNITED STATES

Several HEL projects in the United Sates are underway, mainly conducted by the military. A list of some projects and their funding can be found in Table 2.[21]

Discussions as to whether place HEL in space initially originated in the 1980s More recently, however, they have sparked renewed interest. The *Space Based Laser* (SBL) program as part of the missile defense projects of the second Bush Administration is primarily intended as a tool to intercept incoming ballistic missiles. The aim of this project is to fit satellites with chemical hydrogen-fluoride (HF) lasers (wavelength[22] $\lambda = 2.7\mu m$) together with high performance large diameter optics and fire control systems. It would then be possible to employ these SBLs to intercept intercontinental or medium range ballistic missiles primarily in the boost-phase of their ballistic trajectory. In the past it was also planned to apply SBLs against other satellites (as anti-satellite (ASAT) weapons).[23] However, according to the Defense Science Board, a federal advisory committee established to provide independent advice to the Secretary of Defense, for technical reasons, it has not been possible yet to launch such satellites into space.[24]

From a military point of view, a missile defence system based in outer space is appealing for several reasons. Firstly, the interactions between the beam and the atmosphere would then be reduced to a minimum. Also, positioning a missile defence system in space would substantially increase its range. Nevertheless, a space-based system also faces significant difficulties. It has been estimated that in order to reach adequate protection from hostile

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[20] The following information has been gathered through public sources. Apart from the US, it is quite difficult to find information about military laser research. The reason for this could be a more restrictive handling of this information in other countries or just the result of smaller defense budgets.

[21] The numbers are the result of our research conducted using a search engine of the US DOD's budget office, which has been available until March 2005. Our result for the ABL is identical with a publication of the United States Government Accountability Office, 'Defense Acquisitions: Status of Ballistic Missile Defense Program in 2004' (as in n. 28). Sources for the funding of the THEL can be found in n. 59.

[22] Wavelengths greater than 0.8 µm are part of the infrared, making the beam invisible for the eye.

[23] US Space Command Director of Plans, 'United States Space Command Long Range Plan – Implenting USSPACECOM Vision for 2020', March 1998, http://www.fas.org/spp/military/docops/usspac/lrp/toc.htm – viewed 14 October 2005, pp. 20, Fig. 5-2; W H Possel, 'Defense - New Concepts for Space-Based and Ground-Based Laser Weapons', *Occasional Paper - Center for Strategy and Technology*, no. 5, Air War College, Air University, Maxwell Air Force Base, United States,July 1998, http://www.au.af.mil/au/awc/awcgate/cst/csat5.pdf – viewed 14 October 2005, p. 11.

[24] US Department of Defense, *Defense Science Board Task Force on High Energy Laser Weapon Systems Applications,* (as in n. 12), p. 129.

theatre ballistic missiles, the US would require a minimum of twenty satellites in different orbits.[25] In light of the fact that each repair would require astronauts or robots to be sent into orbit, the maintenance of these satellites may prove to be extraordinary difficult. Another problem is energy supply, as the built-in power supply will cease after time, which will also require space launches to refill or repair the space-based system. Since 2002, no funds have been allocated for the SBL program in the unclassified part of the US Department of Defense's budget.[26] However, this does not necessarily imply an end of the research for space-based HELs *per se*. Some authors believe that the HEL research can proceed in 'black programmes' or under different budget titles. Hitchens et al. note, for instance (especially mentioning the SBL), that the current US administration is willing to classify controversial projects in the face of congressional and public opposition.[27]

Another project currently under research and development is the Airborne Laser (ABL) program. Also aiming for ballistic missile defense, the intention of the project is to use a Boeing 747 airplane as a flying platform for a multi-megawatt HEL. The estimated range of an ABL is between 200 and 600 kilometres. The ABL would circle around hostile missile bases and destroy launched missiles in their boost phase. The ABL will employ a chemical oxygen-iodine laser (COIL) (wavelength λ = 1.315 µm). At the moment, about 500 million US dollars are spent per year for the construction of a first prototype.[28] Further details of the ABL will be introduced below.

