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Pulsed High-Power Microwave Source Technology

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Administrative Note

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Summary

This paper provides an overview of the major types of high-power microwave (HPM) sources and the critical technologies required to build them. Pulsed HPM technology has been of scientific and military interest for several decades. Originally, the interest focused on the area of high-altitude electromagnetic pulse (HEMP) concerns.

HEMP is produced when a nuclear weapon is detonated high above the earth's surface, creating gamma radiation that interacts with the atmosphere to create an intense electromagnetic (EM) energy field that is harmless to people as it radiates outward but can overload computer circuitry with effects similar to, but causing damage more swiftly than, a lightning strike. HEMP effects became fully known in 1962, when a high-altitude nuclear test (codenamed "Starfish Prime") over the Pacific Ocean disrupted radio stations and electronic equipment 800 miles away in Hawaii. The HEMP effect can span thousands of miles, depending on the altitude, design, and power of the nuclear burst. It is speculated that a single device detonated at high altitude over the central United States could affect the entire country, since the HEMP would be picked up by conductors, such as wires and power cables, acting as antennas to conduct the electrical energy into various electronic systems. This EM radiation was found to have field levels on the order of several hundreds of kilovolts per meter with onset or rise times of a few nanoseconds and a duration of nearly a microsecond. Fields of these magnitudes were found to have severe detrimental effects on numerous electrical systems and items, such as the power grid, automobiles, communications equipment, and aircraft.

Much testing was done in the 1960s and 1970s to determine vulnerabilities and to find mitigation solutions. The HEMP is essentially a wideband microwave pulse, and several EMP simulators were devised and built for use in testing its effect on various electronic systems. In addition, several programs were established to investigate the possibility of generating and radiating other spectrums of EM radiation that may have some of these same effects without requiring a nuclear detonation. This was the impetus for the advancement of pulsed HPM technologies for weapons.

HPM radiation is composed of shorter waveforms at higher frequencies than is HEMP, which makes it highly effective against electronic equipment and more difficult to harden against. Whereas HEMP weapons are large in scale and require a nuclear capability along with technology to launch high-altitude missiles, HPM weapons are smaller in scale, involve a much lower level of technology, and are within the capability of almost any state. HPMs can damage computers and electronics similar to the way HEMP can, although the effects are limited to a much shorter range. Technical accessibility, lower cost, and the vulnerability of U.S. electronic equipment could make small-scale HPM weapons attractive to terrorist groups. HPM devices are now categorized as directed-energy weapons.

One major use of HPM by the military is for electronic attack, or what is referred to by the media as an "ebomb." HPM sources developed for this purpose provide peak powers in excess of 10 gigawatts. The goal of such a weapon is to disable communications and computer systems prior to any troop movements and render the enemy unable to stage a response. The technology used to drive such sources has its roots in pulsed power, and for narrowband sources requires the use of tools that have been developed in the plasma physics community. Reliance on microprocessors that have an increasing density of circuits packaged onto each chip makes such systems ever-more vulnerable to HPM effects. As an example of the possible effects of HPM weapons, on 28 May 2001, a U.S. Commanche helicopter, flying in New York state while performing tests involving HPM weapons, was reported to have generated a low-level energy pulse that disrupted the Global Positioning System devices used to land commercial aircraft in Albany.

The use of this type of weapon can be based on several scenarios, depending on the asset it will be used against. Sometimes, it may only be necessary to upset a data bus transfer to produce a success; other times, success may not be so simple. Some of the kill mechanisms obtained from microwave weapons include semiconductor overheating or burnout, arc generation, computer upsets, voltage induction into sensitive circuits, display upset, and overvoltage in discrete components. The asset to be neutralized will often determine the specific type of microwave source to be used; for example, assets with slots designed for communications purposes may be most vulnerable to narrowband HPM of a specific frequency, while assets with several computers linked by a communications bus may be more vulnerable to ultrawideband (UWB) pulses of a specific pulse repetition rate (PRR). Often, the variety of EM radiation that would be most effective is not obvious, and therefore several must be evaluated.

If EM radiation is able to penetrate a target, the issue then becomes the susceptibility of the many semiconductor devices, which make up the various circuits of the target. Failures in semiconductors owing to thermal effects occur when junction temperatures are raised above 600° Kelvin. Since thermal energy diffuses through the semiconductor, failure mechanisms depend on the microwave pulse duration. If the pulse duration is short compared with thermal diffusion times, then the temperature increases in proportion to the deposited energy. Pulse durations (t) shorter than about 100 nanoseconds fall into this regime, and the threshold power for damage varies as 1/t. Experimental testing has shown that for pulse durations between 100 nanoseconds and 10 microseconds, the power required for damage scales as $1/t^{1/2}$. And for pulses longer than 10 microseconds, a steady state in which the thermal diffusion rate equals the rate of energy deposition and temperature is proportional to power, resulting in a constant power requirement for damage. In this case, the power requirement scales as t. The consequence of these scaling factors is that short pulses require very high power but little energy, while very long pulses require large amounts of energy but little power. This analysis results in a vast range of HPM sources capable of damaging semiconductor devices. The above applies to single-shot pulse durations, but if

a PRR is applied such that there is insufficient time for thermal diffusion between pulses (about 1 millisecond), then there will be an overall constant rise in temperature. For this reason, the PRR capability is of extreme importance for any HPM source.

As a matter of course, assets to be tested include those of friend and foe alike, the goal being to find vulnerabilities in both and correcting those found in our own assets. Several techniques are employed to mitigate vulnerabilities found in assets, including filtering of conductor lines, using metallic enclosures, eliminating any unnecessary openings in the outer enclosure, and using ferrite or other magnetic materials. Any electronics inside a completely sealed metallic container (Faraday cage) would have no vulnerability to HPM of any variety; however, such a scenario is also of little or no use, since there could be no communication to or from the enclosure. Assets therefore must include some openings for communications, instruments, air flow, and sensors, sometimes as a matter of fulfilling their function.

From the HPM source perspective, care must be taken to prevent fratricide and harm to friendly assets. To prevent fratricide, all connections to the source must be filtered to prevent fast transients from returning to the control unit. Some signals can be transmitted using fiber-optic cable; however, there is usually a piece of equipment at the source end that must be filtered. Some connections, such as the high-voltage power supplies, can make good use of high inductance filtering to eliminate fast transients, while others, such as trigger lines, must make use of other filtering means, such as transformer coupling, lightning arrestors, transorbs, and fast-acting, high-voltage diodes. Preventing harm to friendly assets is difficult and is a major reason why HPM has rarely been employed in actual battlefield settings. To ensure there is no harm to friendly assets, all assets would have to be tested for vulnerabilities, something that is not done at present. The antenna is a major factor in this matter. Unfocused antennas radiate a pattern that spreads as it progresses outward and, thus, the area subjected to the EM fields increases with distance. It is then harder to separate one's own assets from the radiated fields.

In addition, it is very difficult to detect these sort of pulsed sources, since the pulses are very short (typically 1-500 nanoseconds), and even in burst mode, the bursts are usually less than 10 seconds. The short burst mode operation is necessary because of the high peak powers and subsequent heating of key components such as switches. The UWB sources would be the most difficult to detect, since they have nearly zero energy at any one frequency and so would not be detected at all by instruments such as spectrum analyzers.

Critical Technologies

Several technology areas are critical to the design and fabrication of a working HPM source. First, because the pulsed-power section of the source must operate at high voltages, it must contain insulating materials capable of withstanding the required voltage. The insulating scheme chosen is critical to the success of the project; therefore, several insulation techniques will be discussed, along with the merits and drawbacks of each. Another pulsed-power technology that is critical to the success of any source is high-voltage switching; various types of switches will be discussed, along with applications. Finally, cathode materials are a technology area that has been thoroughly researched and is critical to narrowband HPM generation; several cathode materials will be discussed, along with needs for future cathodes.

INSULATION

Electrical insulating materials or dielectrics are essential not only for pulsed power and HPM generation but for the proper functioning of all electrical and electronic equipment. In fact, usually the size and operating limitations of a piece of equipment are determined by the choice of insulating material. In the past, all manner of varnishes, tars, petroleum asphalts, natural resins, gums, saps, and minerals were used for electrical insulation. Now there is an almost endless list of possible insulating materials. The question now is, which material is the most appropriate for the task at hand? In pulsed power, and even more so in HPM applications, the choice is critical. All properties of a material must be weighed against one another to make the proper choice. Such properties as voltage breakdown, dielectric loss, dielectric constant, cure temperatures, hardness, tensile strength, flow modulus, and the variation of all these with frequency, voltage, and temperature must be considered before an appropriate insulating material can be selected. Many of these properties have never been published for most materials, and even when they have been published, they are typically known only at one or two frequencies. Designing insulation for challenging applications is at best a compromise between evils. Most of the material studies are carried out for the power industry, making them valid only at 50 or 60 hertz. Measurements at these low frequencies usually provide little or no clue about the values at much higher frequencies. Therefore, it is often up to diligent engineers to obtain materials data on their own.

One recent research area of interest is in developing what are termed artificial dielectrics in an effort to decrease insulation weight. This material is made by suspending hollow glass microspheres in a lightweight dielectric medium. Depending on the concentration of these spheres, the dielectric constant can be lowered and tailored for the application, and the loss tangent of the media can also be reduced. Coating the spheres with a conductor such as aluminum can also raise the dielectric constant. Thus far, as might be expected, the dielectric strength of such materials is much lower than that of many thermoplastics, but they have been useful for applications such as radomes.

Insulation generally falls into one of three categories: (1) homogeneous insulation, where the entire insulating volume is filled with the same media, be it solid, liquid, or gas; (2) laminated insulation, where the insulating volume is filled with some manner of layering of different materials; and (3) insulation by other means, such as magnetic insulation—these are usually used only where special conditions apply.

UNIFORM HOMOGENEOUS

Uniform homogeneous insulation implies that the insulating material is consistent throughout the volume. However, in some cases, such as that of epoxies, there is a uniform loading of some other material, usually to increase some desired characteristic of the final product. Examples are loading with silica to increase dielectric strength and loading with glass fibers to increase mechanical strength. The loaded material is typically of such small dimensions that it has only a very small effect on other material parameters from the truly homogeneous case. The use of uniform homogeneous insulation also results in a more easily modeled design.

SOLID

Solid insulation is often the easiest and typically the most desirable form of insulation since it does not require maintaining or replacing a liquid level or containing or monitoring pressure. This fact is often critical to a source project if maintenance or long shelf lives are important factors.

Plastics

The true title for this section should be "Thermoplastic Polymers (Plastics)," as they comprise one of the largest groups of insulating materials used in pulsed power and HPM generation. The term "plastics" includes acetals, acrylics, amides, imides polyarylate, polybutylene, polycarbonate, polypropylene, styrene, and sulfone polymers. Plastics were first used as insulation in the 1930s, and it is hard to conceive of constructing a high-voltage pulse source without them. Plastic materials have been tailored to suit a wide variety of applications. In the early 1980s, plastics manufacturers soliciting Sandia National Labs stated that they could engineer plastics to meet any set of material properties desired. It later became apparent that this was not the case and that, as usually occurs in nature, when one parameter was made more desirable, others were made less desirable. In spite of this fact, some well-engineered plastics are now available for some very demanding applications, such as switch housings and transmission lines. Nevertheless, virtually no new plastics are being introduced today. For the past 20 years, engineers have worked with essentially the same plastic materials, although some improvements have been made in the quality of resins and extruding and casting methods. In spite of this, there is still much more variation in specifications (especially mechanical specifications, such as tensile strength) for plastics from batch to batch than there is for metals. For this reason, the most demanding plastics applications where the limits of some specification will be approached require purchasing and independently testing a specific batch to assure confidence. One interesting and well-documented phenomenon associated with plastics is the nonlinearity of electrical breakdown strength with thickness. In very thin layers, some plastics display extremely high breakdown strength. For instance, polypropylene in half-mil (1 mil = 1/1000 inch) layers yields 7,000-volts-per-mil breakdown strength, while in one-eighth–inch thickness, this figure drops off to 900 volts per mil. One theory to explain this is that the proximity of imperfections in the material across the thickness reduces the dielectric strength in thicker samples. This fact can be used to advantage by layering thin sheets of insulation together to form thicker insulating regions (see section on laminated insulation). Many plastics come in a wide variety of shapes, forms, and grades, including bulk volumes, a variety of sheet thicknesses, and various rod diameters. The subject of using plastics as insulation fills volumes in reference books and has yet to be exhausted. Table 1 shows selected dielectric properties, collected over several years, on some of the most common plastics for high-voltage use.

