TRANSFORMATIVE PULSED POWER SCIENCE AND TECHNOLOGY

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Final Report

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14. ABSTRACT
This study has focused on advanced concepts for generating high peak power, low energy, nanosecond time-scale pulses, and demonstrating that nanosecond pulsed power is an enabling technology. The project has also supported transitions of nanosecond pulsed power to important applications. Single, repetitive, and/or highly repetitive bursts of high peak power pulses can enable and/or enhance physical processes. Applications include combustion, compact, portable pulsed power generators, plasma-based accelerators, and bioelectric applications including cancer. Technology transfers include the initiation of two new companies: Transient Plasma Systems (TPS), started by students inspired by and supported by the AFOSR supported research, a US-based company that produces nanosecond pulse generators, now available to the DoD for applications including ignition and flow control, and for the future a valuable DoD asset, and another new venture under development for medical applications including skin disease therapies. 10 PhD student have graduated supported all or in part by this grant. The archival record includes 9 patents, 35 refereed and 13 conference papers.

15. SUBJECT TERMS
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Accomplishments (200 words max):

This study has focused on advanced concepts for generating high peak power, low energy, nanosecond time-scale pulses, and demonstrating that nanosecond pulsed power is an enabling technology. The project has also supported transitions of nanosecond pulsed power to important applications. Single, repetitive, and/or highly repetitive bursts of high peak power pulses can enable and/or enhance physical processes. Applications include combustion, compact, portable pulsed power generators, plasma-based accelerators, and bioelectric applications including basic studies of fundamental bioelectric processes, and useful therapies including cancer. Technology transfers include the initiation of two new companies: Transient Plasma Systems (TPS), started by students inspired by and supported by AFOSR supported research, and another new venture under development for medical applications including skin disease therapies. TPS is a US-based company to produce these nanosecond pulse generators, which are now available to the DoD for applications including ignition and flow control, and the company is now and for the future a valuable DoD asset. 10 PhD students have graduated with support all or in part from this project. A detailed archival record is provided in ≈35 refereed papers, 13 conference papers, 2 book chapters and 9 patents, listed below.

Archival publications (published) during reporting period (2009 to 2014):

Refereed Publications


**Book Chapters**


Conference Proceedings and Other Publications


Invited Presentations, Partial List


Contributed Presentations without papers, Partial List

Presentations accompanied by conference papers are included in “Conference Papers and Other Publications”, and are not included below.


**Changes in research objectives**, if any: None

**Change in AFOSR program manager**, if any: Dr. Robert J. Barker to Dr. John Luginsland and currently Dr. Jason Marshall

**Extensions granted or milestones slipped, if any**: None

Include any new discoveries, **inventions, or patent disclosures** during this reporting period (if none, report none):

**Patents Granted and Applied for**


7. High voltage nanosecond pulse generator using fast recovery diodes for cell electro-manipulation (U.S. Patent 7,901,930 B2), Mar. 8, 2011) *(there are three patents with the same name)*


Representative recent achievements specifically related to nanosecond pulsed power:

1) Development of a new type of magnetic pulse compression (MPC) line that is capable of achieving voltage multiplication at 100% energy transfer using less magnetic material than traditional lines. Sharing similarities with the stepped impedance transmission line invented by I. Smith and S. Darlington, as well as Fitch’s resonant voltage doubler, this line makes use of precharged capacitors. An energy and charge conservation analysis shows that properly choosing the pre-charge voltage of downstream capacitors enables voltage multiplication at full energy transfer. This is not possible for traditional magnetic compression lines, which can only achieve voltage multiplication at the expensive of energy transfer. Applying the analytical results to a practical four stage line has resulted in a design that is capable of producing an output pulse with a nominal voltage gain of 5 and full energy transfer to the load. This is a meaningful improvement over traditional pulse compression lines, which sacrifice 25% of the initially stored energy for a 50% increase in voltage amplitude per stage.

2) Reduction of jitter in high rep rate MPC systems to less than 1.5% by means of a simple core reset method that requires only a single snubber. Amplitude jitter is frequently a problem in high rep rate systems due to difficulties associated with resetting the cores to a consistent initial flux. As the time between output pulses reduces, core reset circuitry typically becomes more complex as higher voltages are required. In order to avoid additional high voltage circuitry that would be required for an active reset approach, a simple method has been developed that only requires a simple resistive snubber. A flux conservation analysis indicates that, provided the given reset time is approximately 5 times larger than the snubber’s time constant, choosing a snubber with a value \( C \cdot V_o / \Phi \) where \( C \) is the stage’s capacitance, \( V_o \) is residual voltage, and \( \Phi \) is the magnetic flux, will fully balance the core’s flux while leaving no residual energy in the system. This approach was applied to a 10kHz unit, and the output jitter was reduced from 40% (in the case of no reset or inadequate reset) to less than 1.5%. The tradeoff to this approach is increased dissipation, however, for applications with modest average power (< 1kW), this approach significantly reduces complexity. It also reduces system size for modest rep rates, roughly 10 kHz and below. This approach can be utilized over a large range at a fixed energy cost, up to the point where the snubber’s time constant begins to approach the resonant period of the compression stage. At this limit, the fraction of the stored energy that must be reserved for reset grows proportionally with \((PRR)^2\), where PRR is the repetition rate.