The Tactical High Energy Laser (THEL) is intended for point defence. Its primary task would be defending a limited area against mortars and artillery rockets. The program has already resulted in the development of a field tested prototype. This prototype managed to destroy mortars and rockets in a test environment.[29] The THEL is a ground-based chemical laser (deuterium-fluoride DF, wavelength λ = 3.8 µm). The system consists of several portable, container-sized units. Current research is aimed at building a more mobile version, the MTHEL.[30]

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[25] Possel (as in n. 23).

[26] J Lewis & J Cowan, 'Space Weapon Related Programs in the FY 2005 Budget Request', 26 March 2004, http://www.cdi.org/news/space-security/SpaceWeaponsFY05.pdf – viewed 25 October 2005.

[27] T Hitchens et al, 'Space Weapons Spending in the Fiscal Year 2006 President's Request- A Preliminary Assessment', 10 February 2005, http://www.cdi.org/PDFs/FY06-1.pdf – viewed 14 October 2005.

[28] United States Government Accountability Office, 'Defense Acquisitions: Status of Ballistic Missile Defense Program in 2004', Report to Congressional Committees GAO-05-243, March 2005, p. 59.

[29] J Shwartz, G T Wilson & J M Avidor, Tactical High Energy Laser, in S Basu & J F Riker, (eds), *Proceedings of SPIE on Laser and Beam Control Technologies*, volume 4632, SPIE, Juni 2002, pp. 10-21, http://www.st.northropgrumman.com/media/SiteFiles/
mediagallery/factsheet/SPIE_Manuscript_Tactical_high-energy_laser.pdf.

[30] US Department of Defense*, Defense Science Board Task Force on High Energy Laser Weapon Systems Applications* (as in n. 12).

The ZEUS system is a laser application used to defuse mines and unexploded ordnance (UXO) from safe distances.[31] The system's main part is a standard industrial laser, which is mounted onto a modified 'hummer' all-terrain vehicle. A beam director, an adjustable mirror, is used to guide the beam onto its targets. In the best case scenario, the explosives would burn but not explode. The range of the system is about 300 meters, the output power is only a few kilowatts. A prototype has been used in Afghanistan and is currently being tested in Iraq.[32]

Program	**SBL**	**ABL**	**THEL**	**ZEUS**
Laser	HF	COIL	DF	Nd:YAG
Applications	missile defense / ASAT	missile defense / ASAT (?)	defense against artillery	mines / UXO
Range	Global	200-600 km	5 km	300 m
Funding 2005	n.a.	approx. 500 Mio. USD	approx. 50 Mio.USD	private (Sparta Inc.)
Status	n.a.	construction of prototype	testbed	tests in Iraq

Table 2: HEL Projects in the US

LASER DEW PROGRAMS OUTSIDE THE US

Several other countries have also conducted R&D of laser DEW. These include France[33], Israel[34], China, Germany and Russia. Reports about Russian HELs tend to be inconsistent. Some authors have claimed that the output powers of systems tested by the former Soviet Union ranged from 20 kW to 1 MW.[35] After group of US scientists, led by Frank von Hippel from Princeton University, had visited a Soviet ballistic missile defence test site at Sary Shagan/Kazakhstan, it became clear that the Soviet Union had been conducting laser experiments for tracking satellites before 1989. This system

[31] ZEUS is a registered trademark of Sparta Inc., Lake Forest, CA, US.
[32] N Shachtman, 'Call it a comeback: Laser Hummer', 2005, http://www.military.com/soldiertech/0,14632,Soldiertech_Laser,,00.html – viewed May 2005.
[33] France looked into the technology of chemical lasers, too. There has been research using a DF-laser with a beam director. The project was named latex (laser associé à une tourelle expérimentale), see B Anderberg & M L Wolbarsht, *Laser Weapons: The Dawn of a New Military Age*, Plenum Press, New York, 1992; quid.fr, 'Armes ? faisceaux de particules et lasers', quid.fr, 2000, http://www.quid.fr/2000/Q055040.htm – viewed October 2005.
[34] Israel works together with the US on the THEL. The aim of the co-operation was to built a defense system against Katyusha rockets. Companies from Israel contributed the radar and the control system. Further information can be found in section 6.2 and in Shwartz et al (as in n. 29)
[35] Anderberg & Wolbarsht (as in n. 33), p.133-4.

