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# Directed Energy Applications for High Power Vacuum Electronics

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## Directed Energy Weapons

Directed energy technologies are advancing rapidly and are now beginning to be applied to meet the needs of national defense. While these technologies have been described by some leading military thinkers as “the next arms race”, directed energy technologies and their impact on warfare are not well-understood by the warfighter, since the hard lessons of the battlefield have not yet been taught, and indeed, rapid progress is being made in these technologies so it is difficult to forecast the future of directed energy with certainty. Some trends, however, are apparent to thoughtful observers.

In recent years, the changing face of warfare is creating opportunities for the insertion of directed energy weapons on future battlefields, which are now described as consisting of air, space, land, sea, and cyber domains. The cyber domain is the information world that gathers, processes, and disseminates all the information necessary to wage war, to anticipate, find, fix, track, engage and assess effects on targets: “anyone, anywhere, anytime”. The cyber domain is linked to all the other domains, which contain sensors, weapons platforms, personnel, command and control assets, etc. The breadth and pace of warfare, continuing the trend of many centuries, continues to accelerate, pushed by technology. The presence of reporters embedded in combat units, with near instantaneous relay of information and images to a sleepless global media is also impacting warfare.

It is therefore increasingly important, when the use of force is necessary, to use that force in ways that will minimize collateral damage and non-combatant casualties, and reduce post-conflict reconstruction costs, while still rapidly winning the fight. Directed Energy Weapons (DEWs) have many characteristics that potentially offer these benefits.

DEWs are sometimes classified by the type of technology: high energy lasers, high power microwaves, millimeter-waves, and particle beams, both charged and neutral. Particle beams are not presently a major area of technology development, and will not be mentioned further. The remaining technologies project beams of electromagnetic energy towards targets. The energy moves at the speed of light and the weapon cannot therefore be dodged. To the warfighter, this velocity is best communicated as nearly a

million Mach, or a muzzle velocity of nearly a billion feet per second - far exceeding the speed of conventional kinetic weaponry. Many DEWs require the beam to dwell on the target so the deposited energy can achieve the desired effect.

A wide variety of effects can be caused by DEWs, ranging from denying the use of a sensor to destruction of a target. Effects can also be described as ranging from non-lethal to lethal. Non-lethal weapons are defined by the Defense Department (Ref 1) as “Weapons that are explicitly designed and primarily employed so as to incapacitate personnel or materiel, while minimizing fatalities, permanent injury to personnel, and undesired damage to property and the environment.” Non-lethal weapons are intended to have relatively reversible effects on personnel or materiel. Examples of non-lethal weapons might be lasers that would dazzle sensors, or the Active Denial system that repels adversaries with non-damaging skin heating.

The unprecedented precision offered by some types of directed energy is a major advantage, enabling very accurate aimpoint selection. Collateral damage and unintended casualties are avoided by the absence of blast and fragmentation effects that are caused by conventional weapons.

As the technology for directed energy weapons improves, they will increasingly be driven electrically. Some DEWs, such as mm-wave devices, are already electrically powered. The use of electricity enables DEWs to have deep magazines, where the number of shots is not restricted by the number of bombs or bullets carried, but by the fuel used to move the weapons platform and to generate electricity for the weapon (usually much less fuel is required to fire the weapon than is required to move the platform). In addition, the logistical penalty of producing, transporting, guarding, and loading conventional weapons onboard platforms is largely avoided by DEWs. Imagine an airborne high power microwave weapon that can fire thousands of shots during a single sortie, as opposed to delivering a few munitions.

The desirable characteristics of directed energy weapons: ultra-precision engagement, deep magazine, low collateral damage, minimal non-combatant casualties, reduced logistics tail, and diminished post-conflict reconstruction costs are all important reasons to keep developing these promising technologies. A word of caution is required; in

the foreseeable future, directed energy weapons will not replace, but will complement conventional weaponry.

Another few words of background are necessary. The warfighters are interested in effects and the capabilities offered by various technologies. Capability is created by systems. It is therefore in the context of systems, capabilities and effects that technologies compete for investment.

The purpose of this talk is to discuss directed energy applications for vacuum electronics, and the focus now narrows to high power microwaves and millimeter wave technologies. For the remainder of this talk, high power microwave technology is discussed in general terms, and millimeter wave technology as a counter-personnel non-lethal weapon is described.

### High Power Microwave Technologies

High power microwave (HPM) effects on electronics can be described in many ways. The number of different electronic systems that are potential targets for HPM weapons is huge, since electronics are ubiquitous on the battlefield and are critical to the infrastructure of a modern nation. One way to proceed is to consider the physical timescales for energy deposition and dissipation in targeted electronics. Another useful way to approach HPM is to consider other target characteristics such as clock speeds, coupling apertures, and control loop frequencies. These considerations, among others, lead to desired parameters that cover a broad range of frequencies, output power levels, pulse lengths and pulse repetition rates.

HPM sources are typically classified as either narrowband or wideband sources. A wideband source radiates an impulse field with energy spread over a wide frequency band, whereas a narrowband source produces a pulse with a much narrower frequency spread. There are also HPM sources with characteristics that are intermediate between these extremes. Narrowband sources are vacuum electronic devices, while wideband sources are not.

