DEW TECHNOLOGY AT THE TITAN CORPORATION

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ABSTRACT

The Titan Corporation has been developing directed energy technologies since the early 1980's. 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, intermediate energy storage and power conditioning elements. 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.

1 INTRODUCTION AND PREVIOUS WORK

Directed energy weapons (DEWs) are emerging as a key defense technology of the early 21st Century. The first laser anti-missile and anti-artillery systems are within perhaps five years of deployment, and newly envisioned information warfare and non-lethal point defense missions are hastening the deployment of high power microwave 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 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 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 paradigm.

The initiatory HPM programs in the USSR and USA have evolved and influenced foreign allies and threats to take an interest. Major programs are in the USA and China; medium scale programs in the UK, France, Germany, and Russia; and emerging programs in Sweden, Japan, India, Taiwan, Australia, Israel and Korea. The collapse of the USSR has 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) increasing dependence of both military systems and civilian support infrastructure on sensitive electronics, and (2) after more than a twenty-year effort, maturing understanding of the susceptibilities of military and commercial systems to HPM threats.

For these reasons the Titan Corporation as 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 USA. Physics International 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 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 commercial names in pulsed power are combined as the Pulse Sciences Division (Titan-PSD) of the Titan Corporation.

In March of 2002, Titan completed the acquisition of Jaycor and its subsidiary California Tube Laboratory (CTL). This acquisition establishes 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 Super-Reltrons, short pulsed, ultra-broad bandwidth systems and MW-

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 pulsed power technology for DEW applications.

2 Previous Titan Work in Support of HPM Programs

Titan-PSD has been developing directed energy technologies since the early 1980's. In that 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 (Figure 1). Over the past forty years, Titan-PSD has delivered 200 pulsed power systems for EMP; x-ray and lightning simulation; flash radiography and other applications world-wide. Although somewhat peripheral to DEW research proper, these projects have nonetheless formed much of the experience base supporting Titan's directed energy technologies contributions.
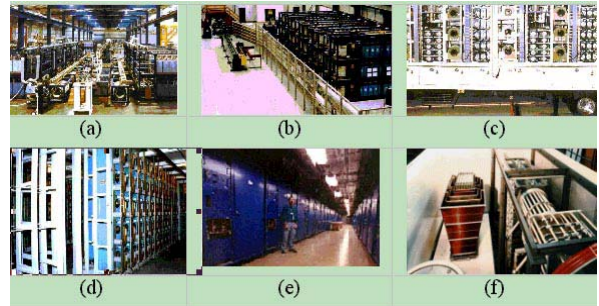
F1. Titan-PSD has designed, fabricated and delivered pulse power subsystems for major facilities world-wide. (a) Decommissioned 32 MJ Thunderbolt System built for a SDIO project. (b) Existing 32 MJ Kirkcudbright system currently being operated by the UK. (c) First transportable pulse power subsystem designed for an electric weapon system under the Army/ARDEC Balanced Technology Initiative (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. (f) A portion of the 100 Hz, 750 kV, 1.25 µs modulator for NRL's EMRLD laser.
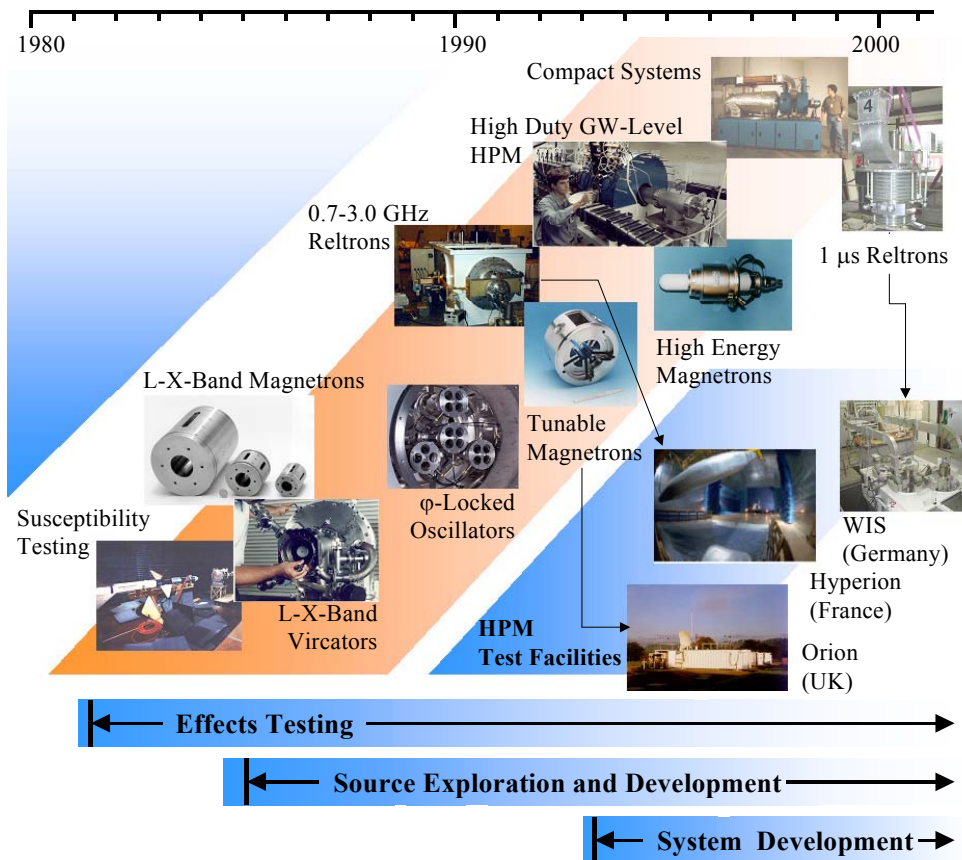
F2. Titan has contributed to the field of high power microwaves in three distinct eras: (1) Susceptibility effects testing, (2) HPM source development, and (currently) (3) DEW system development.