featured a 20 kW CO_2 laser. The laser was coupled with a beam director and controlled by a simple (1960s) computer.[36]

China also seems to have developed DEWs. In early 1995, a Chinese company, Norinco, introduced a blinding laser weapon, the ZM-87, on an arms fair in the Philippines. According to a corresponding fact sheet, the ZM-87 permanently damaged the eye in a range of about 3 km and temporarily damaged it within a distance of up to 10km.[37] In October 1995 China signed the Blinding Laser Protocol (and ratified the instrument in 1998). A recent visit to Norinco's web pages revealed the absence of any advertising of blinding laser weapons.

Germany reportedly attempted to develop a gas-dynamic CO_2 laser for air defence purposes in the late 1970s.[38] The companies involved in this project were Diehl and MBB. However, it proved impossible to establish whether the project delivered any results or whether and when it was cancelled. Today, the company Rheinmetall-DeTec focuses on DEWs based on medium energy lasers. It plans to use pulsed solid state lasers against optical sensors.[39] According to the company's 2003 business report, the project is funded by the German Ministry of Defence.[40] Aside from Rheinmetall, Diehl, the European Aeronautic Defence and Space Company (EADS) and the German Aerospace Center (Deutsches Zentrum für Luft und Raumfahrt DLR) currently engage in a joint project to examine properties of a future medium energy laser weapon.[41] The project, entitled Medium Energy Laser weapon - COIL (MEL-COIL), accomplished the construction of a prototype COIL, which is located at the Federal Office for Defence Technology and Procurement and aims to assess air defence capabilities.[42] The laser developed in the course of this project has reached output powers in the 'higher kilowatt' range.[43] The MEL-COIL uses the same kind of laser as the ABL, namely a COIL.[44]

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[36] F von Hippel, 'A Visit to Sary Shagan and Kyshtym', *Science and Global Security*, vol. 1, no. 1-2, 1989, http://www.princeton.edu/~globsec/publications/pdf/1_1-2vonHippelA.pdf, pp. 165–174.

[37] Peters (as in n. 7), p.11.

[38] Anderberg & Wolbarsht (as in n. 33).

[39] G Wollmann, 'Direct Energy Weapons Close Gap: Dr. Gerd Wollmann on laser technology and high-power microwave', 2003, http://www.rheinmetall-detec.de/index.php?lang=3&fid=716 – viewed May 2005.

[40] Rheinmetall DeTec AG, 'Business report 2003', 2004.

[41] Aviation Week, 'Germans Come Closer To a Laser Weapon', *Aviation Week Show News ILA 2004*, May 2004, http://www.aviationweek.com/shownews/04ila/images/sn_ila04_3.pdf – viewed May 2005, p. 13.

[42] Deutsches Zentrum für Luft-und Raumfahrt e.V., 'Institute und Einrichtungen: Institut für Technische Physik', March 2003, http://www.dlr.de/tp/publikationen/handout/handout/itp_handout.pdf – viewed May 2005.

[43] Bundesverband der Deutschen Luft- und Raumfahrtindustrie e. V., 'EADS-LFK erforscht Lasertechnologie - Deutscher Know-how-Vorsprung mit MEL-COIL', LRI Fakten - 03/2004 Informationen aus der Luft- und Raumfahrtindustrie , March 2004, http://www.bdli.de/index.php?

Two Advanced HEL Projects in the United States

The ABL and THEL are currently the most advanced projects. The following sections will thus examine both applications in more detail.

