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Compact Pulsed Power for Directed Energy Weapons

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The Titan Corporation has been developing directed energy technologies since the early 1980s. Over this time Titan has provided advanced power supplies for electromagnetic gun and laser research while making broader contributions in the field of high-power microwaves (HPM). Titan's HPM work expanded from initial efforts fielding and operating the first gigawatt-level oscillators for susceptibility test applications, to research and development maximizing the peak and average output powers and overall efficiency realized from such systems. As interest in HPM technology has spread globally, Titan has leveraged this core competency and provided the HPM equipment for nearly all of the major European effects test facilities. Titan's current interests focus on compact, efficient and reliable directed energy weapon systems and the advanced subsystems and components that enable the same. Specific subsystems of interest include pulse-forming networks and intermediate energy storage and power conditioning elements (electronically reconfigurable batteries and power ride-thru subsystems). These subsystems are designed for reduced size and weight while still meeting severe service, platform integration, lifetime, and thermal management constraints. Specific components under development at Titan include laser-gated solid-state switches and both high peak and high average power, frequency-agile, HPM oscillators. Status and recent results from this research are presented.

KEYWORDS: Electronically reconfigurable batteries, High-power microwaves, Laser-gated solid-state switches, Magnetron, Power-ride thru, Pulsed power, Reltron

1. Introduction and Previous Work

Directed energy weapons (DEWs) are emerging as a key defense technology of the early 21st century. The first laser antimissile and antiartillery systems are within perhaps five years of deployment, and newly envisioned information warfare and nonlethal point defense missions are hastening the deployment of high-power microwave (HPM) systems. Department of Defense (DoD) programs in "more electric" and "all-electric" platforms and electrically driven weapon and self-defense systems are promoting the development of laser, high-power radio frequency (RF) and both electromagnetic (EM) and electrothermal/chemical (ETC) gun technologies. In fact, the DoD's current fundamental "transformation" efforts are based on stressing the development of capabilities to deal with threats emerging in the

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Table 1. Triservice directed energy applications

- U.S. Army [Future Combat System (FCS)—hybrid electric drive vehicles]
  - Advanced armaments—electrothermal/chemical guns
  - Enhanced area air defense—solid-state heat capacity laser system
  - Counter-HARM
  - Counter-ATGM
  - Countermine (electronically fuzed and wide-area threats)
- U.S. Navy [All-Electric Ship Programs (Integrated Propulsion System and DDX)]
  - Advanced stand-off shore bombardment—electromagnetic guns
  - Advanced anti-ship missile defense (free-electron laser and HPM)
  - Nonlethal area denial
- U.S. Air Force (more electric aircraft program and advanced UAV programs)
  - Enhanced self-defense—solid-state heat capacity laser system
  - Space-based laser program
  - Airborne laser
  - Suppression of enemy air defense
  - Aircraft self-defense
  - Close air support
  - Defensive and offensive counter air
  - Strategic attack/strike warfare, attack operation/air interdiction
  - Combat search and rescue
  - Area denial
  - Cruise missile defense

Table 2. Countries now developing high-power RF technology

Programs	Countries
Major	United States, China
Medium-scale	United Kingdom, France, Germany, Russia
Emerging	Sweden, Japan, India, Taiwan, Australia, Israel, South Korea

Information Age instead of emphasizing countermeasures to specific threats. DEWs hold the promise of engaging multiple threats and multiple threat types, thereby fitting very well into this conceptual paradigm. Some specific examples of defense applications of DEW technologies are shown in Table 1.

The initiatory HPM programs in the USSR and United States have evolved and influenced foreign allies and threats to take an interest (Table 2). The collapse of the USSR led to the dispersal of Russian and Ukrainian HPM workers and the proliferation of the Soviet technology to the Third World. This global emergence is driven by at least two factors: 1) The dependence of both military systems and civilian support infrastructure on sensitive electronics is increasing, and 2) after a more-than-20-year effort, an understanding of the susceptibilities of both military and commercial systems to HPM threats is maturing.

For these reasons the Titan Corporation has taken a keen interest in the development of systems, subsystems, and advanced components across several different technologies to support HPM and laser directed energy programs.

In 1997, Maxwell Technologies purchased Physics International (PI) from Primex Technologies and merged two of the three most prominent, commercial, pulsed power entities in the United States. PI and Maxwell pulsed power capabilities were combined into a new entity, Maxwell Physics International, which became a component of Maxwell's Systems Division. Maxwell subsequently decided to leave the DoD and Department of Energy (DOE) pulsed power business altogether and sold the combined Maxwell/PI pulsed power divisions to the Titan Corporation, the parent company of Pulse Sciences Incorporated (PSI). Now, the three most prominent names in commercial pulsed power are combined as the Pulse Sciences Division (Titan-PSD) of the Titan Corporation.

In March 2002, Titan completed the acquisition of Jaycor and its subsidiary California Tube Laboratory (CTL). This acquisition established Titan as one of the world's primary industrial authorities on electromagnetic effects and suppliers of RF and narrow-band microwave DEW technologies and associated electrical power systems. High average power, high efficiency, magnetrons; high peak power, pulsed, relativistic magnetrons and superreltrons; short pulsed, ultra-broad-bandwidth systems and megawatt-class power supplies and power conditioning subsystems are all designed and manufactured by Titan. This paper will chronicle some of the past and report on some of the current contributions that Titan has made to the development of pulsed power technology for DEW applications.

1.1. Previous Titan work in support of HPM programs

Titan-PSD has been developing directed energy technologies since the early 1980s. In this time, Titan has delivered capacitor banks for electromagnetic gun research with a total stored energy exceeding 200 MJ and advanced pulsed power systems for several large laser systems (Fig. 1). Over 40 years, Titan-PSD has delivered more than 200 pulsed power systems for electromagnetic pulse (EMP), x-ray, and lightning simulation; flash radiography; and other applications worldwide. Although somewhat peripheral to DEW research proper, these projects have nonetheless formed much of the experience base supporting Titan's directed energy technologies contributions.

Titan's primary contributions have been in the field of HPM (Fig. 2). Work started in 1984 when Titan set up and began operating a susceptibility effects test facility for the Defense Threat Reduction Agency (DTRA). A 30 × 20 × 16 ft anechoic chamber to support this work was originally designed to operate in X-band and above. At the outset of the U.S. HPM directed energy program the community felt that the higher gains possible from fixed antenna sizes at higher frequencies would drive technology development into these bands. Over the next 10-plus years, the 25 effects test programs conducted on strategic and tactical systems in the Titan facility and tests conducted at other sites both confirmed that the lowest susceptibility thresholds are observed in the S-band and below. HPM source development history has mirrored these findings.

1.1.1. HPM source developments at Titan. In 1983 Titan initiated HPM source research in its test facility by developing first C-X band overmoded vircators[17] and later an L-band vircator.[13] These systems produced gigawatt outputs through the oscillating virtual cathode mechanism. Their main shortcoming was their broad bandwidth due to chirping induced by diode gap closure. To address this shortcoming Titan developed the first cavity vircator[3] that reduced the output bandwidth from several hundred megahertz to a few tens of megahertz. Versions of these devices were soon after sold to Nucletudes in France

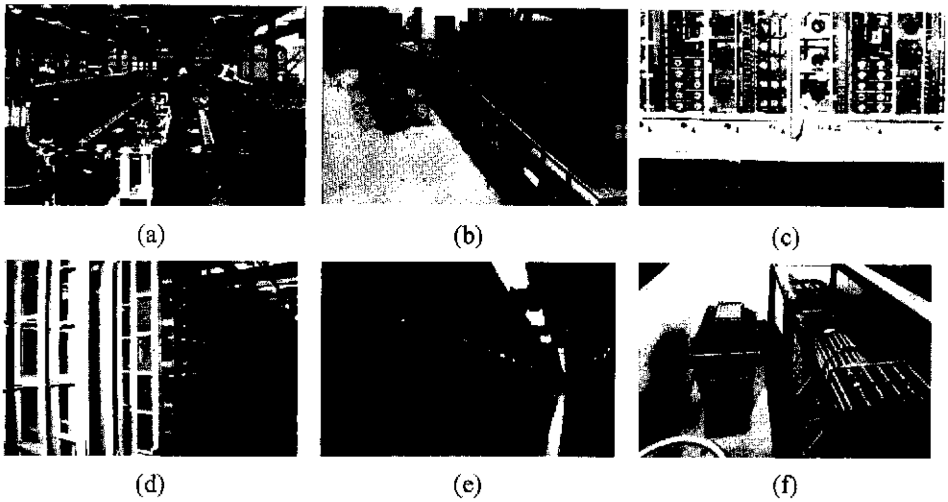

(a) (b) (c)
(d) (e) (f)

Fig. 1. Titan-PSD has designed, fabricated, and delivered the pulse power subsystems for most of the major electric gun facilities worldwide: (a) the decommissioned 32-MJ Thunderbolt System built for a Strategic Defence Initiative Office (SDIO) project; (b) the existing 32-MJ Kirkcudbright system currently being operated by the United Kingdom; (c) the first transportable pulse power subsystem designed for an electric weapon system. [This 8.5-MJ stored energy subsystem, consisting of four separate PFNs, was designed by Titan-PSD under the Army/Army Research Development and Engineering Center (ARDEC) Balanced Technology Initiative and was capable of delivering up to 5 shots at 3 rounds per minute.]; (d) the 52-MJ bank delivered to the ARDEC for electromagnetic and coil gun research; (e) the pulsed power driver for the 40-MJ OMEGA laser at the University of Rochester; and (f) a portion of the 100-Hz, 750-kV, 1.25-μs modulator for NRL's EMRLD laser.

and Culham Laboratory in the United Kingdom to help kick-start HPM effects testing and technology development programs at each location.