Titan's primary contributions have been in the field of high power microwaves (Figure 2). Work started in 1983 when Titan set up and began operating a susceptibility effects test facility for the Defense Threat Reduction Agency (DTRA). A 30' x 20' x 16' anechoic chamber to support this work was originally designed to operate in X-band and above. At the outset of the USA 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 ten plus years, the twenty-five effects test programs conducted on strategic and tactical systems in the Titan facility and tests conducted at other sites confirmed that the lowest susceptibility thresholds are observed in S-band and below. HPM source development history has mirrored these findings.

HPM Source Developments at Titan

In 1983 Titan initiated HPM source research in its test facility by developing first C-X Band over-moded Vircators [1] and later an L-Band Vircator [2]. 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 MHz to a few ten's of MHz. Versions of these devices were soon after sold to Nucletudes in France 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 MIT [4]. These devices were integrated into the Titan test facility and within two years an L-band version of this same design was developed [5]. An S-band magnetron was sold commercially to Thales in France in 1987 to help 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 with capacitive energy storage and voltage adders with

magnetic compression power conditioning). These advancements are described briefly in the following.

In the late 1980's, 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 [6]. Many mission scenarios for DEW systems that could produce burn-out 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 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 a middle ground between HPM and Electronic Warfare (EW) DEW concepts must exist. The HPM approaches were characterized by super-power, 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 required of any DEW system if only to engage multiple threats deployed in sorties. In response to these weaponization considerations, Titan-PSD developed relativistic magnetrons capable of 1 kHz bursts [7]. 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 burst average power of 12.6 kW is still 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 separation between pulses.

In the early 1990's both Jaycor and PI were actively extolling the use of frequency-agile waveforms to enhance backdoor lethality. Frequency-agility exploits the characteristics of typical coupling cross sections that show pronounced dependence on 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 single frequency source. 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 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 [8] which is still the state-of-the-art. In the mid-1990's these magnetrons were integrated into advanced concept demonstrations for the Army and were also exported into the UK as part of an HPM test facility.