AIRBORNE LASER

The ABL is intended to be employed as missile defence system. As indicated, in theory, a modified Boeing 747 aircraft would patrol in range of an enemy's missile bases and engage any missiles launched during their boost phase. The problem is, of course, that, depending on the size of the hostile country and the range of the ABL, the aircraft might have to fly in hostile air space. Since its speed is significantly slower than that of tactical combat aircrafts, the laser-fitted aircraft is vulnerable to attack.[45] As a consequence of diverging laser beams and the limited laser intensity delivered, the beam would have to be focused on the respective missile for several seconds. Missiles consist of a warhead and the booster. The warhead is located on the top of the booster, the latter providing the acceleration. Since the warhead mounted on the missile's top is designed to withstand extreme temperatures during re-entry into the atmosphere, the laser beam is probably incapable of destroying it, even if it tracks it for several seconds. The laser would be therefore rather employed to heat up the metal skin of the booster. In theory, the forces at work during acceleration will then tear the missile apart. If the missile is powered by liquid fuel, which is highly pressurized, this internal pressure would further accelerate this process.[46] However, this also means that the warhead would remain intact and could potentially detonate in the following crash. This problem is called 'short fall problem' and could still lead to catastrophic collateral damage.[47] 'Short fall' might endanger people living in the flying area of the ABL.

Technical Properties of the ABL

In order to raise the temperature of the missile's hull to a critical point it is necessary to focus a laser beam of sufficient intensity on the same spot for several seconds. Because of diffraction effects and interactions with the atmosphere, however, the beam is only focusable to a certain degree. As a consequence, it is imperative to supply an output power of several

option=com_docman&task=docclick&Itemid=108&bid=14&limitstart=0&limit=12 – viewed 19 October 2005.

[44] Wehrtechnische Dienststelle für Waffen und Munition (WTD91), 'Mittelenergie-Lasertechnik', Bundesamt für Wehrtechnik und Beschaffung, April 2004, http://www.bwb.org/C1256DF2004FF94C/vwContentByKey/W25YAC4W930INFODE – viewed May 2005.

[45] Another option would be to destroy all possible threats to the aircraft in advance. As these would include all sorts of surface-to-air weapons, this does not seem to be a viable choice.

[46] G Forden, 'Ballistic Missile Defense: The Airborne Laser', *IEEE Spectrum*, vol. 34, no. 9, September 1997, pp. 40-9.

[47] *Idem*, 'Laser defenses: What if they work?', *Bulletin of the Atomic Scientists*, vol. 58, no. 05, September/October 2002„ http://www.thebulletin.org/past_issues/058_005.htm, pp. 48–53.

megawatts.[48] The ABL's laser is a COIL.[49] The invention of COIL dates back to the 1970s, but as its working principle is complex, other lasers can be used more easily if output powers in the kilowatt range or below are required. Hence COILs have not matured into a standard tool so far. In a COIL, several toxic chemicals (e.g. hydrogen peroxide) react with each other in order to deliver the energy which is needed to create the beam. To ensure the safety of the crew, it is necessary to seal off the crew compartment airtight from the actual laser.

Since all of the laser's optical elements are extremely sensitive to misalignment, it is planned to use an automated sensor-actor system to work against the vibrations in the airplane. An adaptive optics system using a deformable mirror is supposed to compensate turbulence in the atmosphere between the ABL and the target. Turbulence otherwise distorts the beam. To finally shape and direct the laser beam, a 1.5 m diameter telescope will be used. The telescope will be gimbal-mounted on the aircraft's nose (see Figure 1). The engagement of the ABL begins as soon as the missile passes the cloud cover. The missile is detected by a system consisting of three other lasers and several infrared sensors.[50]