Titan initiated work on magnetrons by acquiring S- and X-band, A-6 versions from Bekifi at the Massachusetts Institute of Technology.[2] These devices were integrated into the Titan test facility, and within two years an L-band version of this same design was developed.[16] An S-band magnetron was sold commercially to Thales in France in 1987 to help kick-start HPM effects testing and technology development programs there.

This HPM source development work soon expanded from the initial efforts to field gigawatt-level vircators and magnetrons for the effects testing applications to the development of other high-power sources. These include narrow-band klystrons (both high- and low-perveance variants) and reltrons, as well as ultra-wide-band systems. In parallel, the peak and average power and spectral characteristics of these HPM sources were being explored in research involving phase locking, repetitive pulsing, and frequency agility. Other related Titan work included the development of pulsed power systems to drive these HPM sources involving several different architectures [pulse-forming networks (PFNs) with capacitive energy storage and voltage adders with magnetic compression power conditioning]. These advancements are described briefly in the following.

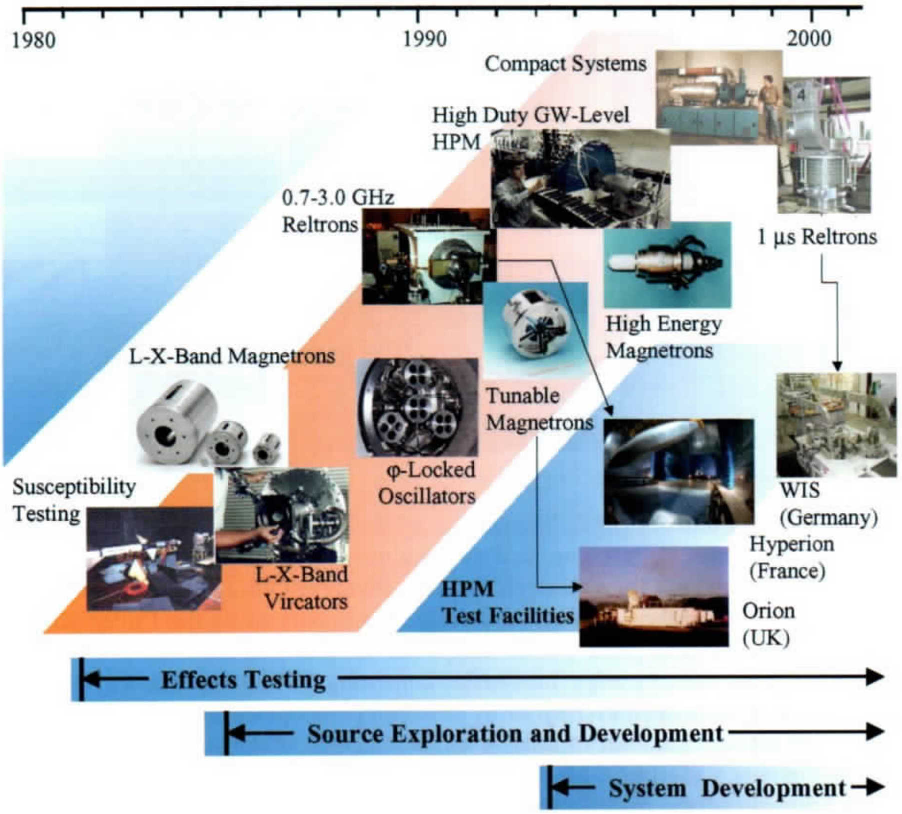


Fig. 2. Titan contributed to the field of HPMs in three distinct eras: 1) susceptibility effects testing, 2) HPM source development, and (currently) 3) DEW system development. The effects testing work started in 1984. Then, Titan operated the DTRA susceptibility effects test facility supporting tests for external DoD users. Soon thereafter Titan began using the facility for its own end-to-end DEW research programs. In parallel, Titan HPM source development efforts initially focused narrowly on providing the facility with minimum essential capability but soon expanded to meet specific weaponization and testing requirements. During this period, Titan performed some of the seminal narrowband HPM work associated with phase-locking, frequency agility, and repetitive operation. Source development work continues today, focusing on improving energy output and tunable bandwidth. These efforts are combined with the development of other advanced pulsed power subsystems and components needed to realize compact, efficient, and reliable DEW systems.

In the late 1980s, Titan S-band magnetrons were used in a three-year effort to understand how to achieve output powers exceeding 10 GW from a phase-locked array.[9] Many mission scenarios for DEW systems that could produce burnout or upset in military targets using only a single HPM pulse drove output requirements to this 10-GW level. The combination of gigawatt-level sources locked in phase appeared an effective way to realize this output level without increasing the RF fields and beam energies within individual diodes (and dealing with the RF breakdown and thermal issues that would certainly ensue). In this effort both master/slave and peer configurations were investigated to understand the optimal architecture for such an array. In the end, a module of seven "peer-coupled," 2.8-GHz, magnetrons was built that produced an output power of 2.9 GW. Extrapolation to even higher output levels appeared feasible.

At this time, the HPM community was beginning to recognize that there must exist a middle ground between HPM and electronic warfare (EW) DEW concepts. The HPM approaches were characterized by superpower, single-shot, single-frequency, pulse formats, while the EW approaches made use of very low powers but incorporated modulations in the output pulse formats to effectively exploit susceptibilities within their intended targets. To access this middle ground the HPM sources had to first be shown capable of operation in repetitive or burst modes. This burst capability would be surely required of any DEW system, if only to engage multiple threats deployed in sorties or clusters. In response to these weaponization considerations Titan-PSD developed relativistic magnetrons capable of operation in 1-kHz bursts.[4] A 1.1-GHz, L-band, magnetron was driven by a magnetic pulse compression modulator (see discussion below) and achieved 250-pps repetitive operation at 1.2-GW peak power, in a burst of 100 shots. The average power of 12.6 kW during the burst remains today the state of the art for gigawatt peak power sources. To demonstrate that the magnetron's diode could recover in a time short enough to support higher repetition rates, the device was run for ~5 pulses (limited by the modulator) with 1 ms between individual pulses.

In the early 1990s both Jaycor and PI were actively extolling the use of frequency-agile waveforms to enhance lethality in backdoor attacks. Frequency agility exploits the characteristics of typical coupling cross sections that show pronounced dependence on microwave frequency. An HPM source that can sweep or hop frequency across a band has a higher probability of matching to a coupling resonance than a source fixed at a single frequency. Because of this strong dependence of backdoor coupling and susceptibility levels on microwave frequency, it was apparent that test facilities needed the capability to vary frequency continuously in order to obtain a comprehensive and accurate assessment of any given test asset's susceptibilities. In response to these testing and weaponization considerations Titan-PSD developed frequency-tunable magnetrons. These oscillators can be tuned ±17% about a central frequency,[10] which today still represents the state of the art. In the mid-1990s these magnetrons were integrated into advanced concept demonstrations for the Army and were also exported to the United Kingdom as part of an HPM test facility.

In the late 1980s and early 1990s Titan-PSD developed several ultra-broad-bandwidth (UWB) systems for Army and Air Force DEW research programs. The first system was based on a spark gap-switched Marx that drove a variety of different broadband antennas. It could launch 200-MW total RF power in 3-ns pulses with rise times of ~300 ps at a repetition rate of a few pulses per second. This compact, self-contained system was used in both indoor susceptibility tests and outdoor technology demonstrations. A second project produced a system that could launch impulse waveforms at 200 pps in burst mode.[15] A 3.66-m-diameter paraboloidal reflector was driven at its feed by a hydrogen switch that was integrally coupled to a novel electromagnetic lens. The radiated waveform had a rise time of ~100 ps and a 10–90 rise-to-fall pulse width of 45 ns. The peak electric field on bore-sight measured at 305 m was 4.2 kV/m.

Titan invented the super-reltron in 1992. A suite of tubes that operate between 0.7 and 4.5 GHz has been developed since that time.[12] These novel tubes represent a marriage between pulse power and conventional high-power klystron techniques. An energetic electron beam is modulated by periodic virtual cathode formation, and the bunched electron beam is postaccelerated to energies approaching 1 MeV. Microwave power is extracted with ~50%

Table 3. Operating parameters of Titan-built modulators for DEW applications

Modulator	Voltage, kV	Current	Pulse width	Pulse repetition frequency	Pulse energy	Average power	Switch type
LS-15	50	10 kA	100 ns	1.9 kHz	50 J	95 kW	Spark gap
NED laser driver	±40	260 A	2 μs	10 Hz	3 kJ	30 kW	Thyratron
EMRLD PFN	750	38 kA	1.3 μs	125 Hz	35 kJ	4.4 MW	Spark gap
EMRLD (trigger)	600	260 A	400 ns	125 Hz	100 J	12.5 kW	Spark gap
OMEGA[a] laser driver	15	128 kA	200 μs	Single shot	40 MJ	—	Ignitrons
CLIA HPM driver	750	10 kA	100 ns	250 Hz	750 J	188 kW	Magnetic
ORION HPM driver	500	10 kA	50–500 ns	100 Hz	250 J	25 kW	Thyratron
Compact HPM driver	450	9 kA	450 ns	10 Hz	1.8 kJ	18 kW	Spark gap

[a] 120 modules, each storing 0.33 MJ.