In the late 1980's and early 1990's Titan-PSD developed several ultra-wide bandwidth (UWB) systems for Army and Air Force DEW research programs. One system was based on a spark gap-switched Marx that drove a variety of broadband antennas. It could launch 200 MW total RF power in 3 ns pulses with risetimes of ~300 ps at a repetition rate of few pulses per second. This compact, self-contained system was used in indoor susceptibility tests and outdoor technology demonstrations. Another project produced a system that could launch impulse waveforms at 200 pps in burst mode [9]. 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 of ~100 ps and a 10 - 90 rise-to-fall pulse width of 45 ns. The bore-sight peak electric field 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 [10]. 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 post-accelerated to energies approaching 1 MeV. Microwave power is extracted with ~50% 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 joules, 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 and have been provided to France and Germany as HPM threat simulators.

Titan Pulse Power Modulators for DEWs

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 multi-megawatts (Table 1). They also range from relatively simple units to complex, state-of-the-art devices with various different architectures and subsystems. These include Pulse Forming Networks (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 risetimes 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 MOSFETs, IGBTs and Thyristors (Figure 3).

(a)   (b)   (c)
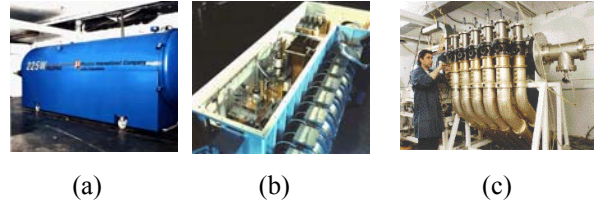
F3. Titan-PSD pulsed power systems based on (a) spark gap, (b) thyratron and (c) magnetic switching.

Table 1. Operating Parameters of Titan Built Modulators for DEW Applications

Modulator	Voltage	Current	Duration	PRF	Energy	Power	Switch
LS-15	50 kV	10 kA	100 ns	1.9 kHz	50 J	95 kW	Spark Gap
NED Laser Driver	±40 kV	260 A	2 µs	10 Hz	3 kJ	30 kW	Thyratron
EMRLD PFN	750 kV	38 kA	1.3 µs	125 Hz	35 kJ	4.4 MW	Spark Gap
EMRLD (Trigger)	600 kV	260 A	400 ns	125 Hz	100 J	12.5 kW	Spark Gap
OMEGA Laser Driver	15 kV	128 kA	200 µs	Single	40 MJ	-	Ignitrons
CLIA HPM Driver	750 kV	10 kA	100 ns	250 Hz	750 J	188 kW	Magnetic
ORION HPM Driver	500 kV	10 kA	50-500 ns	100 Hz	250 J	25 kW	Thyratron
Compact HPM Driver	450 kV	9 kA	450 ns	10 Hz	1.8 kJ	18 kW	Spark Gap

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 DARPA EMRLD modulator (a lumped-element PFN to pump an excimer laser) was specifically designed for and demonstrated a lifetime of 10^{10} shots.

The ORION pulser (Figure 3b) design has command resonant charge and intermediate energy storage sections each switched by thyratrons that drive a step-up transformer and pulse forming network. The modulator can fire 1000 pulses in a burst at repetition rates up to 100 pps and produces 500 kV into a 50 Ω load. It has been used to drive relativistic magnetrons [12] for HPM effects measurements.

The Compact Linear Induction Accelerator (CLIA) (Figure 3c) was developed for moderate-to-high repetition rate HPM source research and development [13]. 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 5000 pulses in a burst. CLIA has been used to drive both magnetron and klystron loads. This technology is scalable to kHz repetitive operation.

Titan Commercial Systems for HPM Simulation

In addition to work 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 Germany (Table 2). Work continues today upgrading those systems and providing similar hardware for several non-European countries.