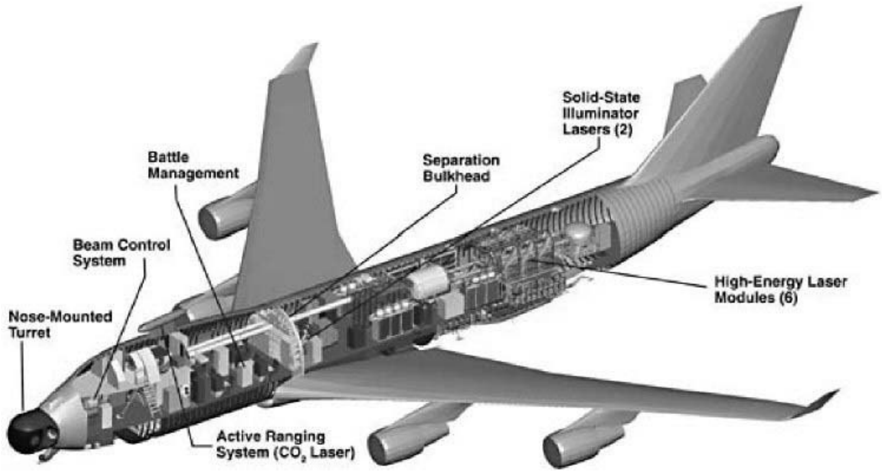

Figure 1: Planned ABL setup. Source: Boeing website.

[48] The diameter of a laser beam, which has the wavelength λ, will expand to at least Lλ/D with distance L, where D is the diameter of the laser aperture. If one assumes the distance to be L = 500 km and is using the values of the ABL, hence wavelength λ = 1.315 µm and diameter D = 1.5 m, the beam diameter will be at least 0.44 m.

[49] For more information about this particular chemical oxygen-iodine laser see D K Barton et al., 'Report of the American Physical Society Study Group on Boost-Phase Intercept Systems for National Missile Defense: Scientific and Technical Issues', *Reviews of Modern Physics*, vol. 76, no. 3, 2004, http://www.aps.org/public_affairs/popa/reports/nmd03.cfm, pp. 1– here: p. 301.

[50] Detailed information about the design of the ABL can be found in *Ibid* and in Forden, 'Ballistic Missile Defense: The Airborne Laser' (as in n. 46).

The ABL - Will it Work?

All systems of the ABL have to be perfectly coordinated in order to use the aircraft for effective missile defence. This is a very complex task. A first test of the ABL system was originally scheduled for 2002 but postponed due to technical difficulties.[51] According to a recent congressional statement by the director of the US Missile Defense Agency, the first tests of the laser system on the ground are now scheduled for 2006.[52] If successful, the COIL will then be integrated into an aircraft. A first complete test is envisaged for 2008. At the moment, however, the planned compensation for the vibrations in the airplane poses a major challenge, as vibrations hamper both the technical operation of the laser and the targeting itself.[53]

The American Physical Society (APS) formed a study group on boost-phase intercept systems in order to assess US missile defence projects. In its report it concludes that the ABL may have 'some capabilities' against liquid-propellant inter-continental ballistic missiles (ICBMs). To arrive at these conclusions, the APS 'made reasonable estimates' and 'adopted the best-case scenario' in case of doubt.[54] The APS, for example, estimated the necessary flying areas of the plane. The results make it seem unreasonable to use the ABL against large countries, because the plane would have to enter hostile air space. Figure 2 (next page) sheds more light on this particular issue. Examples for possible fields of application are missiles lauched from Iran and North Korea. In Iran, only a small part of the flying area is outside the country, whereas in case of North Korea, the ABL could eventually patrol over the South China Sea and the Sea of Japan.

The APS study also shows, that even with optimistic assumptions, the ABL would be ineffective against solid-propellant ICBMs.[55] Nevertheless, the ABL program is pushed forward, with a planned budget of 4.4 billion US dollars between 2006 and 2011.[56]

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[51] United States Government Accountability Office, 'Defense Acquisitions: Status of Ballistic Missile Defense Program in 2004' (as in n. 28).

[52] Statement before the Strategic Forces Subcommittee of the Senate's Armed Services Committee on April 7th 2005, H A Obering, 'Missile Defense Program and Fiscal Year 2006 Budget', April 2005, http://www.senate.gov/~armed_services/statemnt/2005/April/Obering%2004-07-05.pdf – viewed May 2005.