Table 1. Dielectric Properties of Some HPM Plastics

Material	Trade Name	Breakdown Voltage (kV/mil)
Acetal	Delrin	4.0
Polypropylene		6.0
Polyetherimide	Ultem	7.0
Polysulfone	Ultrason S	7.5
Polyethersulfone	Ultrason E	5.8
Polycarbonate	Lexan	6.3
Polyphenylene Ether	Noryl	0.6
Polyphenylene Sulfide	Ryton	0.4
Polyethylene		5.0
Polyvinylchloride		1.8

Epoxies

One of the greatest advantages of casting epoxies is that a high dielectric strength can be attained with low maintenance, a long shelf life, and ease of transportation compared with liquid or laminated insulation schemes. Some of the best epoxies ever used for high-voltage insulation have only recently become available. These advancements are due mainly to efforts by the automotive industry to miniaturize the ignition coil to the point where a separate coil could be incorporated into the spark plug cap at each cylinder. Technologies have been devised for casting several varieties of epoxy to allow larger volume castings. The goals are to minimize voids and bubbles, deal with any exothermal effects, and reduce shrinkage. In addition, a good candidate material for high-voltage casting must have a high dielectric strength at the frequencies required, a long pot life, good adhesion, and an unlimited cure depth at a low temperature. With many epoxies, shrinkage and the glass transition point are functions of the cure temperature. New, state-of-the-art epoxies have several desirable characteristics never before available in a single product that make them ideal for high-voltage applications. Two such characteristics are a low viscosity at room temperature and a long pot life. This means the epoxy can be mixed (resin and hardener) and the unit to be insulated can be filled under vacuum to eliminate voids and bubbles. Some of these epoxies have the viscosity of milk at about 100 degrees Fahrenheit and a pot life of several hours. A third desirable characteristic is a very low, almost imperceptible exotherm. This allows insulation of items sensitive to heat, such as thin plastics, paper, and electronic components or integrated circuits. A fourth desirable characteristic is low shrinkage, even in large castings. This allows insulation of regions where dimensional stability is important, such as at distances from high-voltage sections and resonant structures. A fifth desirable characteristic is good adhesion, both to itself and to components to be insulated. This is important because any separation from a component creates a void region where the dielectric strength will be compromised.

Adhesion to itself allows casting in several stages without fear of voids or mechanically weakened areas. A final desirable characteristic—one that is of obvious importance—is a very high dielectric strength. With attention to detail and diligence in the casting procedures, dielectric strengths of more then 4 kV/mil on 0.125-inch thickness have been achieved. All these advantages have allowed operation of high-voltage pulse systems at increased power levels and at half the volume of those previously insulated with mineral oil.

Urethanes and Silicones

These materials are used for casting solid high-voltage equipment, as well as for coating components to reduce the effects of shrinkage or shock. Typically these materials are very hard to use with vacuum casting techniques and, thus, have a much lower dielectric strength than do the best epoxies, especially in larger volumes. Another drawback is that many urethanes and silicones require either moisture or volatile ingredients in the curing process, both of which cause problems with high-voltage systems. Nonetheless, a wide variety of these materials are used in the fabrication of high-voltage pulse systems for applications that require their characteristics.

LIQUIDS

Liquid insulation has been the primary type of insulation for high-voltage systems since the beginning of the field. Over the years, mineral oils, vegetable oils, hydrocarbons, and even tars and saps have been used as insulation. Dielectric liquids have long served as electrical insulation in power transformers, capacitors, cables, and switching equipment. Several once commonly used fluids are no longer available because of their toxicity and environmental impact. As a result, liquids for insulation that do not have these problems have now been developed for certain applications, including mineral oils, silicon oils, fluoropolymers, and high-molecular-weight paraffin oils. Most of the dielectric fluids made are tailored to the power industry, which accounts for about 99 percent of the demand for these liquids. As a result, many such liquids contain additives that, while necessary for the power industry, are detrimental to high-voltage applications. These include low-vapor-pressure additives for controlling viscosity and antioxidants for improved aging. In addition, most insulating liquids also contain moisture and dissolved gases, which are only weakly bound to the liquid molecules and are easily freed when high electric field stresses are present. Scientists have for years worked to extend the usefulness of transformer oils, fuorinert, and castor oil. They have also developed corona-processing equipment for improving the high-voltage characteristics of insulating oils. This has allowed state-of-the art insulation design using insulating oils and oil-impregnated systems. The corona processing involves flowing the liquid insulation media through a high-field-stress region while under vacuum to remove dissolved gases and low-vapor-pressure constituents from the oil. The liquid is then filtered to remove particles larger than 5 microns. This process improves the corona initiation voltage limit for the liquid and greatly extends the life of components insulated with the media. It has also allowed a significant reduction in the size and, thus, energy density of pulsed transformer systems.

GASEOUS

Insulating gases are used in many high-voltage applications where weight is a primary issue. Typically the use of gases as an insulating media requires pressurization and, thus, implies heightened safety concerns. Even low-volume vessels can contain hundreds of joules of energy in the compressed gas, and a housing failure can hurl fragments at deadly velocities. Highly compressed gases are used only in cases where some prized benefit is worth the increased cost and design trials to be exacted. One example of this is extremely fast switching where the electrode spacing is proportional to the added inductance during conduction—the smaller electrode spacing requires higher gas pressure for insulation. Almost every common gas has been used as insulation, and many have attributes making them desirable for certain applications. Sulfur hexafluoride, nitrogen, air, argon, helium, oxygen, and hydrogen are commonly used. Of these, only sulfur hexafluoride is an electronegative gas, meaning it has the ability to remove electrons from the volume through the formation of negative ions and thereby increase the dielectric strength. Electrical discharges in sulfur hexafluoride result in foul-smelling sulfur compounds that also deposit on the switch housing and electrodes and require frequent cleaning. These discharge compounds also tend to be highly corrosive, especially in the presence of water. Other gases with electronegative species, typically other halogens such as chlorine, also make good insulators. These gases are usually much denser than air, and breakdown voltage is roughly proportional to density, thus higher voltages can be supported even at low pressures. The halogenated hydrocarbon refrigerants, such as CCl_4, CCl_2F_2, CCl_3F, and $C_2Cl_2F_4$, are also popular for insulation. The breakdown of air has been thoroughly researched, and in fact the breakdown voltage of a calibrated gap can be used to determine the magnitude of high voltages. Table 2 shows the breakdown voltages of several insulating gases relative to that of air.

Table 2. Relative Spark Breakdown Strength of Gases

Gas	N_2	Air	NH_3	CO_2	H_2S	O_2	Cl_2	H_2	SO_2	$C_2Cl_2F_4$	CCl_2F_2
V/V_{air}	1.15	1	1	0.95	0.9	0.85	0.85	0.65	0.30	3.2	2.9

Gaseous insulation as a switch medium limits the pulse repetition rate (PRR) to 500-600 pulses per second because of the creation of numerous metastable states and elevated energy levels by the previous pulses. This is true for all gases listed here except hydrogen. Hydrogen can be used at a much higher PRR; however, its dielectric strength is only 65 percent that of air and, thus, almost twice as much pressure is required for the same operating voltage. When the pressure is doubled, the energy content increases by a factor of four, leading to elevated safety concerns. Using hydrogen for switch insulation poses no explosive danger provided the oxygen content in the gas is kept below about 5 percent. Other handling problems associated with hydrogen include hydrogen embrittlement—it will leak through even tiny holes, including the pores in metal tanks, eventually causing the metal to become brittle and fail. In addition, hydrogen is flammable when mixed with oxygen. A hydrogen flame is colorless but very hot, which can be dangerous if leaks develop in pressurized switches or gas lines. One class of hydrogen switches, hydrogen thyratrons, makes use of the low-pressure characteristics of gases to eliminate the safety concerns associated with high pressures (these are discussed in a later section dedicated exclusively to gas switches).

LAMINATED

Laminated insulation has been used in some very demanding applications in which size is of primary importance and very small repeating structures are required, including high-energy-density capacitors, high-voltage transformers, and high-voltage transmission lines or pulse-forming lines. Laminated insulation schemes make use of the nonlinearity of electrical breakdown strength with thickness mentioned earlier for plastics. Such schemes offer the possibility of significant improvements in state-of-the-art insulation, including a reduction in the size and an increase in the energy density of high-voltage pulsed systems. As new and improved materials become available, the possibilities for such improvements will become more substantial.

PLASTIC-PAPER-OIL

With appropriate attention to process details, very high dielectric strength is routinely achieved using this lamination scheme. This is in fact the insulation method used in most high-voltage and high-energy-density capacitors, with the addition of foil layers on either side of the plastic (usually biaxially oriented polypropylene) to form the capacitor. Use of corona-processed oil dramatically improves the utility of this insulating scheme. The plastic is frosted on at least one side and, together with the very thin (1 mil or less) paper layer, allows the oil to penetrate throughout the volume during the impregnation process. Without the oil, the tightly wound plastic layers can become sealed around small volumes of air that will not be filled with oil, and breakdowns will occur. Once the paper is impregnated with the oil, tests have shown that it attains essentially the same dielectric strength as the oil. Often, vacuum and pressure are alternately applied to ensure full penetration of the oil into the full volume. It is vitally important that no bubbles or voids be left in the insulation volume. For this reason, once the insulating volume is ready for impregnation, it should be left under vacuum at slightly elevated temperature for at least 24 hours. This not only ensures air pockets are removed but also allows the removal of surface moisture from the plastic and paper, which will also contribute to voltage breakdown. The paper not only aids impregnation but also serves as a path for residual charge to dissipate between voltage applications. The plastic has a very high surface resistivity, and some residual charge can become trapped on the surface after each discharge, resulting in charged regions of different magnitudes and even polarities, which can eventually lead to dielectric failure. Using this insulation scheme with biaxially oriented polypropylene as the plastic and Shell Diala AX as the impregnating oil, average dielectric strength of more than 2.1 kV/mil and operating voltages higher than 1.3 MV have been attained in large volumes.

PLASTIC-PAPER-EPOXY

Since the oil is the weakest dielectric medium in the preceding insulation scheme, it is reasonable to assume that replacing it with a stronger dielectric medium can improve the overall dielectric strength. Another advantage of this scheme is that in the end we would have a solid insulated volume with the advantages mentioned earlier. Thus far, only smaller volumes (1-2 gallons) have been successfully insulated with this scheme. The problem is that the increase in viscosity over the oil, although small, makes it more difficult to ensure that full impregnation is achieved. Meanwhile, the programs for which this scheme is desired insist on nearly 100-percent certainty of success. The most successful process to date involves using quarter-inch sections of 1-mil paper followed by quarter-inch open sections for each layer. This is a tedious task in large volumes but has resulted in an average dielectric strength of more than 3 kV/mil for the volumes mentioned. Adapting this scheme to the manufacture of high-voltage capacitors could result in significant improvement over the current state of the art of 1 joule per cubic centimeter.

