Directed Energy Weapons

part 1

Dr Carlo Kopp

Directed Energy Weapons (DEW) have been a recurring theme in science fiction literature and cinema ever since H.G. Wells published the 'War of the Worlds' in 1898. The idea of a 'death ray' that can instantly destroy or burn a target at a distance retains its allure to this very day. More than a century after Wells contrived his 'heat ray' the technology is maturing to the point of becoming deployable soon.

High Energy Laser weapons have been evolving since the 1960s, a path punctuated by a series of important scientific breakthroughs and engineering milestones.

The popular view of a HEL, seen as constructing a huge laser and pointing it at a target with the intention of vapourising it, bears only vague similarity to a real HEL weapon. There are genuine technological and operational challenges involved in creating truly useful and effective weapons.

Kinetic or projectile weapons such as guns, missiles and bombs destroy targets by kinetic effects, including overpressure, projectile, shrapnel and spalling damage, and incendiary effects. The result is structural damage and fire, which can and often will cause fatal damage to a target. A kinetic weapon thus uses stored chemical energy in propellants and warhead explosives, where used, and delivers this energy to a target by means of a projectile of some kind. Whether the projectile weapon is a trebuchet tossing a large rock over 300 yards, or a multimode seeker-equipped long range air-to-air missile hitting an aircraft from 200 nautical miles away, the underpinning principle is much the same, only the implementation is different.

At the most fundamental level, Directed Energy Weapons share the concept of delivering a large amount of stored energy from the weapon to the target, to produce structural and incendiary damage effects. The fundamental difference is that a Directed Energy Weapon delivers its effect at the speed of light, rather than supersonic or subsonic speeds typical of projectile weapons.

Two of the most fundamental problems seen with projectile weapons – getting the projectile to successfully travel a useful distance and hit the target, and then produce useful damage effects – are problems shared by Directed Energy Weapons. Having a powerful laser or microwave emitter maketh not a Directed Energy Weapon system alone.

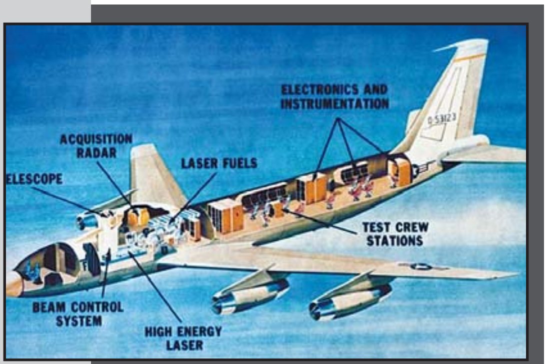
Most contemporary literature lumps together a broad mix of weapons technologies in the Directed Energy Weapon category, including High Energy Laser (HEL) weapons, High Power Microwave (HPM) weapons, particle beam weapons and Laser Induced Plasma Channel (LIPC) weapons. The first two of these four classes of weapon are genuine Directed Energy Weapons. Particle beam weapons are best described as a form of projectile weapon, using atomic or subatomic particles as projectiles, accelerated to relativistic speeds. The LIPC is a hybrid, which uses a laser to ionise a path of molecules to the target, via which an electric charge can be delivered to cause damage.

Of these four categories, HELs have the greatest potential in the near term to produce significant effect. HPM technology has similar potential but has not been funded as generously and lags well behind lasers. LIPC has significant potential especially as a non-lethal weapon. Particle beam weapons at this time are apt to remain in the science fiction domain, as the weight and cost as yet do not justify the achievable military effect.