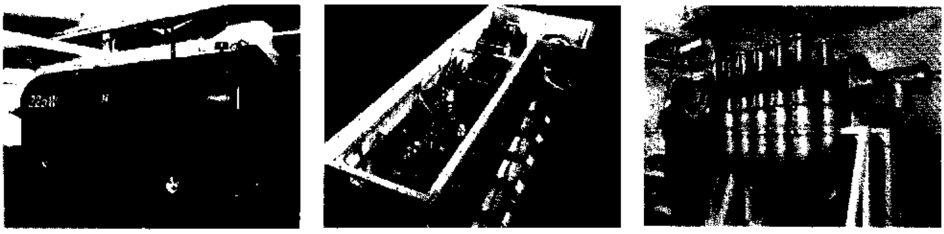
conversion efficiency downstream in a dual-cavity output section that is tuned to the bunch frequency. The reltrons can produce microwave pulse widths approaching 1 μs and pulse energies of a few 100 J, outstripping the relativistic magnetrons that to date are limited to pulse widths of about 100 cycles and pulse energies below 100 J.

In response to the HPM effects testing considerations discussed above, Titan developed frequency-tunable reltrons. These oscillators can be tuned ±10% about a central frequency.[11] These devices are still in development today (see Sec. 2) and have been provided to both France and Germany as HPM threat simulators.

1.1.2. Development of pulse power modulators for DEW applications at Titan. Titan has developed a large number of modulators for a variety of laser and HPM DEW applications, with voltage ratings from tens of kilovolts to several megavolts and average power levels from tens of kilowatts to multimegawatts (Table 3). They also range from relatively simple units to complex, state-of-the-art devices with various different architectures and subsystems. These include PFNs for generating the required pulse shapes; thyratron switching for precise timing of the pulse switching into the load; low inductance layouts for fast output pulse rise times and high-turns-ratio pulse transformers for generating the high voltage outputs. The switching technologies include thyratrons, spark gaps, magnetic switches, and solid-state devices, such as metaloxide semiconductor field effect transistors (MOSFETs), insulated gate bipolar transistors (IGBTs), and thyristors (Fig. 3).

Several of these modulators have been designed for long-lifetime, reliable operations. Such features are essential if these systems are to find their way into military applications. As an example, the Defense Advanced Research Projects Agency (DARPA) excimer Raman-shifted laser device (EMRLD) modulator (a 100-Hz, 750-kV, 1.25-μs, lumped-element PFN to pump an excimer laser) was specifically designed for and demonstrated a lifetime of 10^{10} shots.

The ORION pulser (Fig. 3b) design has command resonant charge and intermediate energy storage sections each switched by thyratrons that drive a step-up transformer and



(a) (b) (c)

Fig. 3. Titan-PSD pulsed power systems based on (a) spark gap, (b) thyratron, and (c) magnetic switching.

Table 4. Key operating parameters in European HPM test facilities

HPM facility	Power density, W/cm^2	Range, m	Frequency, MHz	Maximum pulse width, ns	Maximum repetition rate, Hz	Shots per burst	Source type
UK—Orion	>120	100	1,070–3,300	100	100	100	Magnetrons
France—Hyperion	>1,000	~100	700–3,300	300	1	—	Reltrons and magnetrons
Germany	>170	15	700–1,450	300	10	100	Reltrons
Sweden[a]	~120	15–25	L-Ku	500–5,000	1,000	Continuous	Reltrons

[a]This facility uses conventional high power klystrons in L-, S-, C-, X-, and Ku-bands, with maximum power 25–0.25 MW.

PFN. The modulator can fire 1,000 pulses in a burst at repetition rates up to 100 pps and produces 500 kV into a 50Ω load. It has been used to drive relativistic magnetrons[6] for HPM effects measurements.

The Compact Linear Induction Accelerator (CLIA) (Fig. 3c) was developed for moderate-repetition-rate HPM source research and development.[1] CLIA operates at 250 pps with 750-kV, 10-kA, 100-ns output pulses. The system uses thyratron and magnetic switching throughout and produces 188-kW average power into the load. CLIA is not actively cooled and so is restricted to burst operation with 5,000 pulses in a burst. CLIA has been used to drive both magnetron and klystron loads. This technology is scalable to kilohertz repetitive operation.

1.1.3. Titan pulse power systems for HPM simulation. In addition to work done supporting domestic RF and microwave DEW research and development, Titan has provided HPM simulation systems for all of the world's major HPM test facilities in Sweden, France, the United Kingdom,[14] and, most recently, Germany. The microwave test parameters and operational capabilities achievable in these international facilities are summarized in Table 4. The types of Titan HPM sources that produce the intense microwave environments are also given. Work continues today upgrading those systems and providing similar hardware for several non-European countries.

2. Most Recent Contributions

Titan-PSD has taken an interest in the full spectrum of developments of advanced subsystems and components that the three U.S. services will require to realize their DEW and electric platform goals. These developments enable many different military missions and cut across many different technologies: advanced capacitors, switches, transmission systems, RF, and optical systems. Some of the pulse power and power electronic subsystem and component developments that Titan is pursuing are summarized in Table 5.

The following subsections describe five electrical subsystems and three components that Titan-PSD is currently developing for DEW applications.

2.1. Titan-PSD development of subsystems for DEW applications

2.1.1. HPM modulator. Titan-PSD has a conceptual design of a high-voltage-pulse power subsystem for a short-pulse HPM system. The given RF pulse output parameters led us to choose a specific tube that is compatible with the constraints of an airborne system, namely the magnetron with a 20Ω impedance and 33% efficiency in a short-pulse mode. Our pulse power design concept is driven by the tube input requirements (20Ω load, 40-ns pulse width, 10 pps) and comprises a low-impedance, water-filled, stepped-pulse forming line (PFL) charged by a fast Marx and discharged through a self-breaking, spark-gap output switch. An advantage to using a liquid dielectric PFL is that its impedance can be easily varied along its length to accommodate variations in load impedance. Input power to the Marx is from two 400-V series strings of lithium ion batteries with solid-state switched intermediate voltage multipliers providing ±40 kV. Batteries are recharged from aircraft power through a small voltage converter.

Figure 4 is a simplified circuit diagram of the pulse power modulator coupled to a 20Ω constant impedance load though a transit-time isolator. The transit-time isolation is integral to the two parallel cables that couple the output of the pulsed power modulator to the microwave source. The Marx stores 1,140 J at a voltage of ±40 kV. It erects to a 1,280-kV open circuit voltage after a trigger pulse is applied to several of its switches from the trigger generator. Near peak PFL voltage, the self-firing spark gap closes, and energy is transferred to the tube at a peak voltage of 640 kV.

Figure 5 shows the voltage and current in the load computed from a more detailed version of the circuit depicted in Fig. 4. Note that the current is multiplied by a factor of 10. Voltage rises in about 11 ns (10–90%), and the width at the peak is approximately 40 ns. We recognize that the impedance of the magnetron can vary during RF generation, but the constant impedance model is sufficient here. An advantage to using a liquid dielectric PFL

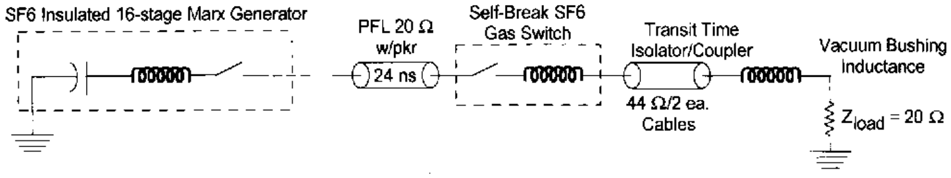


Fig. 4. Simplified circuit diagram of the pulse power modulator coupled to a 20Ω constant impedance load though a transit time isolator. This impedance represents a magnetron electron tube load.

Table 5. Titan advanced DEW power technology development rationales

What need does the development of pulsed power technology fulfill?		What need does the development of high power/high current technology fulfill?	
It is an enabler for advanced electric weapons and self-defense systems.		It is an enabler for advanced electric weapons and self-defense systems.	
System	User	System	User
Dynamic protection	Army (FCS), Navy (carrier)	Solid-state lasers	Army (Anti-Aircraft and Anti-Missile), Navy (ASMD)
ETC	Army (FCS), Navy (shore bombardment)	HPM	Army (FCS), Navy (non-lethal area denial)
HPM/electromagnetic pulse	Army (FCS), Navy (non-lethal area denial and ASMD), Air Force (SEAD)	EMALS	Navy (carriers)
EM gun	Navy (shore bombardment)	Electric arresting gear	Navy
UWB	All services (counter C4I)	Ride-thru	All services
		It is an enabler for electrically driven platforms: • FCS platforms for the Army • Combatants such as DD21 for the Navy • More electric aircraft for the Air Force	
It is an enabler for commercial spin-offs: • Environmental remediation systems • Material surface treatments • Pulsed thrusters for satellite station keeping		It is an enabler for commercial spin-offs: • Electric vehicles • Commercial power distribution and control • Advanced semiconductor lithography	
What must we accomplish at the subsystem level? • Develop compact, reliable, affordable PFNs • Develop compact, reliable, affordable modulators • Develop compact, reliable, affordable intermediate energy stores		What must we accomplish at the subsystem level? • Develop compact, reliable, affordable prime power, power conversion and controls • Develop compact, reliable, affordable intermediate energy stores • Develop compact, reliable, affordable ride-thru systems	
What must we accomplish at the component level? • Develop high-energy-density, fast-discharge capacitors • Develop long-life, reliable, high-current switches • Develop compact inductors for pulse control • Develop affordable ultracapacitors • Develop compact, reliable, efficient, high-average-power HPM sources		What must we accomplish at the component level? • Develop high-current-density, high-voltage stand-off solid-state switches • Develop affordable ultracapacitors • Develop compact, reliable, efficient, high-average-power HPM sources	