DIELECTRIC TAPERING

This insulation scheme is little known but has been used with much success in many high-voltage systems, especially where compact high voltage is required. The basic scheme is to first design the system while minimizing the peak electric field stress. This involves hours of small but well-chosen changes to a design in order to shape the field lines and achieve the least range from minimum to maximum field stress. We then find the surfaces, which have the highest electric field stresses and therefore the highest probability of breakdown. In evaluating these parameters, it must be remembered that dielectric media are much less likely to initiate breakdown than are conducting surfaces under the same electric field stress. The conductor surfaces under highest field stress are then layered with high-voltage coatings (usually acrylics, polyurethanes, silicones, or engineered coatings) with dielectric constants chosen to reduce the electric field strength at the conductor surface. This technique works because the conductor is the source of electrons, without which breakdown will not occur. Since the electric field is excluded from regions of relatively higher dielectric constant, if the insulating volume is filled with mineral oil (relative dielectric constant of 2.2), then a conducting surface coated with 10 mils of polyurethane (relative dielectric constant of 3.6) will have a lower electric field stress than it would without the coating, and the increase in field stress in the mineral oil will be minimal.

Dialectic tapering can be applied using several layers of coatings with progressively lower relative dielectric constant from the conducting surface and dramatically reduces the conducting surface electric field stress. Using finite element electric field solving codes and several hours of iteration, this technique can often reduce peak electric field stress for a system by 50 percent. The technique works best when the volume dielectric fluid has a low relative dielectric constant, such as mineral oil has (ε_r =2.2), since coatings are readily available for ε_r = ~3 to 5. In practice, care must be taken in choosing and applying the coatings to ensure that no voids or bubbles are introduced at the conductor surface. Careful inspection and repair of any flaws is relatively simple with this technique. Another, more recent use of this concept is what is termed continually varying dielectrics in ultrawideband (UWB) guiding structures, such as transmission lines with greatly reduced dispersion at bends.

CATHODE MATERIALS

This area of research is vitally important to any HPM source requiring electron beam generation. All high-power microwave tubes, including virtual cathode oscillators and cavity resonators, rely on a bunched flow of free electrons to set up oscillating electric fields and thereby generate a radiofrequency (RF) output. The electron flow is usually initiated by applying a high-voltage pulse to a vacuum diode. For high-power operation, the cathode must be capable of emitting a very high electron current density using one of several emission mechanisms.

These mechanisms include:

- Thermionic emission (apply heat – 1,000 °Celsius)
- Secondary emission (electron bombardment; > 100 eV)
- Field emission (apply a very strong electric field; 107 V/cm)
- Explosive emission (form a plasma on the surface; ε_{ω}= 0)

The emission mechanisms of major importance for HPM at present are thermionic emission and explosive electron emission; however, field emission shows some hope with the advancements in nanostructures. Explosive emission, creating a dense plasma at the cathode surface, is of primary importance at this point. A review of pure metals reveals a direct correlation between the work function (ε_{ω}) and melting temperatures. When cathodes are made from metals with low work functions, there are problems with metal deposition onto other components. Most cathodes of use in HPM tubes depend on a surface flashover at a dielectric-metal interface. The surface flashover generates plasma, typically at tens–of-kilovolts-per-centimeter electric fields. The threshold and nature of the plasma depend greatly on the cathode materials. Therefore, the choice of cathode material is of critical importance in the design and operation of any HPM tube. No discussion of HPM diodes could be complete without mentioning space charge limited current flow. This stems from the fact that at some magnitude of current density, the density of electrons in the anode-cathode gap begins to shield the cathode from further emission owing to their cumulative effect on the electric field at the cathode surface. The current density at which this happens is given by the Child-Langmuir law:

$$J_{sc}(\mathrm{kA/cm^2}) = 2.33 \times 10^{-6} \, (V(\mathrm{MV})^{3/2} / d(\mathrm{cm})^2)$$

and is dependent on the diode voltage and the anode-cathode spacing. So, if we could have the ideal cathode material, what would its characteristics be? The response has not changed much in more than 60 years, as can be seen in the following extraction from a textbook on the subject.

Primary Characteristics of an Ideal Cathode (J. R. Pierce, 1946):

- Emits electrons freely, without any form of persuasion such as heating or bombardment (electrons would leak off from it into vacuum as easily as they pass from one metal to another).
- Emits copiously, supplying an unlimited current density.
- Lasts forever, its electron emission continuing unimpaired as long as it is needed.
- Emits electrons uniformly, traveling at practically zero velocity.

Efforts are still under way to increase the output power, pulsed emission duration, repetition rate, and emission uniformity by investigating new and existing cathode materials in an effort to draw closer to the ideal cathode. Some of the materials currently being investigated are ceramic cloth and felt, carbon structures including nanotubes and microfibers, and carbon structures coated with cesium iodide.

VELVET

Velvet has been an explosive electron emission standard for more than 20 years. This material works by means of the dielectric-metal surface flashover mechanism mentioned earlier.

Five steps are involved in the explosive emission process for dielectric fibers:

- Surface flashover generates a cold, dense plasma/gas column.
- The applied electric field extracts a space-charge-limited current flow.
- The flow of current resistively heats the gas column.
- The gas columns expand at a rate determined by the gas temperature.
- The gas continues to expand into the anode-cathode gap.

Velvet has several desirable properties that have endeared it to the pulsed power community and kept it a useful material for all this time. First, it emits at relatively low field strengths (~10 kV/cm), allowing a wider range of use than do many other materials. Second, it has a fast turn-on time. Third, the insulating nature of the velvet fibers provides a sort of built-in ballast during operation. Velvet also has a wide range of vacuum compatibility (pressures from 10^{-3} to 10^{-8} Torr), easing the expense of vacuum hardware. Finally, velvet is inexpensive and readily available. All these factors combined have made velvet cathodes common for the past two decades.

However, velvet cathodes also have drawbacks. First, velvet outgases heavily, especially during and after explosive emission. Significant amounts of material are released from the velvet during this process. The increased pressure inside the HPM device then leads to gap closure (conductive bridging of the anode-cathode region) and early termination of the RF output from the device. The closure rate can be estimated from:

Velocity of closure (m/s) = $100\ (d^*/d)^{2/3}\ V_d^{1/2}$

where: d is the diode gap, d* is the velvet tuft density, and V_d is the diode voltage.

Second, velvet has a very limited lifetime, partly owing to the material lost during each shot. Some material lasts for only about 100 shots in single-shot mode. Third, because of the increase in pressure after each shot, the repetition rate is very limited. Finally, lack of control over the manufacturing process results in a wide variation in performance. Results are not reproducible, even between one roll and the next from the same manufacturer.

CARBON

Carbon cathodes have been used in diodes for more than three decades and have some appealing characteristics. The outgassing characteristics of carbon cathodes are much better than those of velvet, although the threshold voltage for emission is generally much higher. The primary material given off during outgassing from carbon cathodes appears to be hydrogen ions, which, because of their low mass, contribute to the problem of gap closure. The gap closure velocity using carbon cathodes quoted by most reports researched is 2-2.5 cm/μsec, and diode gaps from the same reports were 1-4 centimeters. Carbon cathodes also have much longer lifetime than velvet. However, one of the greatest advantages of carbon is the ever-expanding ability to form both macro- and nanostructures using it as a base or substrate. Structures formed using carbon include pyramids, fibers, microfibers, nanotubes, and tufts. Many possible carbon structures still have yet to be formed and tested. Thus far, structures with the most surface area appear to perform best.

CERAMICS

Ceramics, much like carbon, can be formed into at least microstructures and have some features that have attracted interest in them for a couple of decades. These include virtually unlimited lifetimes and extremely low outgassing. A problem with ceramics, however, is that very high threshold fields are required for diode operation. Coatings to improve the performance of ceramic cathode structures may exist, and research is continuing in this area.

CESIUM IODIDE COATED

One of the most recent and impressive materials to be used in cathodes for HPM tubes is cesium iodide. Cesium is a pure metal that has a work function of only 1.9 eV and a melting temperature of 28 °Celsius; thus, it is liquid at only slightly above room temperature. Cesium ions are quite heavy, and that is why this coating was used initially. It was believed that the gap closure rate would be slowed since the heavy cesium ions would progress much more slowly across the anode-cathode gap than would other ion species, given the same electric field. This has proved to be the case, and closure velocities that are about one-fourth those for velvet or bare carbon (0.4 cm/μsec) have been attained. As a result, the HPM emission times have been extended. Typically, the cesium salt is dissolved in water as a saturated solution and then the carbon cathodes are dipped several times. Subsequently, the cathodes must be baked under vacuum for several hours to remove the water from the surface and leave the hardened cesium salt. Once completed, the cathodes have a very long lifetime unless contaminated by back splatter of material from the anode. At present, HPM programs investigating the performance of cathodes having some form of cesium coating over carbon nanostructures show the most potential for progress in the state of the art. The goal of these programs is hundreds of kiloamps for tens of microseconds, resulting in gigawatt narrow-band HPM sources running at repetition rates of possibly 100 hertz and thus capable of 100-megajoule energy output per burst. Also of great interest at present are cathodes termed "hybrids," which utilize multiple emission mechanisms in beam generation. The cathodes developed by these programs are to be used with the magnetically insulated line oscillator (Sandia National Laboratories [SNL]), the relativistic klystron oscillator (Kyle Hendricks, Air Force Research Laboratory [AFRL]), the reltron (Bruce Miller, SNL), and the super reltron, among others.

Table 3 shows findings of cathode material studies at SNL and at the AFRL.

Table 3. Cathode Study Findings

Material	Emission Threshold (kV)	Lifetime (# of Shots)	Outgassing (Neutrals/Electron)
CsI-Carbon Microfibers	< 3 kV/cm	> 72,000	4 – 6.5 (substrate)
"Sandia Red" Velvet	8 kV/cm	~ 8,000	10
"MILO Green" Velvet	10 kV/cm	~ 4,000	10 - 14
***Velveteen* Low**	Low	< 600	> 12
F-Velvet	Low	< 100	> 12
Ceramic Cloth	> 120 kV/cm	---	---
Ceramic Felt	> 100 kV/cm	---	---
Carbon Pyramids	> 80 kV/cm	---	---
Carbon Nanotubes	20-50 kV/cm	Arc rate of ~ 2%	~ 4
Bare Carbon Microfiber (packing density)	15-40 kV/cm	> 36,000	4.3 – 6.5 (substrate)
CsI-Carbon Fiber Tufts	< 3 kV/cm	> 200,000	~ 4
Metal / Ceramic	95 kV/cm (diode collapse unless > 150 kV/cm)	---	8

HIGH-VOLTAGE SWITCHING

High-voltage switching is among the most challenging of technologies for HPM sources. Although high-voltage switches have been used for several decades, and thousands of experiments have been performed on the mechanisms involved in liquid and gaseous breakdown, there are still many aspects of the phenomenon that defy explanation. This is especially true as the time required to reach the fully conducting state becomes extremely short. The usual explanation for this process involves Townsend avalanching, whereby electron streamers begin at the cathode in an average electric field of only 20-25 kV/cm and, by virtue of an enhanced electric field at their tip, progress in an orderly fashion to the anode. At this time, a heating phase begins, and an increasing amount of current is passed through the streamer until the switch finally reaches the fully conducting state. The problem with this explanation is that it is most likely incorrect and relies on exaggerated ion densities to explain how switches can reach full conduction in less than a billionth of a second. Alternative explanations involving runaway electron generation provide a better match to observations. Very fast switching is critically important to the concept of UWB HPM. The basic concept is to generate a square pulse with the fastest rise time possible. A Fourier transform of this waveform results in a frequency spectrum containing frequencies determined by the width and rise time of the square pulse. The period of the lowest frequency is twice the pulse width, and the rise time is about one-quarter the period of the highest frequency.