[53] misselthreat.com, 'Airborne Laser (ABL)', 2005, http://www.missilethreat.com/systems/abl_usa.html – viewed May 2005; United States Government Accountability Office, 'Defense Acquisitions: Assessments of Selected Major Weapon Programs', Report to Congressional Committees GAO-05-301, March 2005; United States Government Accountability Office, 'Defense Acquisitions: Status of Ballistic Missile Defense Program in 2004' (as in n. 28).

[54] Barton et al. (as in n. 49), p. XXII.

[55] Barton et al. (as in n. 49), p. XXII; solid-propellant ICBMs are using a different hull material from liquid-propellant missiles, which is more heat-resistant.

[56] US Department of Defense, 'FY 2006/FY 2007 budget estimates: vol. 2 - Missile Defense Agency',March 2005, http://www.dod.mil/comptroller/defbudget/fy2006/budget_justification/pdfs/rdtande/MDA_PB06_07_Budget_Submission.pdf – viewed May 2005.

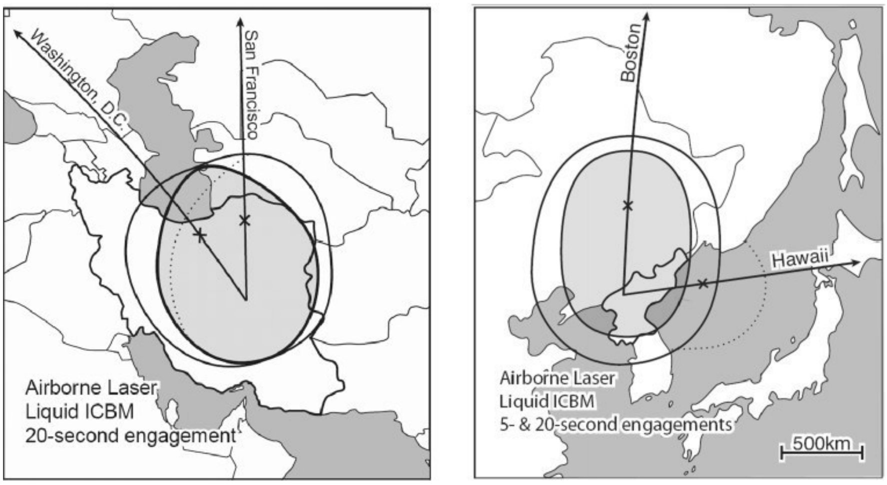

Figure 2: Left: Necessary flying area (shaded) for an intercept of liquid-propellant ICBMs launched from Iran against San Francisco or Washington D.C., if the available time for the intercept is 20 sec. If there is less time available, the ABL has to be stationed closer to the missile base. Right: Flying areas for 5 sec (shaded) and 20 sec engagements against liquid-propellant missiles launched from North Korea, heading for Boston and Hawaii. Source: APS report on Boost-Phase Intercept (as in n. 49, pp. 139, 141).

ABL Applications apart from Missile Defence?

Missile defence based on ABL applications appears to be very difficult. But are there any other possible applications of a flying HEL that justify its R&D budget? One possibility is the destruction of satellites in space. Using the ABL against surveillance satellites could be less difficult because satellites are much more vulnerable than warheads which are built to sustain re-entry into the earth's atmosphere. The optical sensors on board the satellite are built to detect weak signals from the surface. As a consequence, a high power laser beam should be able to overload and eventually destroy the sensors. Furthermore, several attempts can be undertaken in order to destroy the sensors of a specific satellite. It is difficult to decide whether it is possible to track a satellite using the sensors of the ABL alone, because a satellite is more difficult to detect by the ABL's sensors than a boosting missile. If other tracking devices are used outside the ABL, this task seems to be achievable.