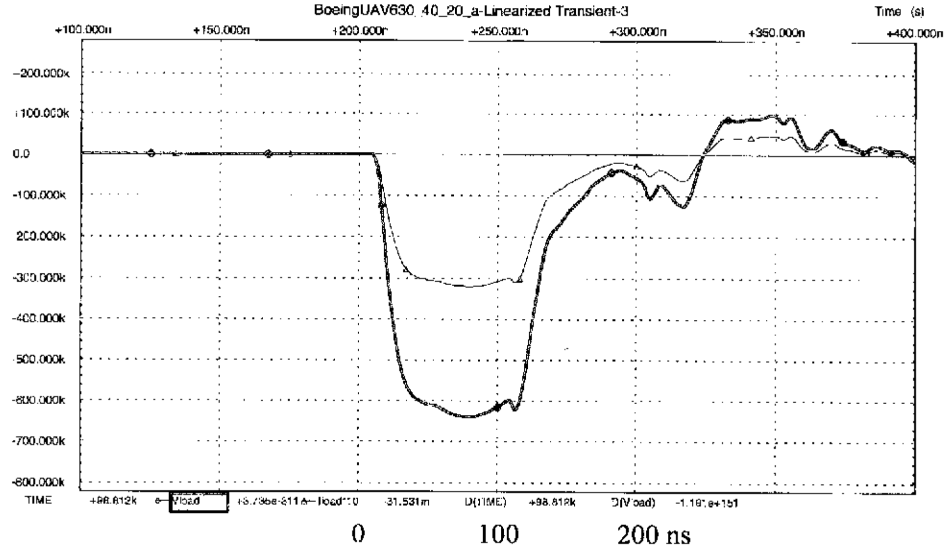


Fig. 5. Voltage and current (multiplied 10×) in the magnetron load computed using detailed version of the simplified circuit diagram in Fig. 4.

is that its characteristic impedance can easily be varied along its length to accommodate variations in load impedance.

Our compact pulse power system conceptual design mounts all of the subsystems and components in a frame that is 24 in. wide × 24 in. high × 144 in. long. The total weight of the system, including the frame, sealed enclosures, and internal mountings, is 1,420 lb. Figure 6 is a dimensioned diagram of the subsystem that is designed to fit into the port bay of an unmanned aerial vehicle (UAV) with the source in the starboard bay. Frames and supports have been omitted for clarity.

2.1.2. Compact PFN.

Titan-PSD has designed, fabricated, and delivered the pulse power subsystems for most of the major electric gun facilities worldwide. These facilities were dedicated to electric gun research and for this reason were designed with a premium on reliability and ease of use of the pulse power subsystem. Compactness was a secondary consideration given the large amount of real estate available for the subsystem.

The 8.5-MJ stored energy subsystem, consisting of four separate PFNs (Fig. 1c), was the first design to use the high-energy-density, 2.5-J/cc (2.5-MJ/m^3) polyvinylidene fluoride (PVDF) Aerovox capacitors; the overall energy density of the PFNs is less than 0.5 MJ/m^3. This low energy density is partially due to the use of "jelly-roll" inductors whose large external fields forced the separation of components and resulted in a low component packing fraction.

Figure 7 is a photograph of a 250-kJ PFN that was constructed under a DTRA/Navy-sponsored ETC gun development project and that was incorporated for a time into the Army/Tank-Automotive and Armaments Command (TACOM) Combat Hybrid Power System (CHPS) system integration laboratory.[5] Titan-PSD designed this PFN module for compactness by developing innovative bus work and a closed-field inductor for use with the 2.5-J/cc PVDF capacitors. These advances in component design allowed us to achieve a

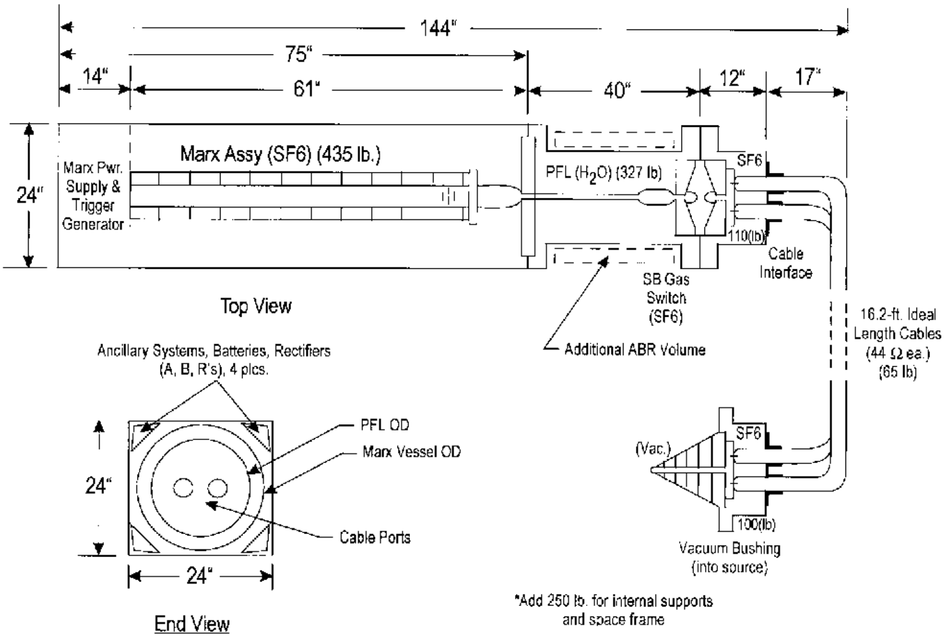


Fig. 6. Top and end views of the pulse power subsystem concept design. The upper portion will be mounted in a frame and placed in one bay of a UAV. The vacuum bushing and the source will be placed in a second bay.

very high packing factor and an overall energy density of 1.25 MJ/m^3. This module designed in 1994 still represents the state of the art in PFN design. Minor variants to the design are under consideration today for EM gun applications.

Titan-PSD has estimated the increases in the overall energy density of small (250–500-kJ) PFN modules that could be realized by achieving specific advances in component technologies.† This includes the use of an existing, more compact vacuum output switch (developed by Titan-PSD) and existing, more compact diodes for the crowbar switches. We would design a higher-energy-density, closed-field inductor and eliminate the dump resistors and associated hardware. Rather than having to dump energy into a resistor, advanced pulsed power systems would be charged by four-quadrant converters capable of returning energy from the PFN to an intermediate energy store. When 5-J/cc film or ceramic, high-energy, reversal tolerant capacitors become available, the utilization of advanced components would lead to a PFN design with an energy density of 3.25 MJ/m^3.

2.1.3. Power supplies for laser applications. Titan-PSD's San Diego operations are actively engaged in building innovative high-average-power systems. Titan is currently delivering power conditioning and control elements for the high-power RF klystrons that will power the DOE Spallation Neutron Source that is now under construction at Oak Ridge, Tennessee, and a series of multimegawatt rectifiers for the U.S. Navy's Electro-Magnetic

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† Higher energy densities could be achieved in the design of larger modules due to economics of scale.

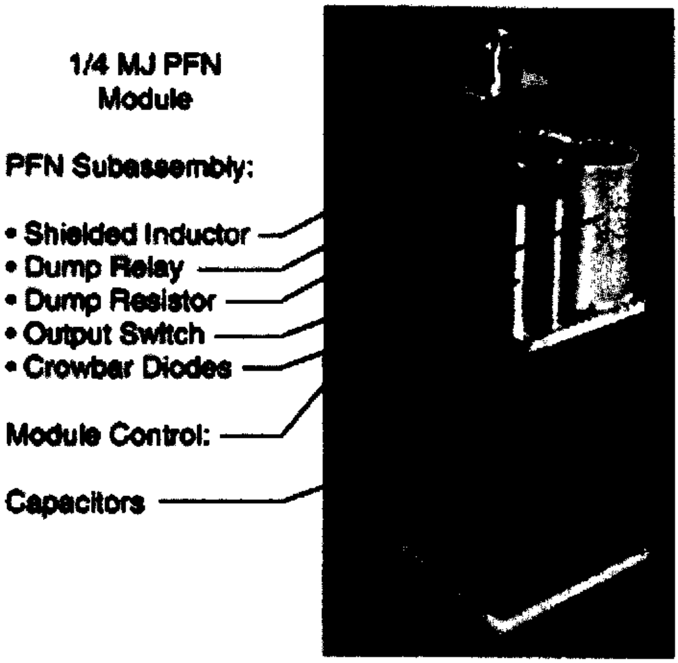

Fig. 7. Photograph of the 250-kJ PFN with the state-of-the-art, 1.25-MJ/m^3 overall energy density. Titan-PSD has operated this PFN into resistive loads at a rate of 1/3 Hz for extended periods. Operational limits were imposed by the heating of the load, not by the performance of any component of the PFN.