An oft-forgotten aspect of the spectral content is that the spectrum also contains only the odd harmonics of the lowest frequency by the definition of a Fourier transform. Thus, the faster the rise time and the wider the pulse, the broader the spectral content. Therefore, switching speed is the most important parameter of a UWB HPM source. The types of switches used for HPM are essentially the same as the types of insulation discussed earlier: gaseous, liquid, and solid state at lower voltages. The single most important attribute of gases and liquids in switching is their self-healing ability, which implies some measure of PRR capability.

GASEOUS SWITCHING

Gas switches are commonly used for HPM sources as both a prime power and a high-speed or peaking switch. As mentioned in the discussion of insulation earlier, when used in a high-speed switch, gas pressure can pose substantial safety concerns. In fact, all of the discussion regarding gaseous insulation also applies to gas switching, since a gas switch is simply a gas-insulated region that we wish to fail in a timely fashion. The higher the voltage impressed across a gas switch, the greater the pressure required to prevent the switch from conducting until the peak voltage is reached. This is why when a gas switch is used as a final-stage peaking switch, very high pressures are often required. A fast-rising pulse is crucial to source design since the rise time determines the upper frequency content. This is why UWB HPM sources usually contain a peaking switch at the output to decrease the rise time and increase the spectral content. If the peaking switch is charged past the DC breakdown level faster than streamers can form conduction channels, then the final breakdown occurs in an overvolted (compared with the DC breakdown voltage) switching state. The higher electric field strength between the switch electrodes results in shortened breakdown times since breakdown develops in an elevated electric field. All switches exhibit some capacitance to an applied pulse because of their electrode spacing, resulting in a displacement current as this switch capacitance charges. This is seen on the other side of the switch as a pre-pulse. The magnitude of the pre-pulse depends on the rate of change of the charging voltage as well as the electrode cross-sectional area and spacing. Sometimes efforts to reduce this pre-pulse are required if it causes problems at the load or undesired spectral content from the antenna. The pre-pulse phase of breakdown occurs at the speed of light in the media since it is essentially a field phenomenon. Because of the added inductance and design of the switch components, pre-pulse has a distinct charging profile. The next phase of breakdown is a resistive phase as the weakly conducting streamer channel heats to the final arc or inductive phase and the switch is fully conductive. Since the final phase is inductive, very low switch inductance and very short gaps are required for fast rise times. Both the resistive and inductive phase periods contribute to the rise time as:

$$\tau = (\tau_r^2+\tau_L^2)^{1/2}$$

where: $\tau_r = (88\text{ns x } \rho^{1/2}) / (Z^{1/3} \text{ x } E^{4/3})$

and: $\tau_L = (L_c + L_h) / Z$

with ρ being the gas density as a multiple of that for sea level air, Z is the circuit impedance in ohms, and E is the electric field between the electrodes in kV/cm. Also, τ_r and τ_L are known as the resistive and inductive rise times, respectively. The resistive rise time is the time required to heat the gas channel to full conductivity, and the inductive rise time is the delay caused by the addition of the switch into the circuit. There are two contributions to the inductive rise time, with L_c being the spark channel inductance and L_h the housing inductance. A shorter switch gap reduces the inductive time by lowering the channel inductance but also increases the electric field in the gap, reducing the resistive time and resulting in a faster rise time. Even though the switch electrodes are usually designed for minimal cross-sectional area at a given current, the very short electrode separation required can still result in high interelectrode switch capacitance. As mentioned earlier, it is also preferable to charge the switch very quickly to achieve an overvolted switching condition, and, therefore, very fast switches always have some level of pre-pulse. Because the PRR is also of great importance, hydrogen has been chosen most often for high-speed gas switching in UWB HPM sources. Switches of this type have achieved rise times of just over 100 picoseconds (ps) and PRRs of 1,500 pulses per second.

Another type of gas switch meriting mention for its utility and indispensability in the HPM pulsed-power driver circuits is the hydrogen thyratron. The thyratron is a partial vacuum switch. Figure 1 shows what is known as the Paschen curve for air; however, all gases exhibit the same curve characteristics. At some product of pressure and electrode spacing, a minimum value of breakdown voltage is reached. While high-pressure gas switches operate in the region on the right side of the Paschen minimum, the hydrogen thyratron operates on the left side, beyond the Paschen minimum. The physics of voltage breakdown in this region results in smaller electrode spacing holding off higher voltages and reduced pressure at the same spacing enabling greater voltage holdoff. The single-stage thyratron operates at only tens of kilovolts, while high-pressure gas switches may operate at several hundreds of kilovolts. When coupled with a good pulse transformer, a properly chosen thyratron forms the heart of an excellent driver for HPM sources. The thyratron also has the capability to initiate breakdown using modest trigger levels (~1 kilovolt) and with nanosecond timing, allowing the use of multiple switches to share current.

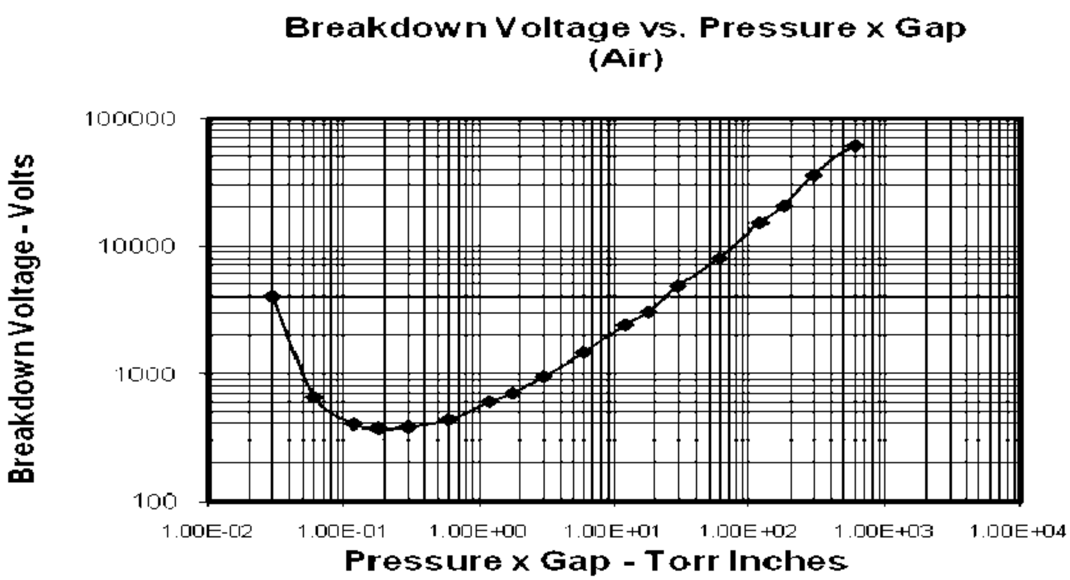

Figure 1. Paschen Curve for Air

HIGH-SPEED LIQUID SWITCHING

Liquid switching has also been used in UWB HPM sources with great success. The same phases of breakdown exist for liquid switches as do for gas switches. The electrode spacing is typically smaller for liquid switches, and electrodes can be made smaller for the same level of energy transfer owing to greater thermal diffusion to the liquid as compared with a gas. Liquid switching does not have the extreme safety concerns associated with gas switching; however, for repetitively pulsed operation, flow of the liquid insulating media is required. Filtering, evacuation, and processing may also be required. Liquid switches have achieved rise times of less than 100 ps and PRRs of 1,500 pulses per second.

SOLID-STATE SWITCHING

Solid-state switches have seen some improvement in voltage holdoff capability but generally still do not have the capability of operating at tens of kilovolts required of HPM sources. The current technology in lateral gallium arsenide (GaAs) switches is greatly improved compared with the old bulk avalanche semiconductor switch technology of the last decade. The power handling capabilities of this technology are impressive; however, it still suffers from short lifetimes because of heat dissipation problems. Source designs using GaAs switches typically involve an array of horns with one switch per horn. The array can then be phased in time to allow steering of the beam. GaAs switches operate at about 10 kV and, therefore, in the large arrays required, several switches fail during any burst mode operation. The most promising new developments in semiconductor switches today are based on physics pioneered by I. V. Grekhov and colleagues at the Ioffe Physical-Technical Institute in St. Petersburg. The AFRL is currently collaborating with Dr. Grekhov and the University of New Mexico in studies of delayed breakdown devices, silicon avalanche shapers, and drift step recovery diodes in efforts to improve the performance of these devices. It is also investigating the use of silicon carbide as an alternative to silicon and GaAs. State-of-the art pulse generators using these devices currently are capable of 6-8 kV output with 100-ps rise times and 20-ps switching jitter. Conventional solid-state devices such as junction gate field-effect transistors (JFETs) have not seen substantial improvement and operate at about a kilovolt with rise times of a few nanoseconds, making them useful for trigger supplies but not in HPM sources.

Photoconductive solid-state (PCSS) switching is still of great interest because of the inherent advantages it could provide. PCSS switches have very low jitter, have fast rise times, and are compact. This technology, sufficiently developed, could allow design of HPM sources with fewer compression stages, allow greater frequency agility and pulse width adjustment, and be used in arrays by phasing many lower power sources together. The technology's main limitations at present are power handling and a limited lifetime. PCSS switches have three modes of operation. In the linear mode, one electron-hole pair is generated by each photon absorbed, and so the conductivity is linearly proportional to the incident photon flux. Linear mode PCSS switches are made from silicon, doped GaAs, and indium phosphide. The electrical pulse output follows the amplitude of the optical trigger pulse. Switching in this mode requires about 1 mJ/cm^2 of optical energy and thus requires a larger laser trigger than do other operating modes. PCSS switches also operate in a lock-on mode in which once the optical trigger causes conduction, carriers remain as long as current still flows, even if the optical pulse ceases. This mode requires much less optical power. Finally, PCSS switches may also be designed to operate in the avalanche mode. Switches operating in this mode are designed for higher voltages, and above some critical electric field, the switch remains closed even without optical energy. Carrier multiplication occurs because of the electric field, and the switching process sustains conduction. Optical energy required for avalanche mode PCSS switches is about 1-10μJ/cm^2. Lock-on mode GaAs is the most commonly used PCSS switch for high-voltage applications. PCSS research at the University of Texas at Dallas (UTD) has resulted in promising techniques for improving the longevity of switches. High current densities in PCSS switches normally result in damage at the metal-semiconductor interface. Research at UTD using amorphic diamond coatings at the metal-semiconductor interface has resulted in significant lifetime improvement for the switches. The process uses a conformal coating with the hardness of natural diamond and extremely high electron emissivity originally called amorphous ceramic diamond and later shortened to simply amorphic diamond. Used in stacked Blumlein pulser configurations, these switches have demonstrated 150-ps switching speed at 100 kV and 10^5-shot lifetimes.

High-Voltage Pulse Sources

HPM sources have three basic components:

- Electrical or explosive prime power.
- RF generator.
- Antenna.

The prime power is supplied by means of pulsed-electrical-circuit Marx generators and transformer-based generators or by single-event explosively driven means.

MARX GENERATORS

Marx generators have been used for several decades now and have seen many improvements in their reliability and repetition rate capabilities. In a Marx generator, some number of capacitors, referred to as the number of stages, are charged in parallel. After the charge cycle is complete, gas switches located between each stage are triggered to conduction, and the capacitor configuration is changed to a series connection. The result is that the charge on each capacitor is multiplied by the number of stages, and the effective capacity is the stage capacitance divided by the number of stages. Because all inductances are also in series, the equivalent inductance is the sum of all circuit, switch, and capacitor inductances. One problem with Marx generator circuits is that approximately half the energy used is lost as heat in the charging resistance for each stage. Using inductive charging can lessen this problem, but care must be taken, since several LC loops can be formed, all of which resonate at different frequencies. The result can be extremely high voltages in circuit locations where these are not expected. This can be especially troublesome in high-repetition-rate circuits.