Table 2. Key Operating Parameters for Titan Equipment in European HPM Test Facilities

| HPM Facility	Power Density (W/cm²)	Range (m)	Freq. (MHz)	3Max. P ul	4Max. R e	Shot Per Burst	5Source Type
6UK-Orion	> 120	100	1170-3300	100	100	100	Magnetrons
France-Hyperion	> 1000	~ 100	700- 3300	300	1	-	Reltrons & Magnetrons
Germany	> 170	15	700-1450	300	10	100	Reltrons

ON-GOING DEVELOPMENT WORK

Titan-PSD is interested in the full spectrum of developments of advanced subsystems and components that the US will require to realize their DEW and tri-service 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. The following describes representative electrical subsystems and components that Titan-PSD is currently developing for DEW applications.

Development of Subsystems for DEW Applications
HPM Modulator
Titan-PSD has developed 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 magnetron with a nominal 20 Ω impedance and 33% efficiency in a short pulse mode that is compatible with the constraints of an airborne system. Our pulse power design concept is driven by the tube input requirements (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 to the Marx is from 400 V series strings of lithium ion batteries with solid-state switched intermediate voltage multipliers providing ± 40 kV. The pulse power modulator couples to the load though a transit-time isolator formed by two parallel cables.

Figure 4 is a simplified circuit diagram of the pulse power modulator coupled to a 20 Ω constant impedance load though a transit-time isolator. The Marx stores 1140 J at a voltage of ± 40 kV. It erects to 1280 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 load at a peak voltage of 640 kV.
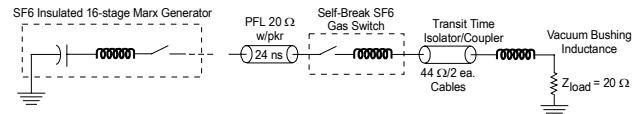

F4. Simplified circuit diagram of the pulse power modulator coupled to a 20 Ω constant impedance load though a transit time isolator.

Figure 5 shows the voltage and current in the load computed from a more detailed version of the circuit depicted in Figure 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.
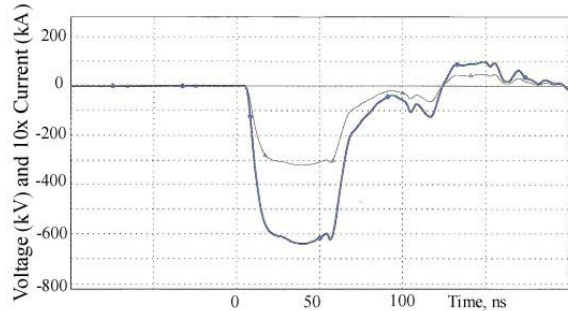
*F5. Voltage and current (multiplied 10x) in a 20 Ω load computed using a detailed circuit diagram.*Our compact pulse power system conceptual design mounts all of the subsystems and components in a frame that is 24 inches wide by 24 inches high by 144 inches long. The total weight of the system, including the frame, sealed enclosures and internal mountings is 1420 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.
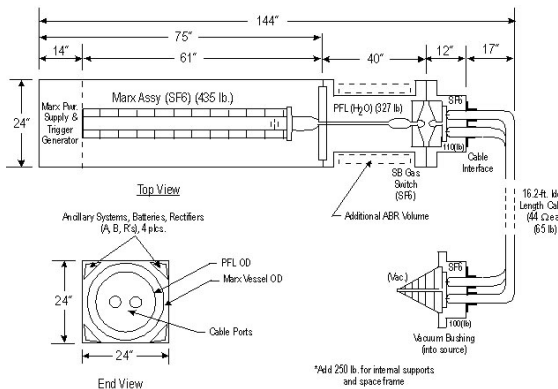

F6. Top and end view of the pulse power subsystem concept design. The upper portion will be mounted in a frame and placed in one bay of na UAV. The vacuum bushing and the source will be placed in a second bay.