3) Improved design for electromagnetic compatibility and the development of diagnostics for measuring instantaneous power delivered to complex loads. Practical use of these systems often takes place in a lab environment in the vicinity of sensitive equipment that is easily perturbed by EMI produced by fast rising, high voltage pulses. These laboratory experiments also frequently involve pulsing complex loads that have unknown, time-varying impedances, making it difficult to measure energy that is delivered on timescales of a few nanoseconds. We have addressed these challenges in the last year by redesigning the layout and subsystem assembly of our high repetition rate units (those most likely to generate EMI) and by designing a custom broadband, high voltage rated power monitor that provides time-resolved voltage and current traces for risetimes as fast as 2 ns. This power monitor is modular, enabling the user to connect it directly to the load, thus alleviating the need to correct for propagation effects that cable interconnect has on fast pulses measured at the output of the generator. This system has proven to be electrically quiet, producing no observable noise in multiple experiments in the last 12 months, including two at the Combustion Research Facility at Sandia National Laboratory and one at the Naval Postgraduate School.
**DoD Benefits:**

The research benefits the DoD in High Power Microwave (HPM) systems; ultra-wideband radar; wireless power transmission; compact, efficient, and versatile HPM components; high bandwidth sources capable of producing high power RF bursts; reduced size and weight to enable mobile applications that are not now possible. **Small engines and HPM:** We anticipate that among the most important benefits will be pulse generation for 1) ignition in small engines, with preliminary results demonstrated in a Capstone project overseen by the WPAFRL (Schauer) and studies elsewhere, including recent collaboration with Sandia National Laboratory, and 2) Design and engineering leading to miniaturization of pulsed power for HPM, through collaboration with the AFRL at Albuquerque (Shiffler, Heidger). **Ancillary DoD Benefits:** Under AFOSR support, enabling nanosecond pulsed power innovations have been demonstrated in collaborations with experts in areas including combustion and medicine. For USC pulsed power research collaborators have included, for combustion collaborations have occurred with the Air Force (primarily WPAFRL), Nissan, Sandia National Laboratories Livermore. Biomedical applications work with cancer research at Cedars Medical Research Center (Koeffler, Marcu), cardiovascular with UCLA and Houston Methodist (Valderrabano), and translational through the Alfred Mann Institute at USC, with Old Dominion U., now include patient studies at Huntington Hospital in Pasadena CA for skin conditions. Our group has also performed preliminary, yet very promising studies of the effects of field-assisted juice extraction from wine grapes in collaboration with the A. Waterhouse group at U.C. Davis Dept. of Enology and Viticulture.
**Graduated PhD Students 2009-2014**

Electrical Engineering unless otherwise indicated, all or partially supported by AFOSR grant (FA9550-09-1-0458).

Charles Cathey 2009 Transient plasma for combustion: physics and applications

Yu-San Liu (Chem E) 2009 Quantum dot fluorescent indicators for nanoelectroperturbation studies of cancer cells

James Liang (Chem E) 2009 Functionalization of carbon nanotubes for introduction into cancer cells

Jessica Hao Chen 2010 Compact Back-lighted thyatron switches

Meng-Tse Chen (Mat Sci) 2010 Biophotonic studies of nanosecond pulsed field induction of apoptosis in cancer cells

Daniel Singleton 2010 Transient plasma ignition

Jason Sanders 2011 Compact pulsed power

Esin Sozer 2011 Compact back-lighted thyatron switches

Scott J. Pendleton (Physics) 2012 Experiments for understanding transient plasma ignition

Zachery Levine (Physics) 2013 Theoretical Studies of Lipid Bilayer Electroporation

Ming-Chak Ho (Physics) 2013 Molecular dynamics simulation of electroporation in phospholipid bilayer

Yu-Hsuan Wu (Chem E) 2014 Biophotonic Studies of Intracellular Responses to Nanosecond, Megavolt-per-meter, pulsed Electric Field

Yung-Hsu Lin (Physics) 2014 Physics of transient plasma at Higher Pressures

Ho, Wu, Levine and Liu were primarily directed by P. Thomas Vernier.

**Awards**

Martin Gundersen received the Sol Schneider award of the 2010 IEEE Power Modulator and High Voltage Conference “For Continuing Technical and Administrative Leadership in the Power Modulator and High Voltage Communities”.