Aircraft Launch System (EMALS). Most recently, Titan has developed conceptual compact power supply designs for deployable pulse power systems for the Strategic Illumination Laser (SIL). The SIL is a diode-pumped, solid-state laser for use as a designator as a part of the U.S. Air Force's Missile Defense Agency's Airborne Laser (ABL). These power supplies will drive compact arrays of light-emitting diodes (LEDs), which will in turn pump the solid-state lasing medium.

Titan's proposed SIL power supply system will consist of a group of innovative ballast-type isolated power converter modules, each fed by its own active-power-factor-corrected rectifier module. By this method the input current harmonic distortion will be minimized, resulting in an overall system power factor of 0.995, which will be acceptable for the Boeing-747 type aircraft (ABL platform) power system. The whole power system will be protected against faults by appropriate fuses and circuit breakers. Initial size and weight estimates for the total power system is 65 liters of total volume and 140 kg of mass. The driving factor in the weight and volume is the need to meet the power factor requirements. Given a dedicated power source, the size and weight could be halved.

Two basic topologies have been examined for power factor correction. They are the "Vienna rectifier,"[8] first proposed by researchers in the Vienna Technical University, and the hex-bridge bidirectional inverter. Both topologies do not contain any magnetic components, operating at line frequency, and both can provide a power factor over 0.99. All merits and drawbacks of both topologies have been initially analyzed, and the Vienna approach is favored for this application.

For the ballast inverter Titan-PSD selected the variable-frequency, zero-power switching full bridge quasi-resonant inverter topology. It is new and until recently not well known but is very promising for multikilowatt power supplies. It shows excellent average to peak ratio for the semiconductor switches, close to the theoretical limit of 50%, and a good power transformer copper utilization factor, typically 90%. It is intrinsically output current limiting and therefore operates well in a current regulated mode and is tolerant to output short circuits. Using this converter topology allows the design to reach unprecedented power conversion efficiency (real value 95%) with excellent reliability.

2.1.4. Electronically reconfigurable battery. We consider a DEW power system in which a 10-kV capacitive store is required to operate repetitively. If the system operates at 3 pps, even for a short period of time, the recharge time would be about 300 ms and the recharge power would be about 500 $\mathrm{kW_{avg}}$ (1 $\mathrm{MW_{pk}}$). An important system issue is the size and weight of the 500-kW power conditioning unit.

Titan-PSD has developed a means to eliminate the need for intermediate power conditioning for many DEW systems mounted on hybrid electric vehicles by using the on-board batteries to charge the capacitive store directly. Our approach uses electronic switching to convert the battery modules in the mobility store from a parallel configuration providing vehicle load leveling and/or silent mobility capability, to a series configuration that delivers 500 kW at 10 kV to recharge the capacitor bank and back again. We refer to this as an "electronically reconfigurable battery" (ERB). Note that all of the batteries are recharged in parallel. A similar approach is used in capacitive Marx generators to achieve very high voltage pulsed output.

Figure 8 is a schematic drawing of the circuit of an ERB in a hybrid electric drive vehicle. In this schematic circuit, some battery modules are always in parallel and connected to the vehicle bus. Others, along the left-hand side of the drawing, can be switched between a parallel configuration, which supports the vehicle bus, and series operation for charging the DEW store. Electronic reconfiguration requires three switches per battery module. All switches, with the exception of the output switch, need only block the voltage of a single battery module and open at near zero current (characteristic of capacitor charging) in normal operation. Passive snubbing controls the transient conditions during erection and de-erection. Reconfiguration can be accomplished in less than 1 ms using off-the-shelf, solid-state switches such as IGBTs or MOSFETs.

Figure 8 shows an erectable battery module charging a Guillemin E-type network. Switches 2 and 3 are battery isolation switches, and switch 4 is a series switch. These switches are rated only for the module voltage (1 kV in this case). Mechanical contactors parallel the isolation switches for better efficiency during periods when the pulse power system is not in use. Switch 5 is the output switch, which is rated for the full output of the ERB (10 kV and 50 A) and is most likely a series stack of the same switches used for 2–4. For fault protection and charge interrupt at current, a vacuum contactor and fuse are placed in series with the output switch. All switches are optically isolated with gate power drawn from their adjacent modules. Switch 6 is a high-voltage and current-closing switch, either vacuum or solid state.

Assuming a 20-ton-class vehicle and extrapolating from CHPS requirements, we have developed a conceptual design of an ERB for a hybrid electric vehicle with a system meeting the following requirements: 1) Deliver up to 400 kW to the vehicle bus at 1 kV in parallel operation; 2) recharge a 150-kJ capacitive store to 10 kV in 300 ms; and 3) support 30–45-min silent operation at 80 kW. These requirements mandate the use of very high energy

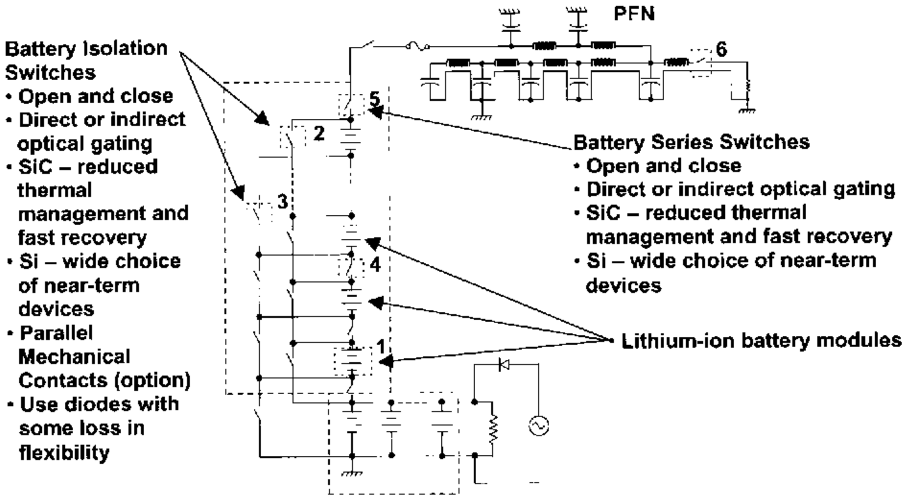

Fig. 8. Schematic circuit of the ERB. Shown is a generic circuit topology for charging a Guillemin E-type network. For the present application, the 10 modules in the dynamic store are all erected in series to produce a 10-kV output. A feature of the ERB is that the dynamic portion of the store may be erected in combinations of series/parallel modules to provide any output voltages that are an integer multiple of the DC bus voltage. This voltage agility, in theory, would allow a single dynamic store to power several loads with different input voltage requirements on the same platform such as ETC guns and HPM systems.

and power density batteries such as the HP series of lithium ion batteries being developed by SAFT and the lithium polymer batteries produced by Ultralife Batteries, Inc., for use in cell phones. The SAFT batteries have a slight advantage in usable power density and packaging for military use, whereas the Ultralife batteries have an advantage in cost due to volume production and a potential for more compact packaging (thin, rectangular) in ERB service. A design and trade study will select the most appropriate cell for the application. We chose the Ultralife cells for the conceptual design used for purposes of discussion in this paper because of our experience with them in our laboratory tabletop ERB and because of the availability of these cells over a range of capacities from 120 mA-h to 3.5 A-h.

The ERB system in this case constitutes only 1/3rd of the total battery for erected (dynamic) operation. The remaining 2/3rds of the store (static) is dedicated to load leveling and silent mobility. The total capacity of ~290 MJ (80 kW-h) accommodates silent mobility requirements. With only 1/3rd (90 MJ, 25 kW-h) of the total capacity configured for on-command electronic erection and de-erection, the vehicle energy storage system maintains its load leveling and silent operation capability even when the pulse power system is active.

For our conceptual design, we assemble 53 Ultralife polymer batteries into individual 200-V stacks. Five of these stacks are placed in series to obtain an output voltage equal to that of the vehicle bus. In the static portion of the store, 20 such series stacks of the UBC34106102 cells (5,300 total cells) are needed to provide the 200-MJ nominal capacity. In the dynamic portion of the store, the UBC383562 cell is used because of its higher current rating. Due to the smaller size of these cells, there can be as many as 4 in parallel by 53 in series per 200-V unit, and five such units will form an erectable module. The module will incorporate all necessary switches and isolation and thermal management hardware.

Ten modules will constitute the entire dynamic store (~90 MJ, 10,600 total cells). The total battery volume in the static and dynamic stores is ~0.282 m^3, and the accessories are expected to add another 0.4–0.6 m^3 for a total volume of less than 1 m^3. The weight for just the batteries would be ~572 kg, with accessories of much lower density adding another 100–200 kg, for a total weight of less than 700 kg. Charging of the ERB is always performed at bus voltage with the dynamic store in parallel configuration.

In load leveling or silent mobility operation, the charge state of the ERB is continuously monitored and controlled by the vehicle's systems. When the pulse power mode is activated, the mechanical contactors bypassing the isolation switches are opened. Next, all isolation switches are opened, followed by the closing of all series switches, and the ERB begins charging the capacitive store. Initially, the load looks like a short circuit, and the charging current is limited by the internal impedance of the ERB cells. As the charge on the bank increases, the charging current diminishes, and the cell voltage begins to rise. Near full charge, the current approaches zero and the ERB output voltage rises to its maximum of ~10 kV. Voltage on the store is monitored and is regulated by chopping the ERB output (i.e., opening and closing the series and output switches as necessary to maintain charge against leakage; this has been demonstrated in the laboratory at rates of up to 1 kHz). When the store discharges, the output switch opens immediately and remains open long enough for the closing switch to recover (1–10 ms). The ERB can remain erected for as long as the pulse power system is active. Recharging of the store is then initiated by reclosing the ERB output switch. When the pulse power system is deactivated, the dynamic store is returned to its parallel configuration by opening the series switches (de-erecting). The dynamic store can then be recharged from the vehicle power bus.