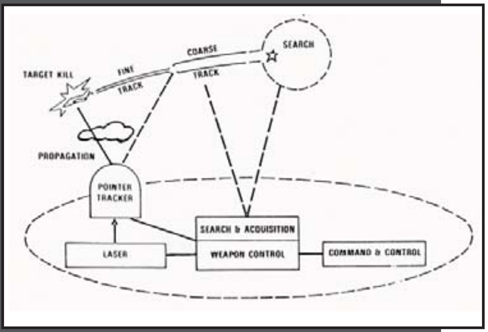
Peace Through Light - the Airborne Laser Lab Program

The first laser was demonstrated as early as 1958 but by the early 1970s it was clear to the US DoD that an airborne laser weapon was feasible using existing laser technology, an idea actively promoted during the late 1960s by physicist Dr Edward Teller, co-inventor of the hydrogen bomb. This led to a series of experiments during the 1970s to demonstrate viability and to identify problems.

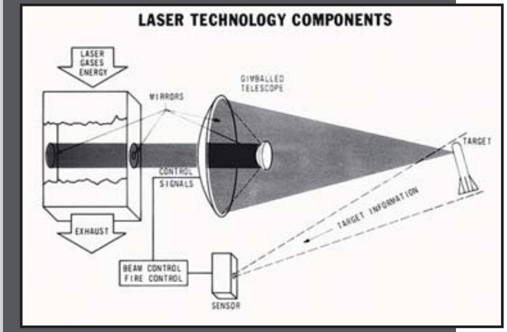
The first such experiment was in 1973 when the USAF shot down a winged drone at their Sandia Optical Range, New Mexico, using a carbon dioxide GDL and a gimballed telescope. Then in 1976 the US Army employed an electrically pumped HEL to destroy a number of winged and helicopter drones at the Redstone Arsenal in Alabama. The USN, in March 1978, then engaged and destroyed an Army TOW missile in flight, using a chemical laser developed by DARPA/USN and a pointer-tracker developed by the USN. These tests were carried out at San Juan Capistrano near Camp Pendleton in California, as part of the Unified Navy Field Test Program.



The ALL system was complex enough to fill a KC-135A fuselage, with the HEL weapon located in the forward and centre fuselage areas, and test crew in the aft fuselage (USAF).



Schematic of ALL Enagement System (USAF)



The US Air Force launched their Airborne Laser Lab (ALL) program in 1976, under the motto 'Peace Through Light'. The aim of this effort was to construct a technology demonstrator, carried on modified NKC-135 Stratotanker serial number 55-3123, which could successfully track and destroy airborne targets.

The ALL system used a gas dynamic laser with CO2 - N2 - H2O propellants and a 10.6 micron operating wavelength. Pratt & Whitney Aircraft supplied the laser, Rocketdyne the combustor, Hughes the optical pointing and tracking system, Perkin Elmer the dynamic alignment system, with GD performing system integration.

The ALL laser system combustors operated at 55 atmospheres of pressure, at 1900 K temperature, driving nickel plated nozzles with an output velocity of Mach 6. The optical resonator used one concave and one convex mirror, with beam extraction via an aerodynamic window, produced using high pressure nitrogen gas, with the efflux at 0.1 atmospheres of pressure. The ventral exhaust port, forward of the wing root under bomb bay like doors, used a corrugated titanium diffuser and vented gas at 870 K temperature, delivering a thrust of 4,000 lbf when operating. The supporting fuel system stored CO and N2O gas in stainless steel tanks, liquid Helium and Nitrogen in stainless steel tanks, with additional water coolant tanks for the mirror and combustors.

This laser produced a raw output of 456 kiloWatts of optical power in an eight-second sustained run, and an output from the optical aiming system of 380 kiloWatts, reported in 1979 literature. At a distance of 1 kilometre, the delivered power density was over 100 Watts/cm2.

The ALL project ran for 11 years, culminating in a series of trials during which five AIM-9 missiles were shot down, and a single BQM-34A Firebee drone destroyed.

While the ALL attracted much media attention as the world's first airborne laser weapon, its real value was in the enormous amount learned during the program. Several key problems rose to prominence.

The first was the issue of power losses in the optical feed, tracking and beam pointing system. Not only did waste heat have the potential to wreak havoc inside the system but also dust particles inside the system when hit by the intense infrared beam would be propelled at high velocity as they partly vaporised and damage optical surfaces. Clean-room air quality was required.