Figure 2 shows an example of a Marx generator circuit.

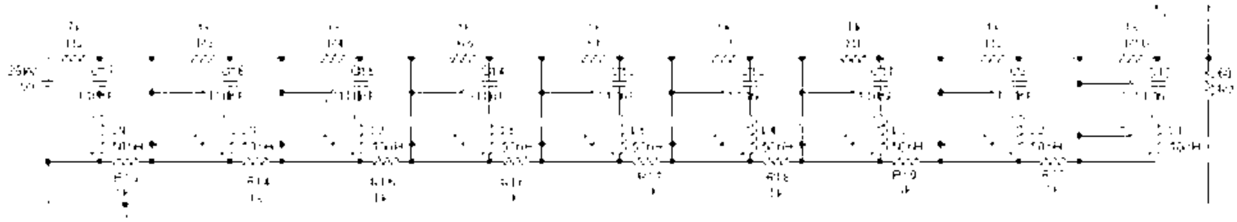

Figure 2. Example of Marx Generator Circuit

TRANSFORMER BASED GENERATORS

Transformer-based pulse generators have also been used for many years as prime power for HPM sources. Transformers with ferrite cores have been used successfully in sources with multigigawatt output powers at kilohertz repetition rates. Ferrite development is an area where substantial gains could be made in HPM sources. Typically, programs are under time or budget constraints and do not give adequate attention to this research. As a result, little or no progress in new ferrite materials for pulsed operation has been made. Ferrites with increased frequency ranges and increased saturation flux density are needed. Air core transformers are used at higher flux densities and are often of the resonant variety because of their decreased coupling levels. Resonant transformers develop peak voltages after multiple cycles owing to coupling effects. Dual-resonant air core pulse transformers are prevalent and require coupling coefficients of 0.8, producing peak secondary voltage and maximum energy transfer after an initial reverse voltage swing. In dual-resonant designs, two frequencies or resonant modes are generated, and the output is the superposition of the two modes. Transformer systems generally require the primary circuit to be matched or tuned to the secondary, or vice versa.

EXPLOSIVELY DRIVEN GENERATORS

Explosively driven generators, also called flux compression generators (FCGs), work by setting up a strong magnetic field between two conductors, usually by discharging a capacitor bank charged to high voltage through an inductive coil. A conducting hollow cylinder filled with high explosives is placed in the center of the coil, filling the region between the two conductors with magnetic flux. The explosives are then used to compress the initial magnetic flux by driving the conducting cylinder surface, which contains the flux, outward into the current carrying coil. Work done by the conductors moving against the magnetic field results in a huge increase in the EM energy. The additional energy comes from chemical energy stored in the explosives. Thus, FCGs essentially convert a portion of the chemical explosive energy into EM energy. The explosively driven conductor is called an armature, and the nondriven inductive coil of the generator is called the stator. Miniaturizing the generators and fine-tuning the magnetohydrodynamic aspects takes years and is still an area of intense research. Material properties under the enormous forces involved are also required for success. Many hours of research and computer code writing and testing go into the selection of every single material used. One problem with this form of HPM source is that of coupling the energy to the load. Attempts to energize the load by direct generation often result in the development of excessive internal generator voltages and breakdown. One solution to these difficulties has been transformer-coupling the load by having the FCG drive the primary of a transformer. The load for HPM production is typically some type of loop antenna with very small inductance and driven directly from the generator. Much research has been done on the effectiveness of this type of antenna, and one method of improving the operation is to fuse the loop along its length such that at peak current, the fuses open and radiate large voltage dI/dt spikes.

Pulsed High-Power Microwave Sources

Pulsed HPM sources can be divided into two types:

- Pulsed electron beam sources – these are typically narrow-band HPM sources such as relativistic klystron amplifiers, backward wave oscillators, traveling wave tubes, split-cavity oscillators, reltron and super reltron, virtual cathode oscillators, magnetrons, gyrotrons, and the magnetically insulated line oscillator.
- Impulse HPM sources – these are typically wideband or ultrawideband sources such as SNIPER, EMBL, Phoenix, Jolt, Thor, GEM II, and the H series.

PULSED ELECTRON BEAM SOURCES

In pulsed electron beam sources, the RF source includes an electron beam generator, a beam transport, and a wave structure. These sources work by converting the kinetic energy of an electron beam into EM energy.

BWOs, TWTs, AND RKAs

HPM tubes, such as backward wave oscillators (BWOs), traveling wave tubes (TWTs), and relativistic klystron amplifiers (RKAs), are also very similar in concept to their conventional counterparts. The main differences lie in the techniques of beam formation; the use of pulsed, large magnitude axial magnetic fields for beam transport; and the application of relativistic voltages and very high beam currents. BWO efficiencies as high as 35 percent have been obtained at moderate power levels, but as power levels are increased, the output levels tend to saturate, and the radiated spectra tends to broaden. These effects are due to beam breakup and turbulent transport. To maintain high beam quality, large magnetic fields are required for high-power operation. An approximately 25- to 50-kG applied axial field implies that mechanically strong solenoidal magnets are required with pulsed capacitor banks to drive them. These requirements in turn dictate a much larger and heavier HPM source. TWTs can be made using many of the same techniques as BWOs. The difference is that the beam-wave interaction is with a forward wave. Thus, TWTs have many of the same issues and limitations as BWO sources. RKAs use cavities for beam bunching and power extraction rather than continuous slow wave structures as in BWOs and TWTs. Some RKA designs use extended structures for power extraction to reduce the power densities and to increase efficiency. They use high beam currents where space charge forces become dominant in the bunching process. Tubes have been developed at the 10-GW power level. They use 0.5 to 1 MeV beams guided by axial magnetic fields of about 10 kG. Efficiencies are on the order of 40-50 percent. Some of the issues with these tubes are beam transport, beam loading of the cavities, base pressure of the vacuum system, xray production, and beam breakup. The combination of x-rays and the high base pressures has led to breakdowns in the cavities and unstable beam propagation.

SPLIT-CAVITY OSCILLATORS

Split-cavity oscillators (SCOs) utilize transit-time bunching of the beam to generate microwave energy. They can generate microwave pulses of about 100 MW for durations on the order of 100 nanoseconds (ns). The SCO can be very compact since no magnetic field is required and low beam quality requiring only basic pulse power sources is adequate. Complete systems, including a power supply and mode-converting antenna, have been built on roll-around laboratory carts.

VIRTUAL CATHODE OSCILLATORS

Virtual cathode oscillators (vircators) operate because of a phenomenon of intense beam physics. They have no conventional counterpart. They have operating frequencies tunable from 300 MHz to 40 GHz, no required magnetic field, simple construction, and low efficiency. Power output varies from 200 MW to 15 GW, and efficiencies range from 1 to 10 percent. Operation is typically in a TM mode in a cylindrical geometry with mode conversion necessary for efficient radiation. The frequency of oscillation of a free-running vircator is related to the relativistic beam plasma frequency and typically chirps upward during the pulse. Plasma closure effects limit the pulse length. Containing the oscillating beam in a resonant cavity can stabilize the frequency. If the resonant cavity is driven by an external source, the vircator can be made to lock to the external signal. Although vircators' simplicity is a major advantage, their very low efficiency poses real problems for weaponization. They have been used as sources for testing, where efficiency and size are not an issue.

MAGNETRONS

HPM magnetrons are basically relativistic, cold-cathode versions of their conventional counterparts. They are characterized by relatively high efficiency, low power densities internal to the tube, robust operation, and compact size. Their modulators and power supplies are simple and inexpensive compared with BWOs, TWTs, and RKAs. Relativistic magnetrons have achieved efficiencies of 10-30 percent in the bands from 0.5 to 10 GHz at power levels of about 5 GW. Pulse widths are on the order of 100 ns, limited by plasma closure of the anode-cathode gap. Magnetrons may be phase locked for higher output power.

The magnetically insulated line oscillator (MILO) is essentially a magnetron that uses the magnetic field of the beam current to provide magnetic insulation between the cathode and anode. This eliminates the need for pulsed magnets and their power supplies while also reducing the size and weight of the system. No mode conversion is required with the MILO.

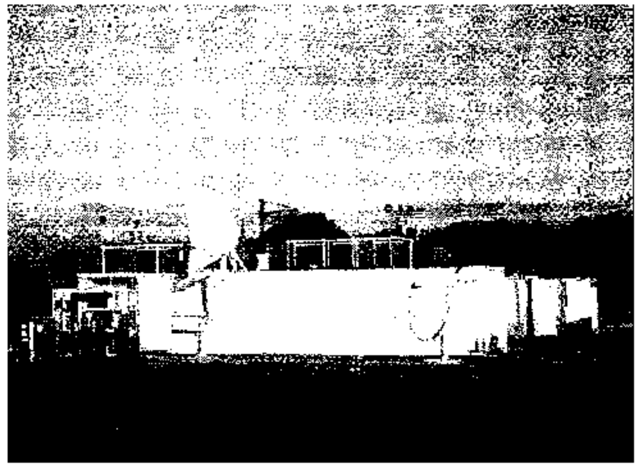

Figure 3. Orion HPM Testing Facility

The Orion system, first fielded in 1995, is a self-contained, transportable HPM test facility housed in five standard shipping containers. It is computer controlled via fiberoptic links. The system is based on four continuously tunable magnetrons with a tunable frequency range of 1 to 3.3 GHz. The thyratron-switched modulator pulse charges an 11-section pulse-forming network through a step-up transformer and a triggered gas output switch. This provides a 100- to 500-ns pulse at 200 to 500 kV and up to 100 PRR that drives the magnetrons. The magnetrons are tuned by stepper-motors and use explosive emission cathodes. The vacuum of 10^{-6} to 10^{-7} is provided by cryopumps. The magnetic field of about 10 kG is provided by cryomagnets. The system includes an entire shipping container housing a combiner/attenuator network to provide continuously variable power over five orders of magnitude. The antenna is formed by two offset, shaped parabolic reflectors, each fed by two pyramidal horns. The antenna produces a 7 x 15 meter elliptical beam spot at a distance of 100 meters. Figure 3 shows the Orion test facility with its antenna.

GYROTRONS

Gyrotrons tap the energy associated with electrons gyrating about strong magnetic field lines. The main purpose for gyrotron development thus far has been magnetic confinement fusion research, in which megawatt-power, long-pulse gyrotron sources operating at more than 100 GHz provide resonant heating, current drive, and instability suppression. These devices use an electron gun to launch an electron beam into a region of slowly increasing magnetic field, where it is compressed. Compression raises the current density and produces a perpendicular component to the beam velocity. After compression, electron-guiding structures are placed at the peak electric field position for the TE_{01} mode. The beam and guiding center structure then enter a resonant cavity. Inside the cavity, the electron motion decomposes into three components: a drift along the magnetic field lines, a slow rotation of the beam about the magnetic axis owing to the $\vec{E} \times \vec{B}$ drift involving the beam self-electric field, and the Larmor rotation of individual electrons about the guiding centers. Resonant cavity fields oscillating faster than the rotational cyclotron frequency of electrons cause the electrons to bunch on one side of their common guiding centers. This bunching causes net electron energy to be given up to the cavity fields, which is then extracted.