We have created an ERB laboratory demonstration consisting of five erectable modules of 40 V. The Ultralife UBC383562 cells were used and arranged on PC boards that were in turn stacked via standoffs. Isolation and series switching was via optically coupled IGBTs. Some figures of merit (FOM) from the ERB testing include a demonstrated current rise time to 80 A of 4 μs at 200 V and an erection/de-erection frequency of 1 kHz for use in voltage regulation. A FOM from the four series cell tests is a demonstrated current rise time to 120 A of 1 μs, in a maximum power transfer configuration.

2.1.5. Intermediate energy storage. In the preceding section Titan-PSD identified a need for and established the technical feasibility of an advanced technology power conditioning element to charge capacitive stores in DEW systems. The ERB is the solution with the highest efficiency and energy and power density possible. This is critical in order to realize a manageably sized DEW system. A second similar, critical issue in the design and use of pulsed electrical weapon systems involves the level of available platform power. If this power is insufficient to support the required operational burst length and repetitive fire rate of the system, then it may be necessary to incorporate intermediate energy storage into the system design. Intermediate storage could be practically achieved through the use of secondary batteries, flywheels, and ultracapacitors (also referred to as electric double-layer capacitors or EDLCs). Figure 9 is a schematic diagram of intermediate energy stores in two DEW systems.

Figure 10 shows a present application of an EDLC energy storage system in providing ride-through of voltage sags and momentary outages for an induction motor. The output of the store is connected across the direct current (DC) link of the asynchronous drive and supports its voltage. Titan-PSD has manufactured a ride-through system that has been demonstrated to respond to sags and outages within 10 ms. It can provide

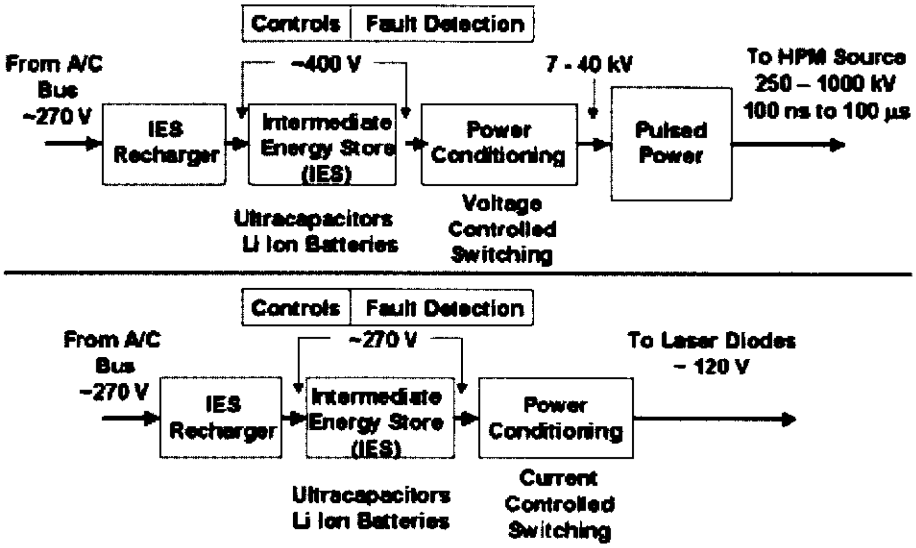

Fig. 9. Two DEW block system schematics with intermediate energy storage.

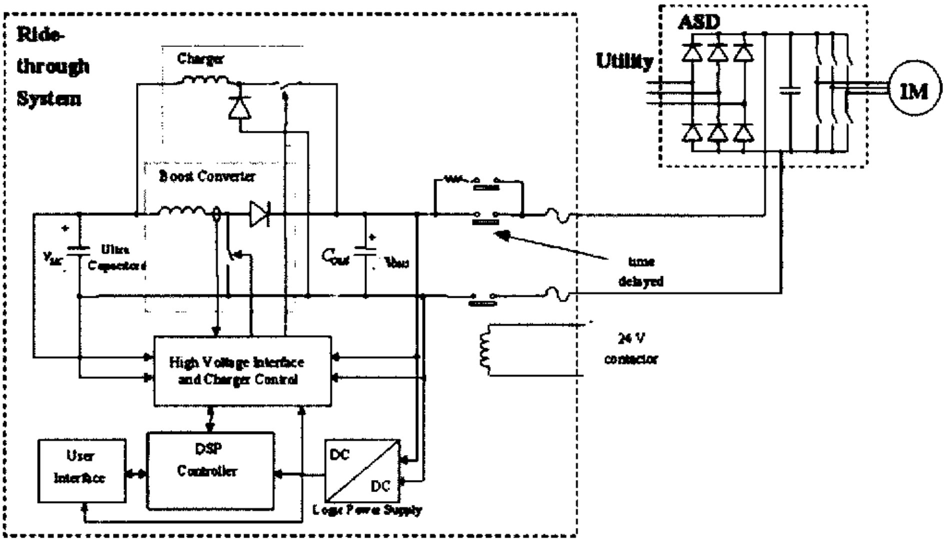

Fig. 10. Circuit diagram of an EDLC ride-through system supporting the DC link of an asynchronous drive (ASD).

100 kW for up to 5 s, which is sufficient to allow for orderly shutdown in a prolonged outage.

Titan-PSD has also developed several concept designs of EDLC energy storage systems for military applications. For example, one EDLC system design would be capable of supporting the DC link in a Navy shipboard system at 480 V for 12.5 s at 250 kW. This system is estimated to be 50% smaller and lighter than a corresponding flywheel system (i.e., the Caterpillar UPS-250 system). With minor modifications, the same system (or several systems in parallel) could be used as an intermediate energy store for DEW systems.

2.2. Titan advanced component developments to enable DEWs

2.2.1. Solid-state switches for severe service. The key enabling technology for nearly all pulse power systems for DEW applications is the switch that initiates and delivers the pulsed electrical output from the electrical energy store to the load. This switch must hold off high voltage (typically $\geq$10 kV), close rapidly ($<$1 μs), carry high peak current (100–500 kA) with high initial rate of rise (50–100 kA/μs), sustain a high total action ($\geq 10^7$ A^2-s), and recover rapidly ($<$10 ms). In addition, the switch must support high current density, operate reliably under mechanically stressing conditions, have minimum weight and volume claims, and not require ancillaries such as vacuum pumps or gas flow subsystems. At present, the hydrogen thyratron is most frequently selected to meet these simultaneous requirements, but thyratrons are large and heavy devices, with auxiliary equipment that consumes several kilowatts and often require immersion in oil. The Army Research Laboratory has been actively seeking solid-state devices for DEW utility[7] and Titan-PSD is weighing in by developing a high fluence, laser gated and pumped (silicon) thyristor (LGPT) that will satisfy these requirements.

High fluence optical gating of thyristor switches has been chosen for numerous pulsed power switching applications. Light activation with high fluence laser sources enables the use of solid-state switching devices in performance parameter spaces previously serviced only by vacuum and gas spark gaps. If the output from the high fluence source is properly distributed within the switching medium, the di/dt capability of the switch does not depend on the rate of plasma spreading. Rather, di/dt becomes a function of the rate of rise of the optical fluence. In addition, optical gating eliminates the extensive and intrusive physical gate structure that limits the conduction area of the highest di/dt conventional solid-state devices. Properly designed laser-gated devices are typically capable of higher di/dt, peak current, and charge transfer for a given silicon area than conventional solid-state devices.

The band edge for intrinsic silicon is ~1.12 eV, corresponding to ~1,111 nm. However, silicon is an indirect band-gap material so that the optical phonon energy (0.063 eV) adds to the photon energy to create e–h pairs out to 1,170 nm. In most previous efforts involving direct laser-gating of silicon devices, a solid-state laser was used; typically either Nd:YAG or Nd:YVO at 1,064 nm. However, over the past 10 years, the development of compact diode-pumped solid-state lasers has significantly reduced the size of the requisite optical sources and improved their lifetime and reliability. More important, the InGaAs laser diode bars that were developed for pumping these solid-state lasers have been pushed to longer wavelengths, approaching and exceeding that of the silicon band edge. In principle, the center wavelength of InGaAs laser diode bars is selectable by design over a continuum from 850 nm through at least 1,150 nm. This allows direct optical gating and pumping of silicon by the diodes without any of the intermediary options of the preceding paragraph. Figure 11 is an illustration of an on-board laser diode gated and pumped silicon thyristor, which is one of the candidate approaches in development now.