It also became evident that high precision target tracking equipment was needed, and the whole beam-pointing system required extremely low jitter when tracking a target. The aim was to put a 'football sized' spot on the target and 'dwell' the beam for long enough to burn through the skin of the target and cause serious damage. Jitter in beam pointing significantly reduced effect, the problem worsening with increasing distance.

Beam propagation through the atmosphere also presented anticipated and unanticipated problems. Water vapour molecules, water droplets and carbon dioxide molecules soaked up the beam, causing localised heating along the beam path and this caused the beam to dissipate. This effect was termed 'thermal blooming' and would become more severe as beam power levels increased. A general limitation of all HEL weapons is an inability to penetrate cloud, dust clouds or haze, which scatter and soak up the beam's power rapidly.

Target damage effects were another issue. Not only did the HEL laser beam have to operate at a wavelength that would experience a minimum of absorption by atmospheric molecules, but it also had to be capable of rapid absorption by structural materials making up the skin of the target. Aluminium for instance has around 98 per cent reflectance for the 10.6 micron CO2 laser.

Other problems arose as a result of scintillation due to turbulence in the atmosphere, which is characteristically made up of pockets of air with slightly differing temperatures. Slight temperature differences mean slight air density differences, and this causes the beam to refract (bend) ever so slightly as it passed between two pockets of air. With thousands of such distortions along the beam path, this problem presented a difficult obstacle to achieving useful range, especially during low altitude operations, as the beam would be severely defocused along the way.

The ALL NKC-135A was retired in 1984, and sent to the Wright-Patterson Air Force Museum in 1988.

Boeing/TRW/LM YAL-1A Airborne Laser Concept (USAF)

The Star Wars Breakthrough – Adaptive Mirrors

The much maligned Reagan era Strategic Defense Initiative or 'Star Wars' program, intended to drive the Soviets to bankruptcy, yielded one very important dividend for the world of HEL weapons, and that was the adaptive mirror.

At the time of the ALL experiments, solutions were in sight for most if not all the practical problems encountered with HEL weapons. Lasers could be scaled, optics made larger, tracking systems more accurate and longer ranging, but the problem of penetrating the turbulent and thermally inhomogenous atmosphere was not solved.

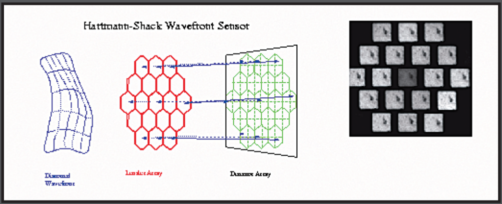
To penetrate the atmosphere without defocusing beam distortion, the beam itself would have to be 'pre-distorted' as it leaves the optics of the HEL weapon, so that the wavefront of the beam arrived at the target undistorted and precisely focused. While this is a simple idea in concept, it is harder in practice; the motion of the HEL platform, motion of the target and movement of the air mass force the need for the pre-distortion of the beam to change continuously. Any solution thus had to include apparatus for continuously measuring the distortion along the path to the target, and a mechanism to continuously distort the HEL beam. Two technologies were developed to solve this problem.

One is the adaptive or deformable mirror, which has up to hundreds or thousands of miniature actuators, each of which can locally raise or depress the surface of the mirror, to distort the beam in a controlled fashion. These 'rubber mirrors' are capable of distorting the wavefront in a controlled fashion, with enough accuracy to compensate for atmospheric problems.

The second technology is a form of Lidar (laser radar) which is used to continuously measure the distortion along the beam path to the target. These systems illuminate the target with a lower power laser operating at a wavelength similar but not identical to the HEL weapon. This laser illumination is backscattered off the target and then fed into a device called a wavefront sensor, which measures the distortion across the whole cross section of the beam path to the target. The most commonly used device, the Hartmann-Shack wavefront sensor, uses an array of tiny 'lenslets' placed infront of an imaging device like a CCD. If the wavefront is perfectly flat, a dot appears centred beneath each of the lenslets. If part of the wavefront is distorted over the position of a lenselet, the dot's position moves in a manner specific to the direction and size of the distortion.