Gyrotrons are important in narrowband HPM production because the only directed-energy weapon system known to be fielded today is based on them. The Active Denial System (ADS) uses a gyrotron operating at 95 GHz that is capable of continuous operation. Power output is 100 kW, and the range is more than 750 meters. The system uses an innovative flat parabolic surface (FLAPS) antenna to radiate a focused beam in a manner similar to a parabolic dish. The ADS is effective as a less-than-lethal weapon for crowd dispersal. The radiation passes through the atmosphere with very low loss and is absorbed in the outer layer of skin, causing a burning sensation sufficiently intense to trigger an involuntary reflex response in the target. Energy is deposited to a depth of about 0.4 mm. Figure 4 shows a deployment of the ADS with the FLAPS antenna.

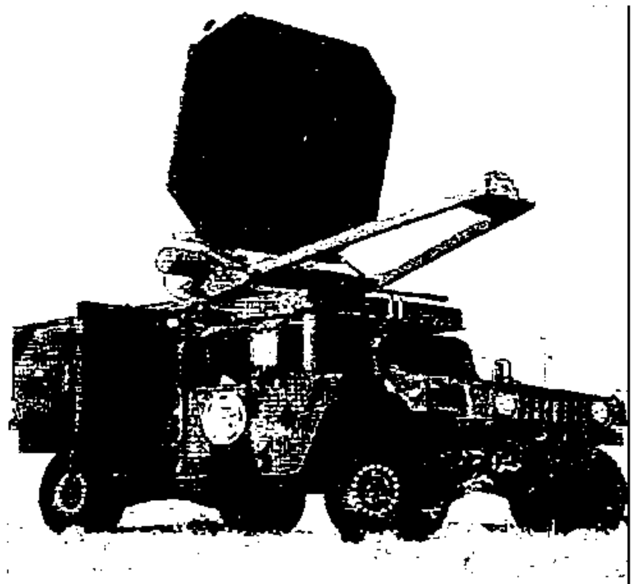

Figure 4. Active Denial System With FLAPS Antenna

IMPULSE HPM SOURCES

Impulse HPM sources are typically ultrawideband. Microwave generation is accomplished by charging the antenna, a transmission line, or a tuned circuit directly with an extremely fast rise-time electrical pulse. This is usually done using a well-designed switch operating in an extremely overvolted condition.

SNIPER

SNIPER (Sub-Nanosecond ImPulsE Radiator) is an SNL HPM source operating at 290 kV that is capable of greater-than-1-kHz PRR. The peak power in the 3.5-ns-wide pulse is 1.25 GW, and the rise time is approximately 150 ps, resulting in spectral content from 100 MHz to 1.5 GHz. The radiated field strength, normalized to a distance of 1 meter, is 120 kV/m using a transverse electromagnetic (TEM) horn.

EMBL

EMBL (EnantioMorphic BLumlein) is an SNL HPM source operating at 750 kV that is capable of 700-Hz PRR. The peak power in the 3.5-ns-wide pulse is 11 GW, and the rise time is about 200 ps. EMBL radiates a 285-ps impulse with a TEM horn antenna. Its spectral content extends from 0.2 to 1.2 GHz, with the peak at 800 MHz. The radiated field strength normalized to a distance of 1 meter is 350 kV/m.

H-SERIES HPM SOURCES

The H-series HPM sources—H2, H3, and H5—were built at the AFRL and used for various tests of assets. They are all currently inactive, except for a modified version of H3, which is being used for research at the University of New Mexico. The H-series HPM sources are all coaxial line pulsers, meaning they contain a pulsed power section that uses a pulse transformer to charge a short section of coaxial transmission line to high voltage. The transmission line is charged quickly enough to overvolt a high-pressure (2,000-psi) hydrogen switch, providing 120-ps rise-time pulses at about 350 kV and 2.5-ns pulse width to another 40Ω coaxial transmission line, which uses a point geometry converter (PGC) to feed an antenna.

Figure 5 shows H2 with a PGC output driving a large TEM horn. The peak power is 2 GW, and these sources were capable of a power supply-limited PRR of 1.8 kHz. Using a flat-plate TEM horn antenna, the radiated field at 10 meters was 25 kV/m. At the AFRL, they compare HPM sources using what is termed a figure of merit (FOM), defined as the field value at some distance multiplied by the distance. Thus, for H3 the FOM is 250 kV. While developing the H series of HPM sources, scientists devised a means of efficiently converting from a coaxial geometry to a parallel-plate geometry. Radiation from a coax forms a doughnut pattern with no field on bore site, and thus the PGC was developed to feed a more interesting antenna.

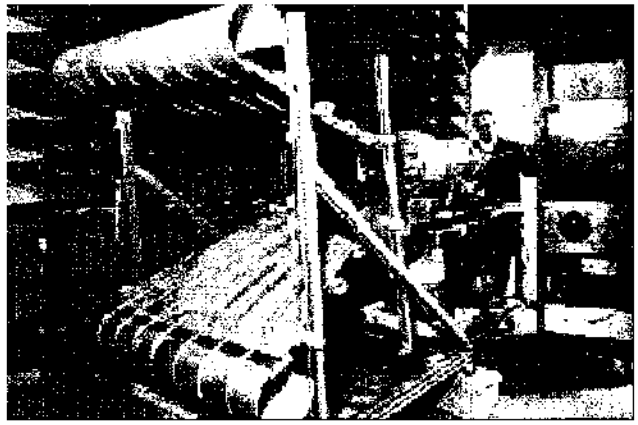

Figure 5. H2 With Large TEM Horn and PGC Output

Figure 6 shows a cross-section drawing of H5 with a PGC feeding a Brewster angle window and an extended-ground-plane antenna. H5 was developed using a much smaller volume high-pressure hydrogen switch than its predecessors used; however, with the pressures involved, personnel were isolated from the source whenever any pressure was in the switch.

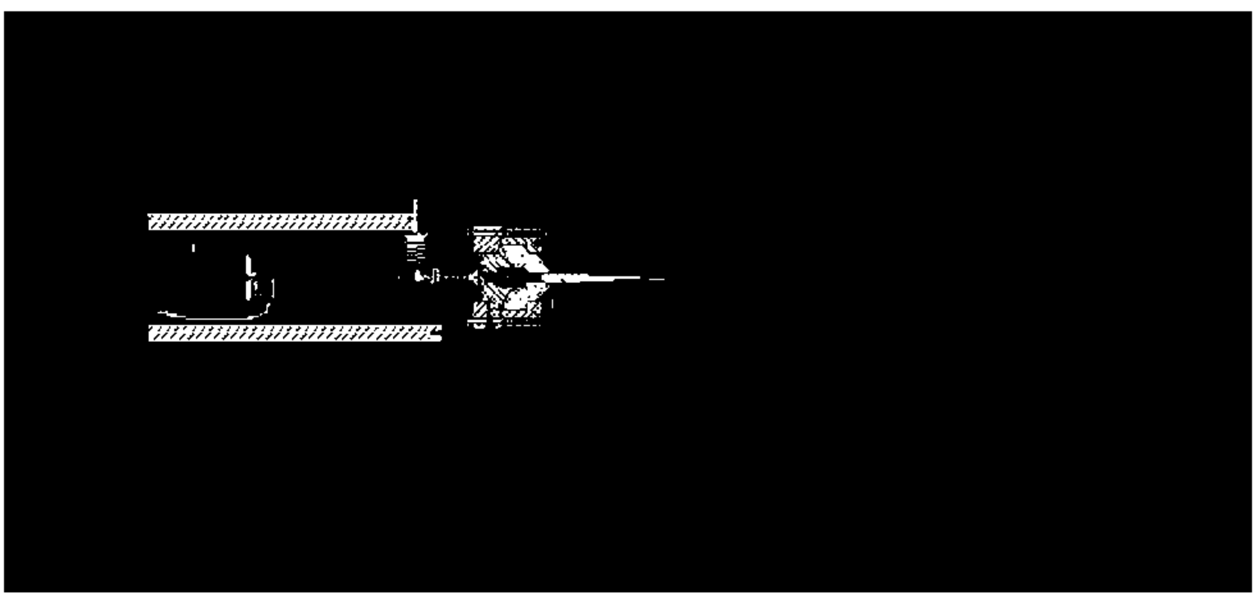

Figure 6. Cross-Section Drawing of H5 With Point Geometry Converter, Brewster Angle Window, and Extended-Ground-Plane Antenna

Figure 7 is a closeup photograph of the same actual components as built and tested at the High Energy Research and Test Facility antenna range. This source was used extensively for testing in the 1990s, including remote tests in which the entire system, including the antenna, a screen room, and far-field diagnostics, was fitted into a trailer specially modified for the purpose.

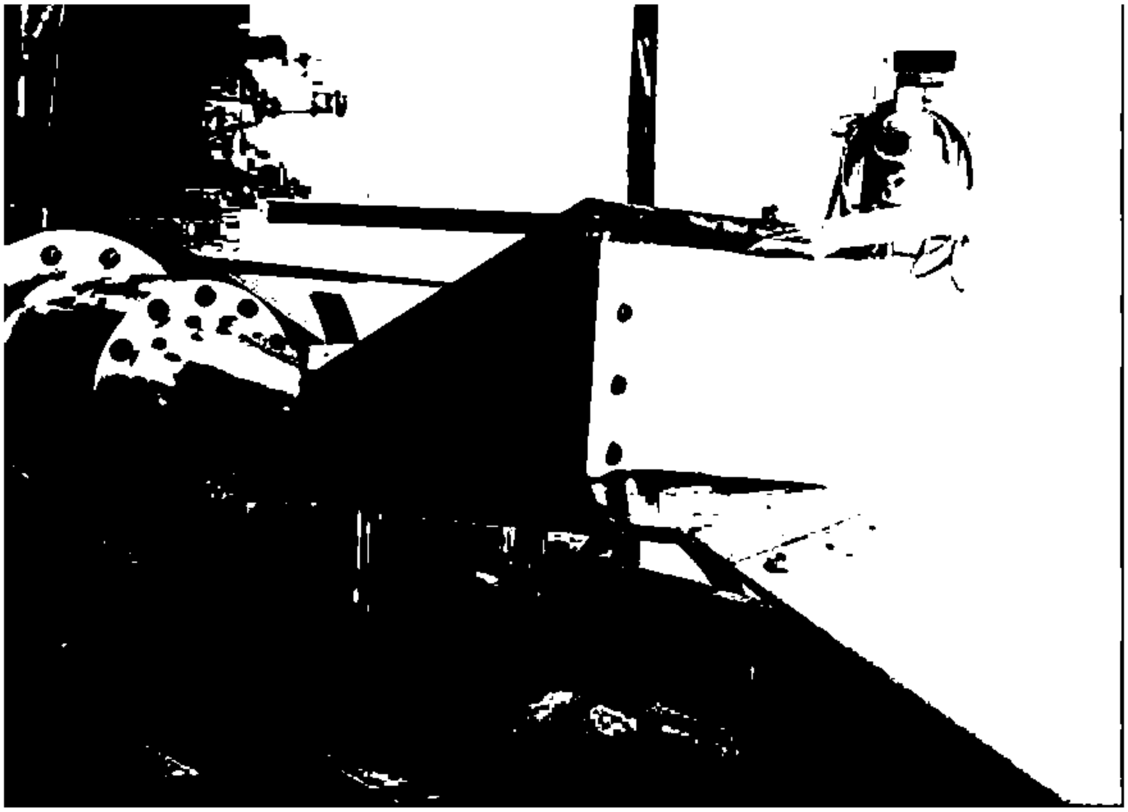

Figure 7. H5 Output Section With the Point Geometry Converter Feeding an Extended-Ground-Plane Antenna Through a Brewster Angle Window

THE PHOENIX HPM SOURCE

The Phoenix was a UWB source developed by the AFRL specifically for asset testing at the High-Energy Microwave Laboratory (HEML). The HEML has a large anechoic chamber and is capable of testing small fighter aircraft. The Phoenix had a ferrite core transformer-based system using two flowed oil switches to generate the fast rise-time voltage pulse. It was bulkier than the H-series sources and thus was less portable. An oil-processing platform with 1-micron filtering and a 5-horsepower DC motor driving the positive displacement oil pump was used. The pumping system was capable of a 7-gallon–per-minute flow rate through the two switches. The oil switches were designed into 50Ω parallel-plate transmission lines. The peaking switch electrode spacing was only 0.015 to 0.020 inches and was highly overvolted. The operating voltage was about 500 kV with a 90-ps rise time and a 1.25-ns pulse width. The peak power was 5 GW, and the radiated field at 9 meters was 45 kV/m, giving it an FOM of more than 400 kV. Phoenix had the fastest rise time of any HPM source to date. Figure 8 shows the waveform of the radiated field at a distance of 8.5 meters. Figure 9 shows the resulting spectral content. Note that the source has good spectral content beyond 2.5 GHz owing to the extremely fast rise time.