Compact PFN Titan-PSD has designed, fabricated and delivered the pulse power subsystems for most of the major electric gun facilities world-wide. 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, shown in Figure 1c was the first design to use the high energy density, 2.5 J/cc (2.5 MJ/m^3) 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 which was incorporated for a time into the Army/TACOM Combat Hybrid Power System (CHPS) system integration laboratory [15]. 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 very high packing factor and an over-all energy density of 1.25 MJ/m^3.
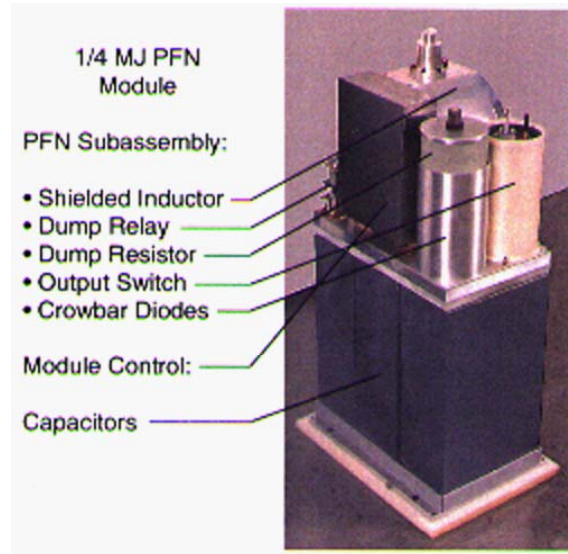
F7. Photograph of the 250-kJ PFN with the state-of-the-art 1.25 MJ/m^3 overall energy density with typical repetitive electrical performance data. Titan-PSD has operated this PFN into resistive loads at a rate of 1/3 Hz for extended periods. Operational limits were imposed by the heating of the load not by the performance of any component of the PFN.

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, then the utilization of advanced components would lead to a PFN design with an energy density of 3.25 MJ/m^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 multi-megawatt rectifiers for the U. S. Navy's Electro-Magnetic Aircraft Launch System (EMALS). Most recently, Titan has developed conceptual compact power supply designs for deployable pulse power systems for the Strategic Illumination Laser (SILL). The SILL is a diode pumped, solid-state laser designator, part of the U. S. Air Force's Missile Defense Agency's Airborne Laser (ABL). These power supplies will drive compact arrays of LEDs, which will in turn pump the solid-state lasing medium.

Titan's proposed SILL 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, the "Vienna rectifier", first proposed by researchers in the Vienna Technical University [16] and the Hex-bridge bi-directional inverter. Neither topology contains magnetic components, but, at line frequency, they can provide a power factor over 0.99. All merits and drawbacks of both topologies have been 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 multi-kilowatt 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.

Intermediate Energy Storage Titan-PSD has identified a need for and has established the technical feasibility of an advanced technology power conditioning element to charge capacitive stores in DEW systems. However, a 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 8 is a schematic diagram of intermediate energy stores in two DEW systems.

Titan-PSD has manufactured systems that use an EDLC energy storage subsystem to provide ride-through of voltage sags and momentary outages for induction motors in commercial applications. The output of the store is connected across the DC link of the asynchronous drive to support its voltage. These systems have been demonstrated to respond to sags and outages within 10 ms and to provide 100 kW for up to 5 s which is sufficient to allow for orderly shut-down in a prolonged outage.
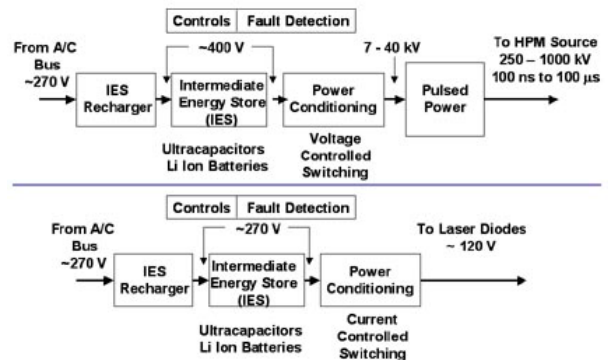

F8. Two DEW system block diagrams with intermediate energy storage.