TACTICAL HIGH ENERGY LASER

In contrast to the ABL, research on the Tactical High Energy Laser (THEL) has already resulted in the development and production of a prototype. Originally intended to be employed as defence against small short-range artillery rockets (Katyusha), the prototype has also been tested against mortars and large-calibre rockets.[57] The THEL system consists of radar, laser, beam director, optical tracking unit and computer-controlled command and control unit (see Figure 3). The radar is used to scan simultaneously the entire surroundings of the guarded area. As soon as e.g. a mortar round is detected, the beam director is aligned to it to use its superior optical tracking system. The laser can be activated automatically or with human intervention. A computer continues tracking until the target is destroyed or reaches it destination. Similar to the ABL, the THEL uses a chemical laser. Several toxic chemicals are used to produce chemically excited deuterium-fluoride. This delivers the necessary energy to create the laser beam. The exact output power of the THEL is classified. However, given that the US Department of Defence has described the THEL as HEL, it is likely that its output power exceeds 20 kW.

The beam director of the THEL shows a high degree of maneuverability.[58] Hence, the use of the THEL against ground targets should be possible in principle, if the control system is modified accordingly. However, the whole THEL system is not movable during its operation. As a consequence, the US DOD initiated a R&D program to develop a mobile version of the system called mobile THEL (MTHEL).

At the moment it is unclear whether the MTHEL program has any future. In the 2005 budget of the US DOD, the MTHEL program is funded until 2009. A first test was scheduled for 2007.[59] Until 2009, 340 million dollars have been allocated. In the 2006 budget, however, the program is noted as cancelled. The remaining 2005 funding is to be used for limited tests, the production of an initial engineering design, and the preparation of the THEL for storage.[60]

Nevertheless, on 4 May 2005, Northrop Grumman (NG), the main contractor of the MTHEL program, held a press conference entitled 'Directed Energy: Out of the Lab - Onto the Battlefield'. According to Reuters, NG recommended use of the THEL in Iraq to guard against 'insurgents mortar

[57] Northrop Grumman, 'Press release: Northrop Grumman-Built High-Energy Laser Destroys Large-Caliber Rocket in History-Making Test', Northrop Grumman, Redondo Beach, CA., US, May 2004, http://www.irconnect.com/noc/press/pages/news_releases.mhtml?d=57129 – viewed May 2005.

[58] Northrop Grumman, 'Press Kit Lists: Tactical High Energy Laser - Media Gallery', 2005, http: //www.st.northropgrumman.com/media/MediaGallery.cfm?MediaType=Videos&PressKit=23 – viewed May 2005.

[59] US Department of the Army, *Supporting data FY 2005 president's budget submitted to OSD - descriptive summaries of the research, development, test and evaluation army appropriation, budget activities 4 and 5 - Vol. II*, edited by Office of the Secretary of the Army (Financial Management and Comptroller); Department of the Army , February 2004, http:// www.asafm.army.mil/budget/fybm/FY05/rforms/vol2.pdf – viewed May 2005, p. 24, 27-28, 33.

[60] *Idem*, *Supporting Data FY 2006/2007 President's Budget Submitted to OSD - Descriptive Summaries of the Rresearch, Development, Test and Evaluation Army Appropriation, Budget Activities 4 and 5 - Vol. II*, edited by *Idem* , February 2005, http://www.asafm.army.mil/ budget/fybm/FY06-07/rforms/vol2.zip, p. 21.

and rocket fire'. Reuters further reported that, according to NG, US Army officials had 'balked' at deploying the THEL so far for logistics and safety reasons.[61] At the same press conference NG also promised that these concerns could be addressed and announced the development of a smaller point-defense HEL weapon within two years. On 4 May 2005, Army officials involved in the matter were unavailable for comments for Reuters, but on 10 May 2005, a US Army officer was quoted in stating that no decision had been announced by the Pentagon about a deployment of the THEL.[62]