A typical narrowband high power microwave system might have an output power in the GW range, be an oscillator in the 100 MHz to 10 GHz frequency range, with pulse lengths ranging from tens of nanoseconds to a microsecond, and with pulse repetition rates of single shot to hundreds of Hz. A number of different devices have been developed to produce HPM pulses with these characteristics, including relativistic magnetrons, vircators, super-reltrons, MILOs, to name a few.

When these HPM sources are considered, a few common characteristics are discernable. In general, HPM sources are energized by pulsed power systems with applied voltages in the 100 kV to 1 MV regime. The interaction circuit is not typically overmoded, and so the field strengths and peak power densities are higher than in conventional vacuum

electronics. Furthermore, the pulsed power waveforms are often not very clean, sometimes leading to relatively poor output waveforms. The device impedances are low compared to conventional vacuum electronics, ranging from sub-ohm to hundreds of ohms, and device efficiencies also tend to be low, ranging from a few percent, typical of vircators, to in the range of 10-20 percent for more advanced HPM sources.

New cold cathode technologies using carbon fibers have been developed that can give very high current densities with relatively long lifetimes and little gas evolution. These technologies have been incorporated into a few HPM sources and have, in some cases, dramatically improved the quality and consistency of output waveforms, and have also enabled sources to be repetitively pulsed.

In the past few years, considerable understanding of effects data using statistical electromagnetic techniques, modeling and simulation, and advancements in many auxiliary technologies such as power transmission, antennas and pulsed power have also occurred.

In future HPM source technology development, there will increasingly be a need to produce sealed tubes with materials that can be baked out to improve power handling and increase rep-rate and average power. Thermal management of internal components will have to be incorporated into existing designs as average power increases. The lifetimes and other characteristics of novel cathodes will see continual improvement. The use of modeling and simulation to provide a true "virtual prototyping" capability for HPM sources has paid a number of dividends already, increasing our understanding of the power flow and efficiency issues associated with these highly non-linear, space-charge dominated systems.

### Millimeter Wave Technologies

For millimeter wave systems, the best example, and the most highly developed directed energy weapon is the Active Denial System. Active Denial uses a powerful beam of 95 GHz millimeter wave energy to heat the outermost 1/64<sup>th</sup> of an inch of skin of targeted adversaries, producing an irresistible, non-damaging repel. These effects have been characterized over many years of research, and have recently been proven during live fire exercises conducted under human use protocols.

Recently, a 100 kW device, System 1 (Fig 1), was developed during an Advanced Concept Technology Demonstration. Raytheon Advanced Electromagnetic Technologies in Rancho Cucamonga, CA was one of the principal contractors. System 1 is integrated into a hybrid-electric HMMWV (High Mobility Multi-purpose Wheeled Vehicle) produced by DRS in Huntsville, AL. In this device, a diesel motor generator charges a large Li-ion battery pack that stores electricity for mobility and the weapon system. A set of modular high speed switching

power supplies provides the high voltage electricity that accelerates an electron beam in a gyrotron oscillator designed and built by CPI in Palo Alto, CA. The gyrotron uses a NbTi superconducting magnet built by Cryomagnetics in Oak Ridge, TN, operating at 4.5 K, which is kept cold with a closed-cycle cryocooler. The gyrotron, which operates in a  $TE_{6,2,1}$  cavity mode, uses a single stage depressed collector to increase efficiency to slightly over 50 percent. The power from the interaction cavity goes thru an internal converter and a mixture of modes approximating a Gaussian beam is produced and power is extracted thru an edge-cooled synthetic diamond window transverse to the electron beam. This power is transported and matched into a high gain, high aperture efficiency FLAPS antenna produced by Malibu Research. A sensor suite, including a thermal imager, visual camera, image intensifier and laser range finder are mounted on the back of the antenna, boresighted with the energy beam. The operator controls the non-lethal weapon from a station on the passenger side of the HMMWV. The operator aims the antenna with a joystick and depresses a trigger to energize the mm-wave beam. System 1 incorporates a number of redundant hardware, software, operator, and effects controls to assure effective non-damaging repel.



**Figure 1.** Active Denial System 1

Based on effects and operational issues, future Active Denial systems will remain at or near 95 GHz, and will produce long (seconds to CW) output pulses with powers between about 10 kW and 2.5 MW. In this parameter regime, there are no practical substitutes for vacuum electronics devices.

For defense applications, and in a system sense, the most important parameter of the mm-wave source is efficiency. Another source component that has a major impact on system size, weight, cost and performance is the superconducting magnet. Future mm-wave source technology development will explore ways to improve efficiency and either eliminate the superconducting magnet or use high temperature superconducting magnet technology that requires less power, much less volume and weight, and allows quicker cooldown than the present superconducting magnet technology. Harmonic gyro-devices, perhaps even gyro-peniotrons are among the technologies that might be promising for future applications of millimeter-waves.

Vacuum electronics are an important enabling technology for Directed Energy Weapons. The technologies developed by the vacuum electronics community have played an important role in the development of both high power microwave and millimeter-wave systems. Modeling and simulation, leading to virtual prototyping of sources, is now central to the development of vacuum electronics-based DEWs. The future of HPM and mm-wave DEWs rests on the vacuum electronics technology base.

#### Reference

1. Department of Defense Directive 3000.3, "Policy for Non-Lethal Weapons", 9 July, 1996