Building on this commercial technology, Titan-PSD has developed concept designs using 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.

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 ≥ 10 kV), close rapidly (< 1 μs), carry high peak current (100 – 500 kA) with high initial rate of rise (50 to 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 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 [17] and Titan-PSD is responding by developing a high fluence, optically gated and pumped silicon thyristor (LGPT) that will satisfy the stated 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 but 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.

Over the last 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 importantly, 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 1150 nm which allows direct optical gating and pumping of silicon by the diodes. Figure 9 is an illustration of an on-board laser diode gated and pumped silicon thyristor that is one of the candidate approaches in development now.

(± 16.4 kV working)
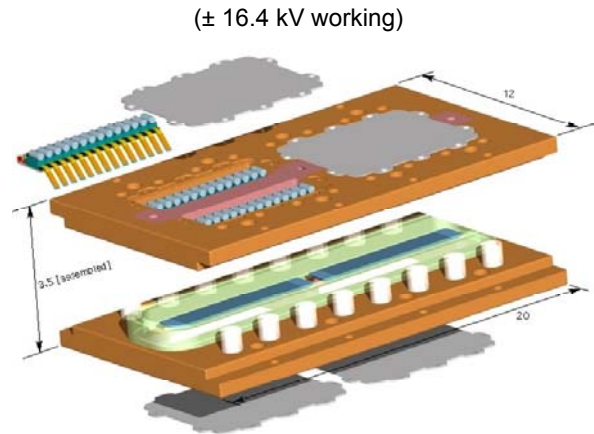
F9. Conceptual design of IFE compatible LGPT.

Titan-PSD is currently executing two programs that provide technical leverage for further switch development. Our Electra Advanced Pulsed Power Program is a 5 year, 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 developing an on-board laser-gated and pumped thyristor (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, repetition rate 5 pps continuous. The lifetime requirement limits the thermal excursion per pulse to a few degrees and therefore the action per cm^2 is low (~2 A^2-sec).

Another current Titan-PSD program is developing compact pulsed power components for AFRL at Kirtland AFB. The components under development will 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 both the LGPT, and a solid-state laser activated switch.

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 in LGPTs 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 and 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 μs. Several kW/cm^2 fluence is desirable for initial gating in many DEW applications. That requirement drops to 250 to 500 watts per cm^2 for continuous pumping, after thyristor action is present.

Next Generation Reltron Microwave Generator Development Reltron high power microwave sources were invented and developed at Titan Advanced Innovative Technologies from mid-1980's thru 1998 [11]. The Pulse Sciences Division of Titan assumed responsibility for Reltron contracts in 1998. Projects included a complete HPM simulator for a German government research laboratory and eight other Reltron tubes of varying specifications. Sufficient mechanical and electrical modifications have been included in the development of these tubes to justify their designation as "2nd generation" designs.

Reltrons are both compact and efficient. The electron beam is highly modulated over ~10 cm and post-accelerated prior to drifting to the output cavities and beam collector. This beam transport requires only ~75 cm overall length for L-band tubes (Figure 10). The output cavities are incorporated into a standard rectangular waveguide. Microwave power is efficiently extracted (~ 80%) directly in TE10 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 MHz to 1450 MHz. Programs are in place now to further extend this range.
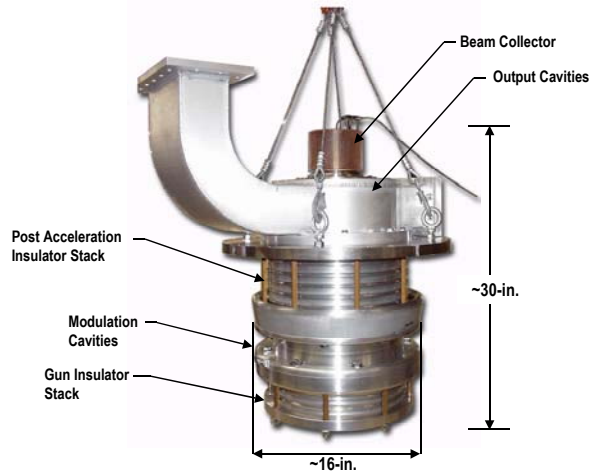
F10. L-band Reltron capable of generating flat 200 MW, 900 ns pulses with frequency stability δf/f < 0.3.