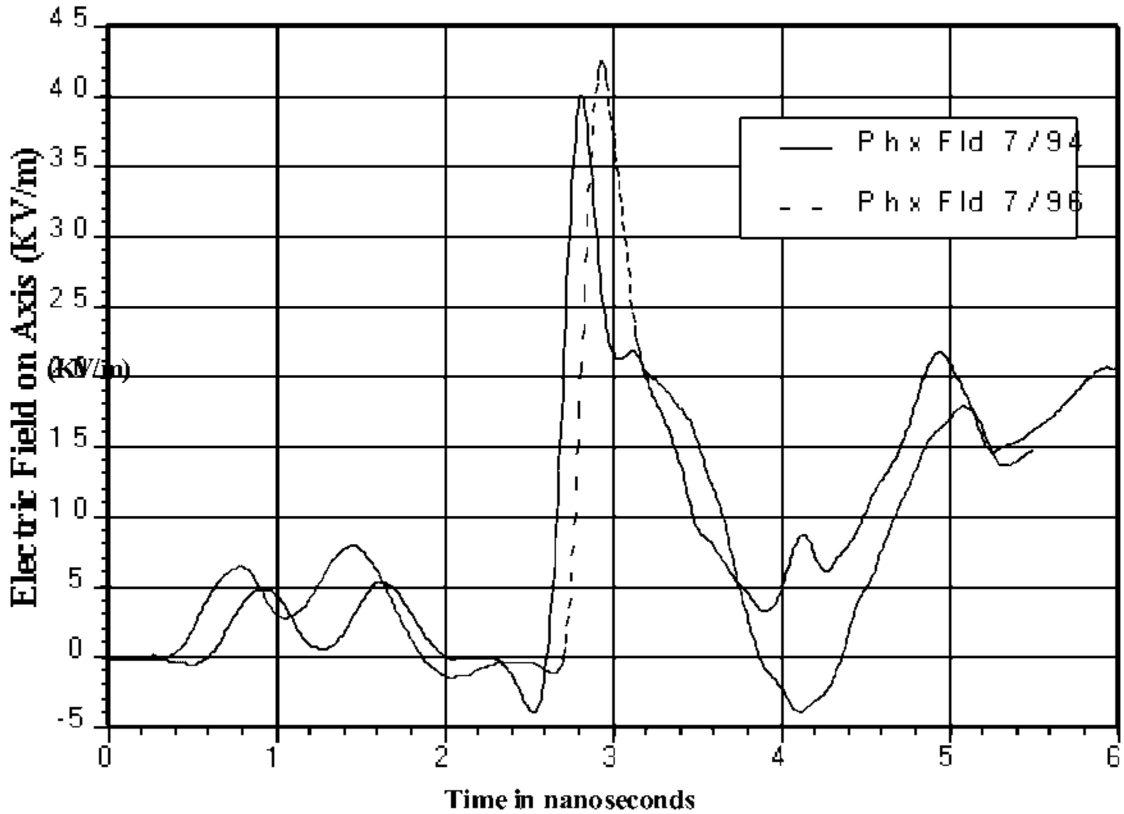

Figure 8. Phoenix Radiated Pulse at 8.5 Meters

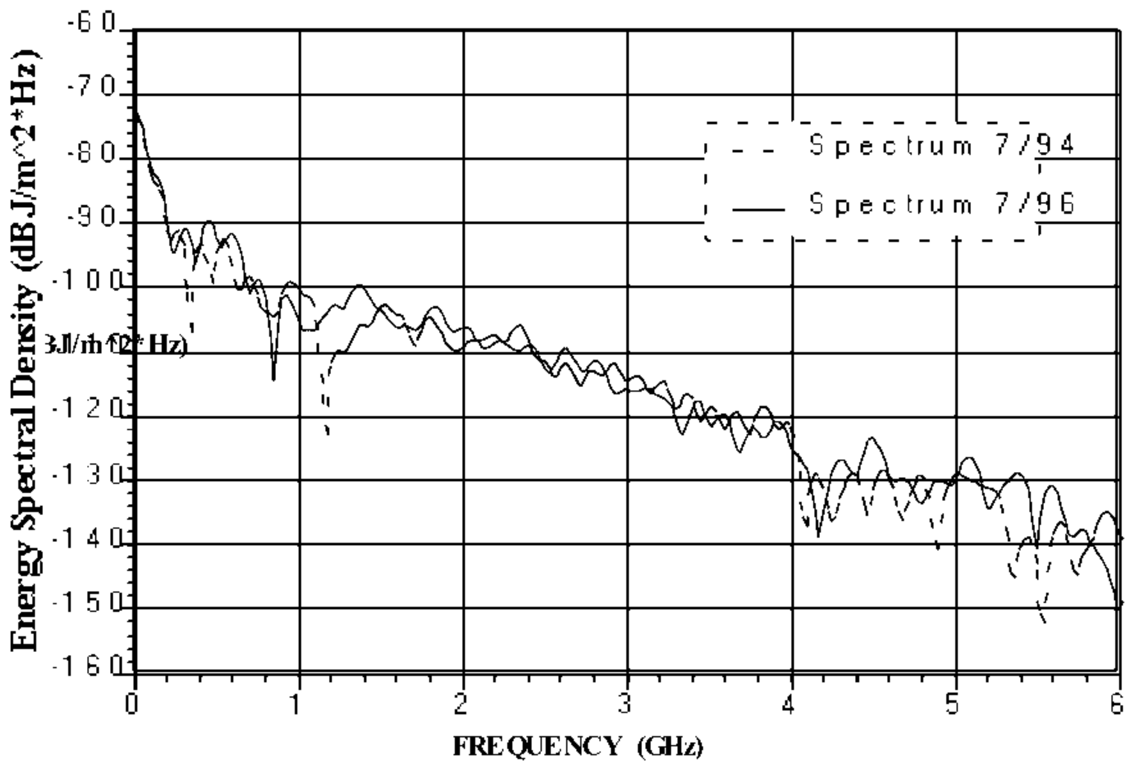

Figure 9. Phoenix Radiated Spectral Content

THE GEM II HPM SOURCE

The GEM II source was based on PCSS switch technology using GaAs bulk avalanche semiconductor switches (BASS). GEM II was built by Power Spectra, Inc., in the mid-1990s and was evaluated by the AFRL. The source was built from individual modules, each containing a rectangular horn output with a BASS switch at the feed point. The modules were assembled in a 12 x 12 array to form a planar radiator measuring 1.6 x 1.6 x 0.85 meters. By timing the switching sequence of each BASS module, the beam was steerable up to 30° off center. The HPM output reached 22 kV/m at a distance of 75 meters and was capable of repetition-rate operation at 3 kHz. The rise time of each module was about 200 ps, and the pulse width was about 2 ns. The major problem with GEM II was switch lifetime; typically, a few switches failed during each burst.

THE JOLT HPM SOURCE

The Jolt, shown in Figure 10, was designed especially to feed the half-IRA antenna. The AFRL refers to this source as hyperband, meaning the frequency band ratio is greater than 10. On the pulsed-power end, Jolt uses a dual-resonant transformer operating at 1.1 MV. The transformer charges an intermediate capacitance discharged by an oil-insulated peaking switch at the focal point of the half IRA to two flat-plate transmission lines terminated at the edge of the dish. The voltage rate of rise is 5 x 10^{15} V/sec, and the repetition rate is a maximum of 200 Hz. The radiated electric field waveform recorded at 85 meters is shown in Figure 11. The half-power point frequencies are an upper frequency of 2 GHz and a lower frequency of 30 MHz.

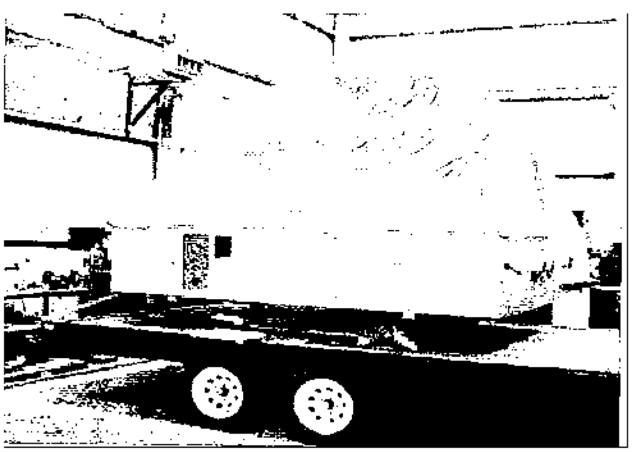

Figure 10. Jolt Hyperband HPM Source

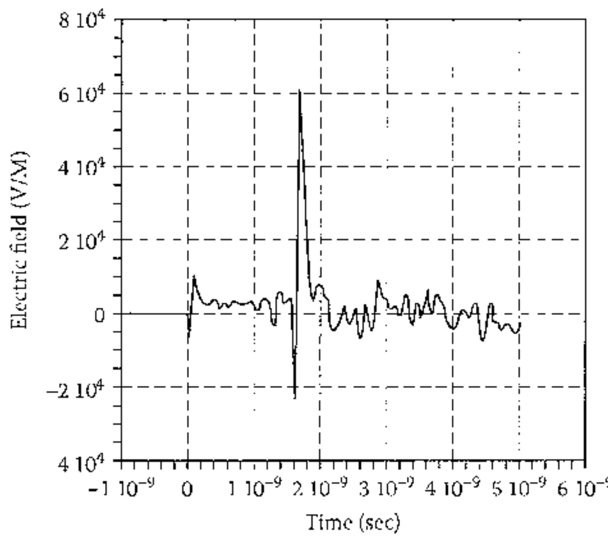

Figure 11. Jolt Radiated Electric Field Waveform at 85 Meters

MESOBAND SOURCES

The AFRL has defined mesoband or moderate band sources as those with a bandwidth ratio between one and three. These sources usually generate HPM energy between 50 and 900 MHz. They are designed using two techniques. The first is to feed a damped sine wave onto a wideband antenna. The second is to switch a transient pulse onto a resonant transmission line connected to a wideband antenna. One such system at the

AFRL, called the Matrix, is simply a quarter-wave, high-voltage coax line that is switched onto a half-IRA antenna by a high-pressure hydrogen switch. This produces a damped sinusoid with a frequency variable from 180 to 600 MHz by means of different coax line lengths.

DIEHL Munitiossysteme in Germany manufactures several mesoband sources for sale to the public. One is a suitcase-sized system using a compact 600-kV Marx generator to provide an impulse to a loop antenna. It is made tunable by changing the size of the loop antenna and can radiate a damped sinusoid at 70 kV/m at 2 meters' distance.