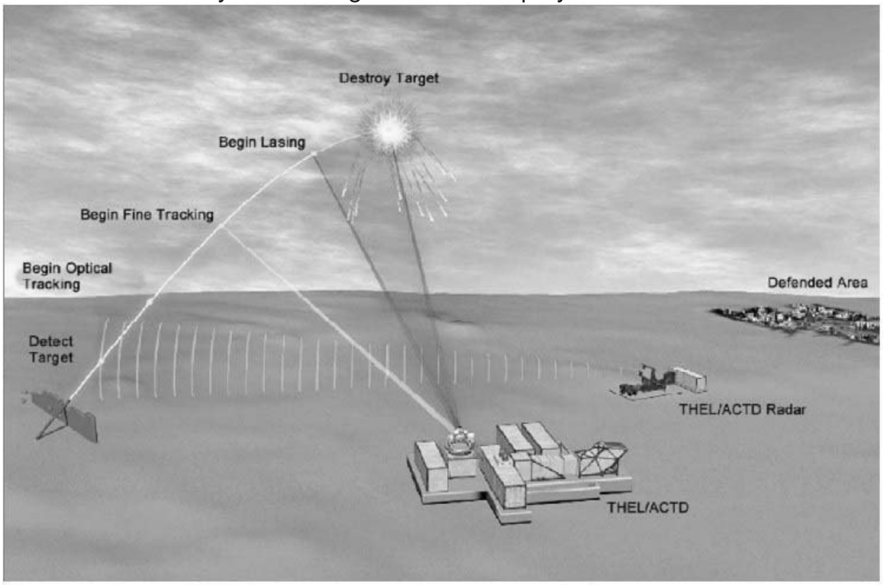

Figure 3: Progress of a THEL Engagement. Source: Shwartz et al. (as in n. 29).

It seems that at the time of writing (October 2005), a deployment of the THEL in Iraq has not occurred. A major concern is probably the supply of the laser's chemical fuels. These fuels cannot be produced on site and this creates a severe logistical problem. The fuels also represent a security hazard as the chemicals used are highly toxic. This can cause problems during the transport of the fuels and also on the deployment location. One source reports that the THEL is capable of shooting down a maximum of twelve targets per minute, i.e. it takes at least five seconds to shot down one mortar round.[63] As a consequence, it would be possible to overwhelm one system with a coordinated attack, if, for instance, several mortars were fired

[61] Reuters, 'US Army balks at sending laser weapon to Iraq', 5 May 2005, http: //www. reuters. com/newsArticle . jhtml?type=topNews&storyID=8390401 – viewed May 2005.
[62] defensetech.org, 'Ray Hun Two Step: Lasers to Iraq?', May 2005, http: //www. defensetech.org/archives/001540.html – viewed May 2005.
[63] M Becker, 'US-Armee erwägt Einsatz von Laserwaffe im Irak', *Spiegel Online*, May 2005, http://www.spiegel.de/wissenschaft/mensch/0, 1518,355681,00.html – viewed 12 May 2005.

simultaneously from different directions onto the THEL. Hence the possibility of a successful attack on the THEL's fuel tanks has to be taken into account. And a successful attack which might be as hazardous as an attack with chemical agents.

Conclusion

Since the invention of the laser, R&D has been funded to explore possible military applications. So far, High Energy lasers (HEL) in the form of directed energy weapons (DEW) have not been deployed on the battlefield. HELs, however, have matured enough to run in test mode. Hence, it has been possible to build DEW prototypes like the THEL. There are several existing HEL projects, especially in the US. It can therefore be expected that HEL weapons will be introduced in a combat situation sooner or later. Whether these weapons will have the promised capabilities (e.g. as missile defence systems) is uncertain since major technical, logistical and military problems remain to be solved.

As far as short-range HEL weapons are concerned, solutions to these problems cannot be ruled out in the long run. However, as far as long-range weapons are concerned, there are certain physical limits, which cannot be bypassed. As a consequence, it seems unlikely that projects like the ABL will work under every condition, especially not if an adversary can employ effective countermeasures. Nevertheless, the appearance of HEL weapons raises several important policy questions by itself. In addition, it has to be investigated, which other applications might become avaible beside the advertised ones. Such applications may include weapons designed for blinding, arson and anti-satellite (ASAT) warfare. A potential use of HELs as ASAT weapons, for instance, might be destabilizing for international security and could trigger a technological arms race in outer space. Given these arguments, from our point view, further investment in HEL DEWs does not seem to be a sensible choice.

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