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 better infer basic performance parameters and to assist in comparing bench-marking simulations. These calculations simulate performance in the actual geometry and are generated with a three dimensional Particle-in-cell code (the LSP code from the Mission Research Corporation). Measured waveforms generated by a recently delivered L-band tube are shown in Figure 11. 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 and application of accurate three-dimensional EM codes.

High Energy Microwave Magnetron Backdoor microwave effects on electronics systems in modern weapons fall into three broad categories. Two classes are characterized by high peak power density, microwave formats that overwhelm the target system with an electric field that is high enough to cause circuit upset or burnout. In the third class, effects are caused
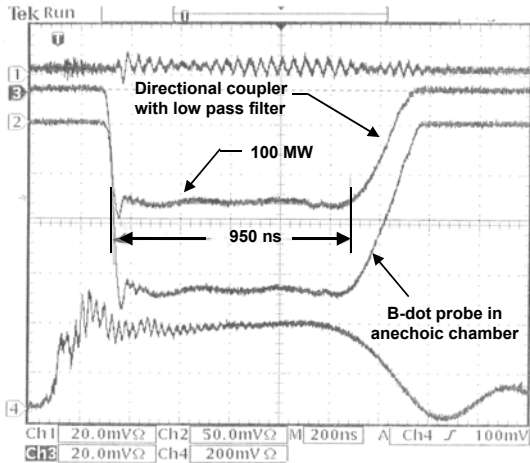
F11. Waveforms from the 185 MW L-band, the top trace is the heterodyne (l.o. = 1.3 GHz) showing excellent frequency stability, the second trace is the steady, flat-top output power measured with a calibrated directional coupler. (The data is conditioned with a low pass filter, higher harmonic content 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.

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 this 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 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 (HEM).

Titan has developed an HEM laboratory source and an HEM advanced technology demonstration 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 Figure 12, has produced 900 kW peak and 150 kW average powers and can easily be upgraded to 300 kW average power. This is the highest average power magnetron that is commercially available. 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 3.

F12. Titan's L-band HEM magnetron.

Table 3. California Tube Laboratory HEM Magnetron

Frequency, fixed	890 to 920 MHz

Power Output
    CW
    Pulse
	
	300 kW minimum
	600 kW peak (900 actually achieved)

Pulse width	10s of microseconds to 5 milliseconds
Peak Anode Voltage	42 kV
Peak Anode Current	17 A
Beam Efficiency	88% typical
Water-cooled Anode	20 gpm typical
Filament	12 VAC, 200A typical standby

Titan-Jaycor has fabricated and tested the Advanced Technology Demonstration system shown in Figure 13 that 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 pounds 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.

F13. In our ground based system, the principal system elements are a power supply, a modulator, an HEM source, and an antenna. These components are supported by control and cooling systems. The power supply and operators' console(s) are housed in a shelter mounted on one flatbed trailer while the remaining components are mounted on a second trailer (out of the field-of-view to the right). The system is designed to broadcast 2 MW peak power pulses with an average power of 300 kW for 30-second missions. This yields a peak fluence of 1 mW/cm² at 2400 ms range.

SUMMARY

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 more advanced DEW systems and the DoD's intent to field more electric fighting platforms depends 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 USA directed energy programs by providing services and analysis and developing advanced technologies since the early 1980's. Today, Titan is the only USA 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 a rapidly growing defense contractor focused on providing C4ISR solutions for national defense and intent on maintaining its industrial leadership in military information technologies.

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