In a HEL weapon system, the Lidar and wavefront sensor are used to continuously measure the distortion along the beam path, and produce corresponding commands to the actuator array used in the deformable main mirror, which reflects the high power HEL beam to the target.

Airborne Laser Laboratory (USAF).



Hartmann Shack Wavefront Sensor (Kiepenheuer-Institut für Sonnenphysik)

This image shows a technician working on the optical telescope turret of the ALL HEL weapon. Note the array of ancillary optical sensors (USAF).

The AL-1A Airborne Laser (ABL)

The solution of the beam distortion problem paved the way for an operationally viable HEL weapon system. At the end of the Cold War the SDI program was quietly killed off, but some key proposals survived. The Airborne Laser (ABL), envisaged as a follow-on to the ALL program, but with an operational role, was one of these. In 1996, the US Air Force awarded a US$1.1 billion contract to Boeing, TRW and Lockheed-Martin to develop a prototype ABL system, to be carried in a Boeing 747-400 aircraft. The ABL was to use a MegaWatt class COIL HEL weapon and a system to compensate for atmospheric distortion, to permit boost phase attacks on ballistic missiles.

A single ABL system would thus defend a footprint of hundreds of kilometres diameter, attacking and destroying launched ballistic missiles during their boost phase - when they are most detectable, slowest and most vulnerable due to heavy fuel load, pressurised fuel tanks and structural stresses.

Ballistic missiles have thin load bearing skins, which are heavily stressed during the boost phase, while the missile boosters are largely filled with pressurised high energy propellants. Therefore, even slight damage to the booster skin will cause catastrophic failure with results seen many times over during failed launches of satellite launch vehicles.

The ABL would be deployed in time of crisis to the borders of a nation threatening the use of ballistic missiles, and should they be launched, destroy them, ensuring that debris with WMD warheads falls on the launching party.

At the time the ABL was conceived, these nations included Iraq, Iran and North Korea. With ongoing growth in Iran's and North Korea's arsenals, and their efforts to deploy nuclear warheads, the ABL could prove to be a vital asset if either of these nations achieves their aims.

One of the design aims of the ABL system was to carry enough laser fuel to destroy 20 to 40 missiles during a single 12 to 18 hour sortie. The ABL would orbit near the border of a threat nation and engage missiles as soon as they cleared the cloud base and within line of sight.

The capabilities of the ABL system have raised the prospect of another operational application, which is the Anti-Satellite (ASAT) role. In the ASAT role the AL-1A would fly an intercept profile to intersect the ground track of a low orbit reconnaissance or surveillance satellite, or manned space vehicle, and damage or destroy it. While satellites are more robust structurally than ballistic missiles, the ABL delivers more power over the same distance when attacking an orbital target, due to the much lower atmospheric density along the beam path, compared to an atmospheric target. Satellites are also equipped with sensitive optics and vulnerable solar panels. Suffice to say even public debate on this application elicited loud complaints from non-US operators of military satellites.

Part 2 will complete discussion of the ABL, and explore other HEL programs, HPM and LIPC weapons.

Further reading:
http://www.ausairpower.net/dew-ebomb.html

Early High Energy Laser Evolution

The connection between laser and microwave weapons runs deep, both in terms of the physics and the evolutionary history of these technologies.

The basic physics of the Maser and the Laser are the same. Dr Charles Townes, who co-discovered the Maser (Microwave Amplification by Stimulated Emission of Radiation) in 1953 at Columbia University, later collaborated with Dr Arthur Schawlow at Bell Labs to create, in 1958, the first Laser (Light Amplification by Stimulated Emission of Radiation).

Both Lasers and Masers act as amplifiers of electromagnetic radiation, and if equipped with mirrors to bounce this radiation back and forth inside the device, can act as oscillators and thus sources of electromagnetic radiation.