Titan-PSD is currently performing on two programs and has finished a third that provide technical leverage for further switch development. Our Electra Advanced Pulsed Power Program is a five-year, Naval Research Laboratory (NRL)/DOE-sponsored effort to develop advanced pulsed power components and systems for KrF laser IFE (krypton fluoride laser inertial fusion energy). The most critical component is the primary switch, and we are

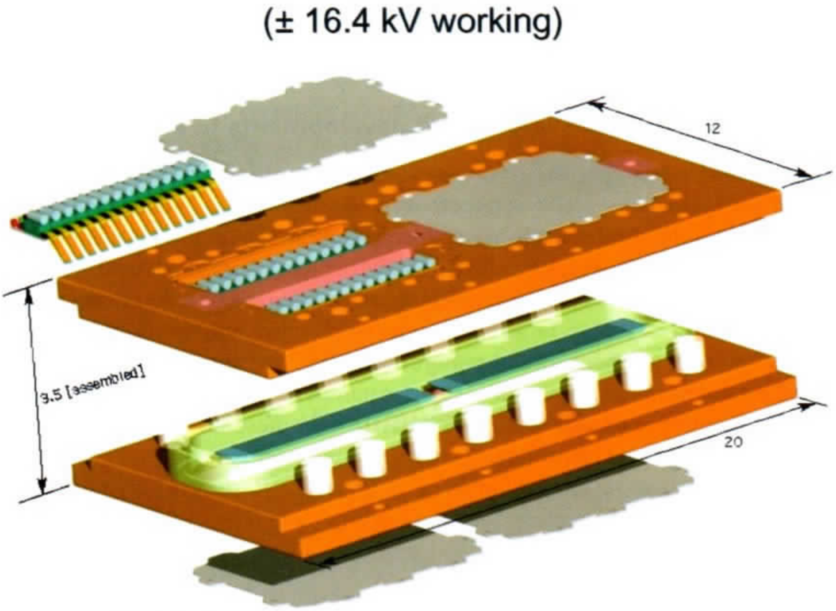

Fig. 11. Illustration of a laser gated and pumped thyristor.

developing an on-board LGPT for this role. The switching requirements are repetitive, high peak current and di/dt, as well as high efficiency (the switch dissipates <1.5% of stored energy) and long lifetime (10^9 shots). The LGPT is to be used in a Marx generator, and the single device operating parameters are 16.4-kV working voltage, current density 2.25 kA/cm^2, peak current 225 kA, max di/dt 900 kA/μs, pulse width 800 ns, and repetition rate 5 pps continuous. The lifetime requirement limits the thermal excursion per pulse to a few degrees, and therefore the action per square centimeter is low (~2 A^2-s).

Another current Titan-PSD program is to develop compact pulsed power components for the Air Force Research Laboratory (AFRL) at Kirtland Air Force Base. Components under development enable a compact, long-lifetime Marx-PFN driver for a narrowband HPM source. The di/dt requirement is a few hundred kA/μs/cm^2(Si) or 2 MA/μs total, with a peak current of 30 kA. To satisfy the switching requirements for this application, we are considering the LGPT, a solid-state laser activated switch, and a hybrid combination of the two.

Although the action and charge transfer in these Electra and AFRL applications are substantially less than that found in some pulse power applications, they serve to illustrate our confidence in the high power laser diode bars for high di/dt service. In both cases, the pulse width of the energy transfer is short enough that thyristor action has barely begun by the time the pulse is over. Because of this, a large fraction of the total charge conducted during the pulse must be supplied optically. The diode laser bars and their drive circuitry are capable of supplying an illumination fluence of up to 6 kW/cm^2(Si) within 20 ns and sustaining that level for at least several microseconds. Fluence of several kilowatts per square centimeter is desirable for initial gating in many DEW applications. The required fluence drops to 250–500 W/cm^2 for continuous pumping.

Another effort was recently undertaken in a conceptual design study for an optically gated and pumped switch for rectification of compulsator (pulsed alternator) output for driving an electromagnetic gun. This completed study was performed by Titan-PSD and the Optiswitch Technology Corporation for the Institute for Advanced Technology (IAT). The on-board LGPT design was chosen because of the customer's desire to reduce the overall device count and silicon area compared with conventional devices. Specifically, we designed a 16.7 kV, 100–115-cm^2 asymmetric (blocks voltage forward direction only) thyristor and series diode. Depending on the allowable temperature excursion per shot, our approach replaces ~80 conventional devices with 3–5 series pairs (6–10 devices total; 340–500 cm^2 active) for the same forward losses. This is possible because continuous pumping of thick (2.5-mm), high-voltage (15–20-kV) devices with photo-carriers mitigates the carrier population deficit in the n-base. Electrically gated devices of the same voltage capability typically exhibit huge commutation and conduction losses and are therefore impractical for this type of service. Reverse blocking was handled by a series optically pumped diode. Separating the forward and reverse blocking functions allowed more freedom in designing for reverse recovery, a feature deemed necessary due to repeated failures of symmetric (blocks voltage both directions) devices in this service. Laser diode pumping served to reduce the forward losses in the series diode element as in the thyristor.

The switch was designed to handle a peak current of 1.6 MA (3.3–4.7 kA/cm^2) for 600 μs when installed in a half-wave, four-phase rectifier. Nine total cycles are rectified per shot of the electromagnetic gun. The initial design (500 cm^2 active) limited the temperature excursion per shot to ~100°C, commensurate with a service life of ~10^4 shots. In the extreme, the current density could be pushed to 4.7 kA/cm^2 and optical pump power doubled, resulting in a ΔT approaching 180°C and ~200-shot lifetime. The laser diode bars in the initial case provided a constant 500 W/cm^2 of silicon for each 600-μs conduction phase. This goes to 1 kW/cm^2 in the extreme case.

2.2.2. Next generation reltron microwave generator development.

Reltron HPM sources were invented and developed by R. Bruce Miller of Titan Advanced Innovative Technologies from the mid-1980s through 1998. The PSD of Titan assumed responsibility for reltron contracts in 1998. Projects included one complete HPM simulator for a government research laboratory in Germany and eight reltron tubes of various specifications. In developing these eight tubes, enough mechanical and electrical modifications have been included to justify their designation as "second-generation" designs.

Reltrons are both compact and efficient. The electron beam is highly modulated over ~10 cm and postaccelerated prior to drifting to the output cavities and beam collector. This beam transport requires only ~75-cm overall length for L-band tubes (Fig. 12). The output cavities are incorporated into a standard rectangular waveguide. Microwave power is efficiently extracted (~80%) directly in TE_{10} mode. The overall efficiency (peak electrical to microwave power) is 30–40%.

In general these new tubes move the reltron technology base in the directions of longer pulsewidths (~1–2 μs), increased frequency tunability (~±13%), lower driver voltages (500–600 kV), and higher repetition rates (~10 Hz for demountable versions, ~300 Hz for sealed tubes). Second-generation improvements include a new high voltage insulator design, new movable current contacts for the modulation and output cavity tuners, reduced outgassing, and monolithic grids. The frequency range for these eight tubes covers 700–1,450 MHz. Programs are in place now to extend this range.

In addition to the objective to extend the frequency coverage, efforts are underway to improve beam optics to reduce current losses and thereby improve efficiency and microwave output power. A new beam current diagnostic package has been recently implemented to

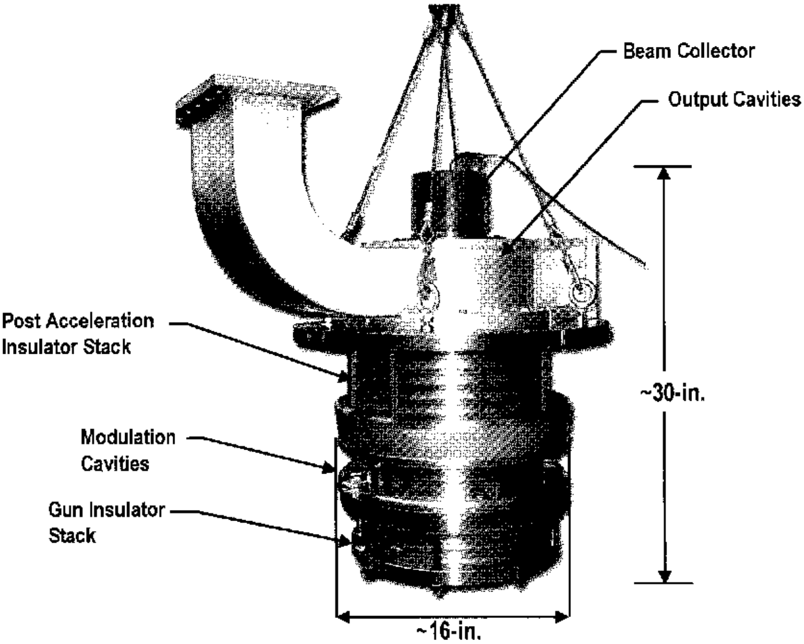

Fig. 12. L-band reltron capable of generating flat 200-MW, 900-ns pulses with frequency stability $\delta f/f < 0.3$. This generation of reltrons is capable of RF pulse widths of ~300 RF cycles, repetitive pulse operation from single-shot to 10 Hz, and ±10% continuous-frequency tunability.

better infer basic performance parameters and to assist in comparing benchmarking simulations. These calculations simulate performance in the actual geometry and are generated with a three dimensional particle-in-cell code (the LSP code from Mission Research Corporation). Measured waveforms generated by a recently delivered L-band tube are shown in Fig. 13. This tube produces ~185 MW in flat, 900-ns pulses with excellent frequency stability. The LSP code was essential during this tube's development. A new era in microwave tube design has emerged with the development of accurate three-dimensional models.