Jason Sanders was recipient of the 2011 IEEE Nuclear Plasma Sciences Society Student Paper Award (Best paper award for both the 2011 IEEE Conference on Plasma Science and the 2011 IEEE Pulsed Power Conference). The title of the paper is “Design and Optimization Techniques for the Generation of Intense, Ultrafast Pulses with Nonlinear Transmission Lines”
Appendix 1: Pulsed Power Specific Future Research Summary

Based on research conducted to date, we believe there is potential for extending these results to shorter temporal regimes, i.e. picosecond pulsed power, which will further impact enabling pulsed power applications with benefits to energy efficiencies and other areas such as bioelectronics. Energy per pulse will be

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<th>Research into High Voltage, Picosecond Pulse Generation</th>
<th>Potential Methods</th>
<th>Notes</th>
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<tr>
<td>Picosesecond Risetime (&gt;1kV amplitude)</td>
<td></td>
<td></td>
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<tr>
<td>Ferrite Shocklines</td>
<td>Rep rate limited by magnetic reset circuitry. Non-ferrites theoretically capable of reducing risetimes to 30 ps, but practical designs require amplitude &quot;~5kV to achieve such short times.</td>
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<tr>
<td>Optically triggered Photoconductive Solid State Switch</td>
<td>Rep rate limited by recombination time/dissipation (avalanche mode) or by dissipation (linear mode). Linear mode operation is a good candidate for a system with adjustable FWHM, but switch will likely have high on-state impedance.</td>
<td></td>
</tr>
<tr>
<td>Solid state avalanche switches</td>
<td>Rep rate limited by recombination time/dissipation. FWHM is determined by circuit timeconstants, not by switch.</td>
<td></td>
</tr>
<tr>
<td>Pressurized spark gap</td>
<td>Rep rate limited by recombination time (typically longer than solid state devices, depending on geometry).</td>
<td></td>
</tr>
<tr>
<td>Picosesecond FHWM (&gt;3kV amplitude)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Optically triggered Photoconductive Solid State Switch</td>
<td>Linear mode operation enables turn-on capability =&gt; Fast laser with sufficient energy at appropriate wavelength could make fast electrical pulse. High on-state impedance is a likely trade-off.</td>
<td></td>
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<tr>
<td>Appropriate circuit design + other picosecond risetime switches</td>
<td>Circuit timeconstants less than 1 ns -&gt; ps FWHM. Requires careful design, likely custom machined components</td>
<td></td>
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<tr>
<td>Failure switch</td>
<td>Employ a short switch that triggers and shorts excess energy to ground during likely unclean pulse with resonance on tail.</td>
<td></td>
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<tr>
<th>Research into High Voltage Pulse Generation</th>
<th>Details</th>
<th>Notes</th>
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<tbody>
<tr>
<td>Recharged Magnetic Pulse Compression</td>
<td>Recharged capacitors as a means to increasing compression gain</td>
<td>Andy Kulhi has written up notes on the theory of this approach</td>
</tr>
<tr>
<td>Circuit synthesis to optimize diode switching</td>
<td>Analytical project focused on maximizing diode pumping efficiency. Measured data on diode performance should guide design.</td>
<td>Jason Sanders has worked on this, but there is opportunity to expand upon it.</td>
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<tr>
<th>Research into Highly Repetitive (High Rep Rate) Pulse Generation</th>
<th>Notes</th>
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<tbody>
<tr>
<td>System miniaturization via increased efficiency</td>
<td>System efficiency increases, load matching becomes increasingly important because highly efficient systems won’t dissipate energy quickly. Load matching is difficult when driving plasma sources, so an actively switched dissipation circuit may be required for some applications.</td>
</tr>
<tr>
<td>System miniaturization via optimal architecture design</td>
<td>In general high voltage switching is the easiest, b/c peak currents will be lower. &gt;1kHz losses are dominant, so it’s desirable to avoid high current where possible.</td>
</tr>
<tr>
<td>Highly repetitive, flat-top, picosecond risetime pulses at modest voltages (0-10kV)</td>
<td>Jason Sanders has done work on 5 kV, flat top pulses at 100kHz and can provide feedback on approaching this topic.</td>
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<tr>
<th>Research into Materials / Devices for Pulsed Power</th>
<th>Notes</th>
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<tr>
<td>Diode Opening Switch</td>
<td>Recombination rate (reverse recovery time) is important, and needs to be long ~ negligible recombination on 100ms timescale.</td>
</tr>
<tr>
<td>Closing Switches</td>
<td>See Picosesecond Risetime Section above.</td>
</tr>
<tr>
<td>Nonlinear Materials for Pulse Compression</td>
<td>Historically magnetic materials are desirable for nonlinear transmission lines b/c ferrites exhibit significant nonlinearity at high freq, and have low eddy loss. Dielectric materials that exhibit significant nonlinearity tend to be high dielectric (~ low cutoff frequency) and lossy at high frequency. The recent availability of BaTiO3 nanoparticles may open up a new approach. Research could look at how BaTiO3 nonlinearity changes with particle size and density.</td>
</tr>
<tr>
<td>Materials/growth methods for high energy density capacitors</td>
<td>High energy density capacitors are important for miniaturizing pulse generator size. Increasing energy density can be achieved by either increasing the dielectric constant or by increasing voltage rating. Dielectrics in IC can withstand very high E-fields before breakdown. Can the growth methods/materials be adopted for pulsed power applications. How does voltage hold-off change as dielectric thickness increases?</td>
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