The inner workings of both devices rely on a phenomenon called 'stimulated emission' whereby an atom or molecule which has been excited to a given energy level, will emit that energy as a photon in the visible light or microwave bands, if it is hit by another photon with exactly that energy level. If you can excite a volume of gas or other material, within which a large proportion of atoms or molecules are of a specific type, with specific energy levels, shooting a single photon of that energy level into the volume will see a cascade effect, with a vastly larger number of like photons coming out the other end.

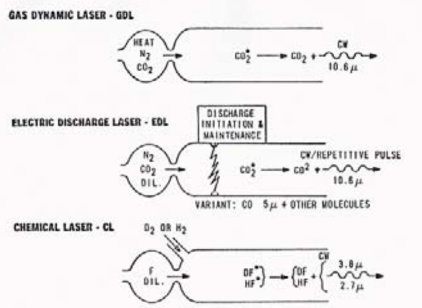
In practical terms such a device converts the energy used to excite the material, into a stream of light or microwave photons of a specific wavelength or colour. The process of exciting the device is termed 'pumping'.

Pumping can be achieved in a variety of ways, using light (flashlamps or other lasers), electrical discharges (in gas lasers), electrical current (semiconductor lasers) or shockwaves in gas flows (Gas Dynamic Lasers or Chemical Lasers).

The earliest lasers of interest involved the use of crystal rods, for instance made of ruby, or discharges in argon or carbon dioxide gas. Because lasers produce light that is coherent and almost spectrally pure, that light can be easily focused. By the mid 1960s researchers were producing many kiloWatts of power and burning holes into plates of metal and other materials.

Unfortunately, crystal rod lasers and gas discharge tube lasers suffer a common problem, power conversion efficiency, typically at best several per cent. As a result most of the power put in to pump the device is converted into waste heat. A period example is a gas discharge laser with a total length of 60 metres producing a mere nine kiloWatts of power, yet wasting at least ten times as much.

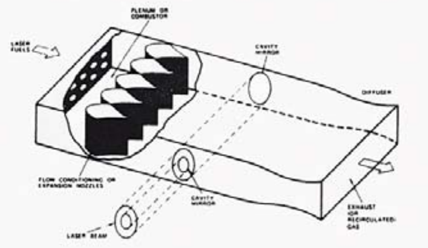
THERMAL (GDL & CL) vs ELECTRICAL LASERS



Before any weapons application was feasible, researchers needed a laser technology suitable for generating hundreds of kiloWatts or MegaWatts of power, and had a conversion efficiency in the tens of per cent.

In the early sixties a number of physicists suggested it may be possible to pump a molecular gas to laser action by rapid heating or cooling. Further research showed that such cooling could be achieved through the expansion of a heated gas through a supersonic nozzle. In 1966, a team of physicists and engineers working for Avco Everett constructed and operated the world's first Gas Dynamic Laser (GDL), operating on a mixture of C02, N2 and H20. By 1970, continuous power outputs of 60 kiloWatts were being generated and a 1973 pulsed GDL delivered 400 kiloWatts for 4 milliseconds. It was then clear that High Energy Laser weapons were feasible.

This technology was the basis of the subsequent US Air Force Airborne Laser Laboratory and underpins the current chemical laser technology used in the YAL-1A ABL system.



SCHEMATIC DIAGRAM OF A HIGH POWER LASER

Gas Dynamic Lasers, now termed Chemical Lasers (CL), bear more similarity to rocket engines than the commonly popularised rod laser. A laser propellant, comprising a suitable mix of chemicals, is combusted or reacted and the exhaust efflux is then directed into an expansion nozzle. The exhaust stream from the expansion nozzle contains highly energetic molecules, which due to the choice of propellants and added agents, have effectively been pumped to a state where laser action can occur. If a pair of aligned mirrors is placed to either side of the exhaust stream, laser action will occur as photons bounce between the mirrors, and power can be extracted if one of the mirrors optically 'leaks'.