BAE Systems in the United Kingdom also sells mesoband sources made using nonlinear transmission lines and solid-state modulators. These are repetition-rate operated to more than 1 kHz.

HPM Antennas

Many types of antennas are used for radiating HPM signals, and the choice of which to use depends on many factors, including power level, bandwidth, size constraints, efficiency and range requirements, and fratricide concerns. This section discusses the most common antennas used for high-power applications: horns, parallel-plate antennas, and impulse radiating varieties.

NARROWBAND ANTENNAS

HPM narrowband antennas have typically been extrapolations of conventional types modified in some way to prevent air breakdown and to support higher electric fields. Antenna arrays are in development, albeit mainly for phase-locked multioscillator systems. The obstacle to using arrays in single-oscillator systems is that little has been done to develop the required antenna subelements (phase shifters and phase splitters) capable of high-power operation. Eventually, however, antenna arrays will be dominant in narrowband HPM because higher powers will require larger area antennas to prevent breakdown and arrays are the only antennas that are compatible with electronic control for tracking targets. To achieve good effectiveness and gain, the array size should be larger than the wavelength to be radiated. The beam width is approximately $2\lambda/L$, and the gain is L^2/λ^2. Also of importance is the separation between elements in the array. Larger distances between elements cause grating lobes offcenter from the main beam. If the distance between elements can be reduced to less than the wavelength, grating lobes will be minimal. In practice, however, breakdown constraints make this hard to accomplish.

In practice, only a very small number of antenna types have been used in narrowband HPM with any success. By far the most common type is the horn in its many forms, including transverse electromagnetic (TEM), pyramidal, and conical. One advantage of horn antennas for narrowband use is that the radiation pattern and the gain can be calculated precisely.

For TEM and pyramidal horns, the gain is given by:

$$G = 2\pi ab/\lambda^2$$

where: a and b are dimensions of the sides and λ is the wavelength.

For conical horns, the gain is given by:

$G = 5D^2/\lambda^2$

where: D is the diameter and λ is the wavelength.

Mode conversion is critically important with horn antennas in order to generate field patterns of use. The fundamental modes, TE_{10} in rectangular waveguide and TE_{11} in circular waveguide, are preferred since they radiate a field pattern with peak field strength on axis. These are the most common modes used in electronic vulnerability testing.

Parabolic dish antennas are the most common type found in conventional microwave applications, but their use in narrowband HPM has been limited because of breakdown problems in center feed geometries. Variations of the parabolic dish have, however, been very successful. The Active Denial System (ADS) uses a flat parabolic surface (FLAPS) antenna. FLAPS uses an array of crossed dipole scatterers placed about 1/8 wavelength above a ground plane to create a geometrically flat surface that behaves like a parabolic dish. Each dipole controls its corresponding polarization. Incident energy causes a standing wave to be established between the dipole and the ground plane. The interaction of the dipole reactance and the standing wave causes the incident RF energy to be reradiated with a phase shift determined by the dipole length, thickness, and distance from the ground plane, as well as by the angle of incident RF, the dielectric constant of the media between the dipole and ground plane, and the proximity to adjacent dipoles. Figure 12 shows the essential elements of the FLAPS antenna with a cross-shorted dipole array. These antennas are easier to store and have less wind resistance than conventional parabolic dishes.

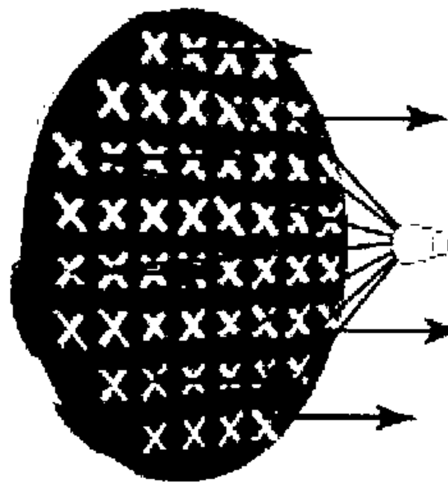

Figure 12. FLAPS Antenna With a Cross-Shorted Dipole Array

The Vlasov antenna is also well suited to narrowband HPM radiation and has some distinct advantages. It can be fed with a TM_{01} mode and produce a directed beam with a nearly Gaussian profile; mates easily to the cylindrically symmetric HPM sources, such as the MILO and vircators; is easily constructed; and has a large feed aperture to support high electric fields. Typically sources that generate their power in the TM_{0n} modes require a mode converter for radiating anything other than a donut beam, but the Vlasov antenna does not; the antenna is actually adapted from a mode converter.

Figure 13 shows (a) Vlasov antenna origins and (b) a Vlasov antenna attached to a cylindrical MILO. Vlasov antennas have one major drawback: the propagation angle is a function of the operating frequency. Thus, if the frequency chirps during the RF pulse, then the beam direction will sweep. The propagation angle is given by:

$$\theta = 90^\circ - \cos\left(\left(1-(f_c/f)^2\right)^{1/2}\right)$$

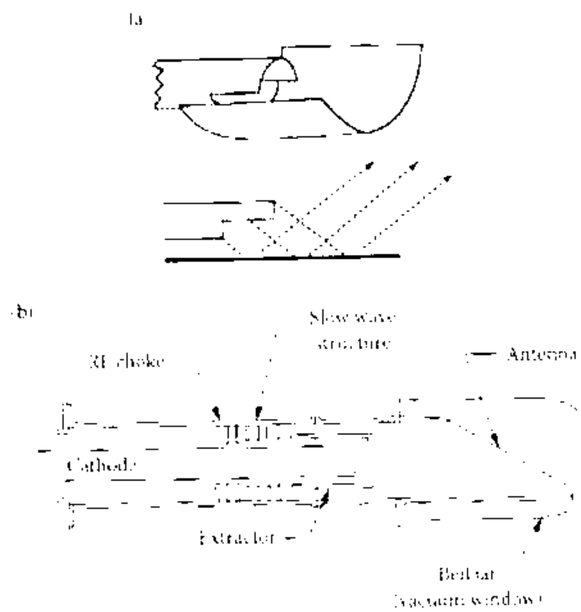

Figure 13. (a) Mode Converter Vlasov Antenna and (b) Vlasov Antenna Attached to a Coaxial MILO

WIDEBAND AND ULTRAWIDEBAND ANTENNAS

Wideband antennas generally present a much greater design challenge than do narrowband antennas. As pulse duration and rise times are shortened, antenna design becomes more difficult. A good wideband antenna must have low dispersion across the entire bandwidth and high gain with minimal sidelobes. These are difficult to achieve because the wavelengths are large, requiring large antenna dimensions for high gain. Often, mission constraints dictate a much smaller antenna, thus the gain will not be constant with frequency, resulting in a distorted radiated pulse shape. The main consideration for transmitting UWB signals is minimizing frequency dispersion. For conventional antennas, the gain is a function of frequency. One approach to solving this problem has been to correct a conventional antenna (TEM horn) for dispersion. A second approach has been to use the dispersive characteristics of a conventional antenna, with the appropriate tailored drive signal, to radiate the desired UWB signal. A third approach has been to develop a new type of antenna. These three approaches cover the limited gamut of UWB HPM antennas.

The basic approach to attaining low dispersion in a conventional antenna is to ensure a slowly varying antenna impedance change along the length, beginning at the source output impedance and ending somewhere close to the impedance of free space (377Ω). In practice, it is found that the final impedance does not have to be very close to that of free space; instead, 220Ω to 280Ω provides the highest efficiency for most TEM horns. Best results are obtained for any length TEM antenna if the impedance is increased at a constant percentage rate (that is, is exponentially tapered). The resulting design may then have electrical breakdown problems at the connection point with the source, since the antenna impedance changes initially are quite small and, thus, plate spacing also remains small. Typically, a specially shaped, solid insulating material is required to obtain a gradual impedance change when transitioning from the source media into air. This is where the highest electric field strength is found and also where the temptation to aid impedance tapering by incorporating abrupt transitions in conductor dimensions is greatest. Any reflections of the pulse from farther down the antenna will also enhance fields at the feed point. All these factors combine to make the design of the antenna feed section possibly the most important factor in HPM sources and, in many instances, the determinant of the radiated signal characteristics. Sidelobes generated using TEM antennas tend to fall off sharply and are accompanied by a stretching of the original pulse duration. The distance from the antenna to where the far field region begins is defined such that the travel time of the differential distance is less than the rise time of the pulse. Parameters such as gain and beam width for UWB antennas are difficult to define because these concepts are from the narrowband world, where the definitions are for a single frequency. For UWB antenna comparisons, the community uses the previously described figure of merit concept to aid with this problem. The FOM is the peak electric field measured at some distance multiplied by that distance, thus the unit for FOM is volts. Using this concept, gain for UWB antennas is defined as:

UWB gain = FOM/V_p

where: V_p is the peak voltage of the driving pulse.

Typical gains are 3-4 but with extreme designs can reach 6 and above. These are the antennas of choice for impulse radars since they can be small and lightweight but radiate UWB pulses quite well. However, sidelobe pulse stretching makes the aiming accuracy of the transmitting and receiving antennas crucial.

Another technique of interest in WB/UWB antennas uses a log-periodic antenna designed with dispersion characteristics such that, when driven with the proper input signal, it produces the fast rise time pulse required. The drive signal in this technique must have a strong increase in frequency from start to end. No high-power designs using this technique appear to have been accomplished.

A new type of antenna, the impulse radiating antenna (IRA), incorporates a parabolic dish as a main component of the design (in fact, it is debatable whether this is actually a new design because it incorporates a parabolic dish). The distinguishing feature of an IRA is its use of a final fast switch located at the focal point of the dish to provide a spherical waveform to the dish. The design also must include a high-voltage transmission line to feed the peaking switch, which in all probability will not be dispersionless. However, the frequency content of the feed signal most likely will be less than that of the wave front from the peaking switch. The design also must include some number of conical transmission lines from the peaking switch back to the dish, providing something close to an impedance match for the feed pulser. The crucial criterion here is that the IRA be driven by a spherical TEM wave front, in which case the phase center of the wave is then fixed and the IRA is dispersionless. There is also a much smaller pre-pulse that is radiated from the front side of the switch and is not reflected from the dish. This signal will be radiated two focal lengths ahead of the main pulse. For a 4-meter dish, the pre-pulse arrives about 10 ns before the main pulse. Fast-acting semiconductor protection devices could in principle be effective in negating the effects of the main pulse. The peaking switch at the focal point must be contained in some insulating media and, thus, there is a reflection associated with the transition to air. The wave front generally is not spherical as it enters the air beyond the peaking switch owing to the physical dimensions of the switch and high-voltage insulation requirements. Successful IRA designs use the switch insulating media and container to form a lens designed to give a spherical wave at the air interface. The IRA, like the TEM horn, transmits a differentiated signal from the applied pulse. This is why the rise time of the driving pulse is so important to antenna response.

Conclusion

This paper provided an overview of the current state of HPM sources and the technologies driving their development. Advanced cathode materials, computer codes for more predictive ability in electron beam generation and propagation, high-speed switching at high power, and low-loss insulation techniques are just a few of the areas where advancement clearly is needed for progress to occur. Advancements in photoconductive solid-state (PCSS) and other solid-state switching and sharpening devices appear to finally be reaching a level of development such that they may soon be of use in high-voltage systems. If PCSS switching devices capable of higher operating voltage and extended lifetime are made available, variations of the phased array will become the HPM source design of choice, given the inherent advantages. More compact antennas are greatly desired; however, the physics of the radiation process requires structure sizes on the order of one-half wavelength of the lowest radiated frequency. With demanding levels of directivity and gain also requirements, compact UWB antenna designs will continue to be difficult, if not impossible, to realize.