2.2.3. HEM magnetron. Backdoor microwave effects on electronics systems in modern weapons fall into three broad categories. Two categories are characterized by high peak power density and microwave formats that overwhelm the target system with an electric field that is high enough to cause circuit upset or burnout. In the third category, effects are caused by coupling spurious signals into the target system, akin to classical smart jamming, interference or spoofing[‡] techniques used by the EW countermeasures community. The DEW microwave pulse formats appropriate to the latter class of effects are generally distinguished from upset and damage pulse formats by lower peak power density thresholds but more specific requirements on frequency and amplitude modulations and

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[‡] Low incident microwave levels can cause "interference" with the operation of threat weapon electronic systems, producing high levels of noise in sensitive circuitry to "mask" true signals. The incident microwave signal is said to "spoof" if it is tailored to "mimic" the true signal and to thereby produce false commands.

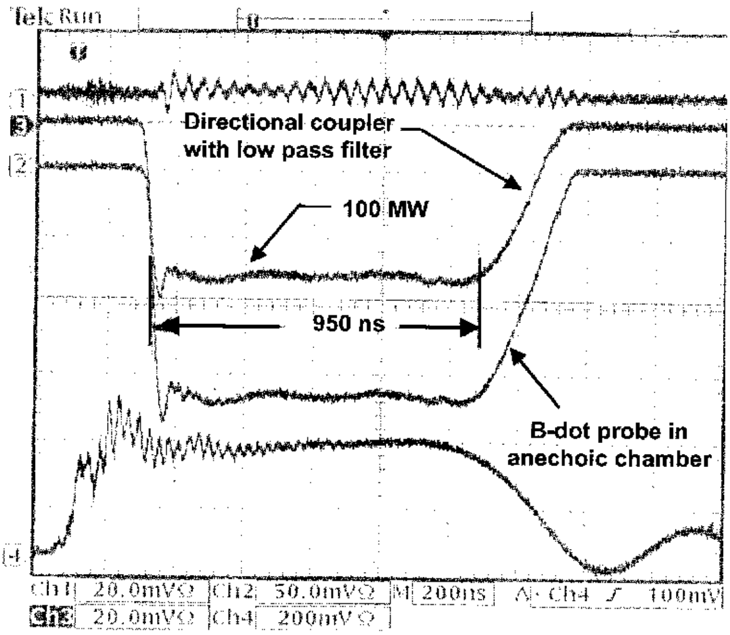

Fig. 13. Waveforms from the 185-MW L-band reltron: the top trace is the heterodyne (l.o. = 1.3 GHz) showing excellent frequency stability, and the second trace is the steady, flattop output power measured with a calibrated directional coupler. (The data are conditioned with a low-pass filter; higher harmonic content is know to be more than 13 dB below the primary L-band signal.) The third trace is the radiated power monitored with an uncalibrated, free-field B-dot, and the last trace is an uncalibrated profile of the Marx current.

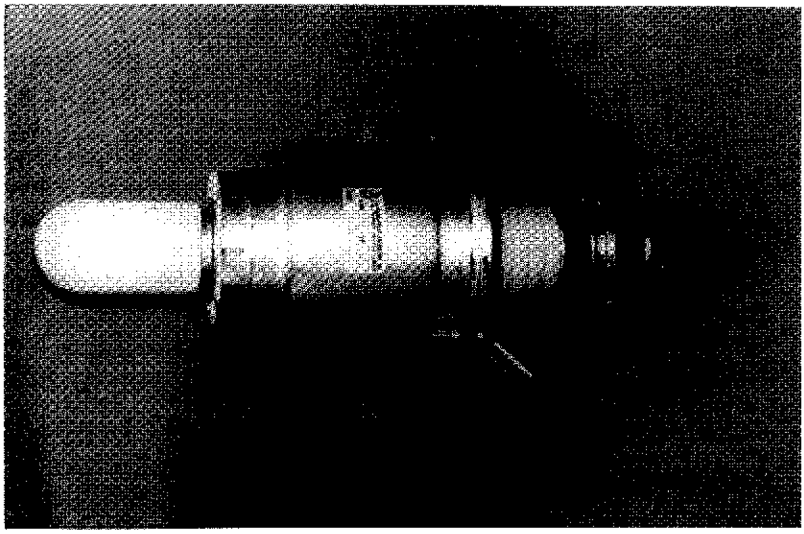

Fig. 14. Titan's L-band HEM magnetron. This is the highest-average-power magnetron that is commercially available.

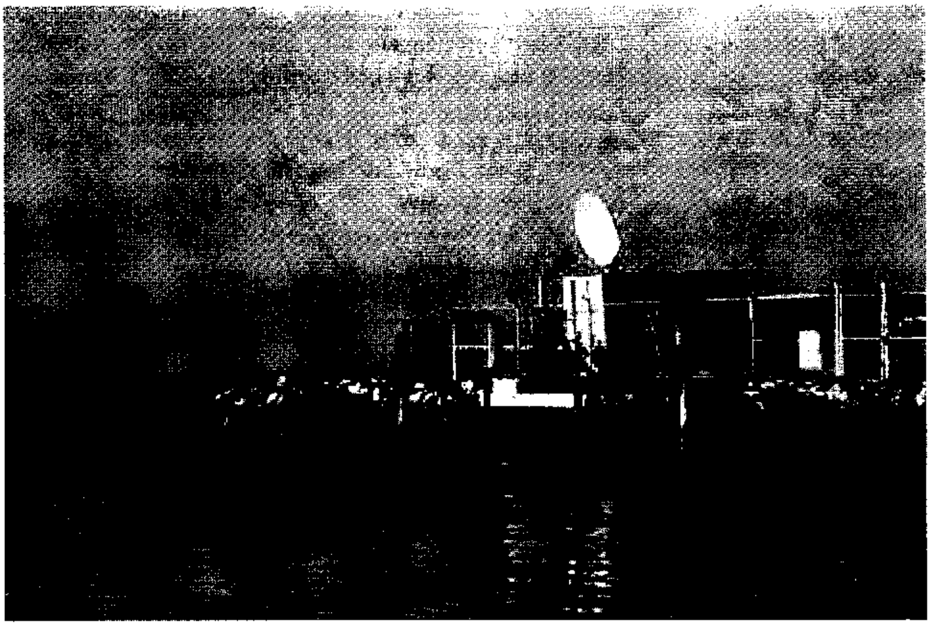

Fig. 15. The principal system elements of the ATD system are a power supply, a modulator, an HEM source, and an antenna. These components are supported by a control system and a cooling system. For the DTRA ATD ground-based system the power supply and operators' console(s) are housed in a shelter mounted on one flatbed trailer while the remaining components are mounted on another flatbed trailer (out of the field of view to the right). The system was designed to broadcast 2-MW peak power pulses with an average power of 300 kW for 30-s missions. This yields a peak fluence of 1 mW/cm^2 at a range of 2,400 m.

repetition rate. All three categories of effects can be induced by DEW systems based on high-power RF, narrow-band, pulsed HPM or long-pulse, high-energy microwaves (HEMs).

Titan has developed an HEM laboratory source and an HEM advanced technology demonstration (ATD) source for DEW purposes at its California Tube Laboratory. These HEM sources have efficiencies of approximately 85%. This high efficiency minimizes prime power and cooling requirements, thus significantly minimizing overall DEW system size and weight. The HEM magnetron, shown in Fig. 14, has produced 900-kW peak and 150-kW average powers and can easily be upgraded to 300-kW average power. The unique modulation characteristics of this magnetron can produce modulation effects of 30 MHz or greater in the target systems. More operational details are given in Table 6.

The ATD system shown in Fig. 15 combines the outputs of two 150-kW-average-output power magnetrons. The maximum peak output power obtained to date is 1.2 MW. The magnetrons with their respective magnet yokes each weigh about 200 lb, and each takes up about 4 ft^3. When combined their efficiency is over 76%, therefore together they absorb only 95 kW and are actively cooled. Variants of this RF system are suitable for Army, Navy, and Air Force missions.

Table 6. California tube laboratory HEM magnetron operational specifications

Parameter	Value
Frequency, fixed	915 MHz (890–920 MHz possible as well)
Power output	
Continuous wave	300-kW minimum
Pulse	600-kW peak (900 actually achieved) 300-kW avg (nominal 50% duty)
Pulse width	10s of microseconds to 5 ms
Peak anode voltage	42 kV
Peak anode current	17 A
Beam efficiency	88% typical
Water-cooled anode	20 gpm typical
Filament	12 VAC, 200-A typical standby

3. Conclusions and Significance

The first laser and HPM DEWs are just now being deployed, and new threats emerging in the information age will sustain the need for continued DEW development and acceptance. The deployment of even more advanced DEW systems and in fact the DoD's intent to field more (or all) electric fighting platforms depend critically on the availability of compact, lightweight, efficient pulsed power subsystems and long-lived, reliable advanced power conditioning and front-end components.

Titan has been supporting U.S. directed energy programs by providing services and analysis and developing advanced technologies since the early 1980s. Today, Titan is the only U.S. industrial supplier of commercial HPM generators. We have advanced pulsed power and power electronics technology development programs involving intermediate and primary electrical energy storage, solid-state switching, power conditioning, electrical-to-microwave conversion, and novel microwave antennas underway now. Titan is focused on providing pulsed power and C4ISR (command, control, communications, computers, intelligence, surveillance, and reconaissance) solutions for national defense and is intent on maintaining its industrial leadership in military information technologies.

Acknowledgments

The authors recognize and acknowledge contributions made by Jim Benford, Jerry Levine, R. Bruce Miller, and David Blank to the development of the primary narrow-band microwave sources that were the precursors of much of the HPM and HEM technology that Titan offers today.

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