While simple in principle, the design and construction of a Chemical Laser is anything but trivial. Combusters operate at temperatures as high as 1000 to 2000 deg C, depending on the laser fuel mix used. The expansion nozzles require precisely controlled flow conditions to work, which results in a complex exhaust system designed to produce the required pressure and flow rates. Some laser fuels and/or their exhaust efflux can be highly corrosive and/or toxic. Mirrors must have very low optical losses, since even a one per cent loss in a 1 MegaWatt laser results in 10 kiloWatts of waste heat dumped into the mirrors.

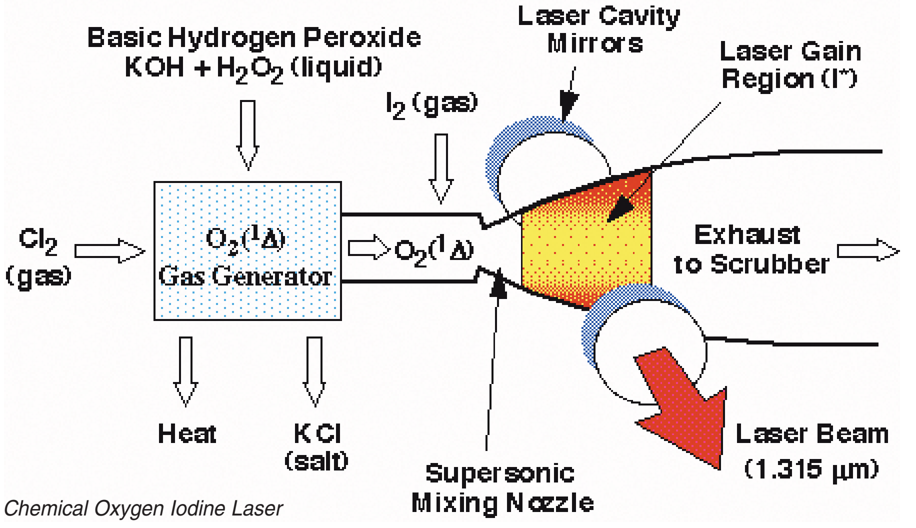
The first chemical laser carbon monoxide (CO) burned in oxygen-nitrogen, with water added to produce the same 10.6 micron band laser action used in carbon dioxide gas discharge lasers. CO burning in N20 and benzene (C6H6) burning N20 were also explored as fuels.

While a single laser, comprising a combustor, expansion nozzle and exhaust duct could produce respectable power levels, it was clear that many such devices needed to be cascaded to produce power levels suitable for weapons applications. This is why all contemporary chemical lasers use batteries of smaller lasers to produce the final high power output beam.

While the carbon dioxide laser was the first in this class it was soon followed by the Hydrogen Fluorine (HF), Deuterium Fluorine (DF) and Oxygen Iodine (COIL) lasers. The HF laser uses atomic fluorine and molecular hydrogen to produce 2.7 - 2.9 micron band radiation, using typical fuels such as highly toxic SF6 or NF3, with hydrocarbons used to produce hydrogen. Its later sibling, the DF laser, uses ethylene (C2H4) burned with a nitrogen trifluoride (NF3) oxidiser, into which deuterium and helium are injected, to produce 3.6 to 4.2 micron band radiation.

The most significant of these three discoveries was the Chemical Oxygen Iodine Laser (COIL), invented by the US Air Force Weapons Laboratory in 1977, and now used in the YAL-1A system. The COIL emits in the 1.315 micrometer range, and uses chlorine gas and an aqueous mixture of hydrogen peroxide and potassium hydroxide to produce excited oxygen molecules, which are reacted with molecular iodine to produced the laser medium, and which is then passed through the expansion nozzles. Conversion efficiencies above 20 per cent were demonstrated very early.

As is clearly evident, building a large laser may be the basis of a HEL weapon but a considerable amount of hardware will be required to actually put it to use.



Chemical Oxygen Iodine Laser