Some Future Directions for Repetitive Pulsed Power

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Invited Paper

***Abstract*—Repetitive pulsed power technology has a lot of potential for growth. After a relatively quiet decade in the 90s, customer interest is increasing. With new interest comes new demands on the technology. Orders of magnitude advances will be needed over the next ten years. This paper speculates where some such improvements may be made. It does not attempt to provide a complete overview of the possibilities. Rather it attempts to identify a few areas where large growth seems possible over the next decade, and to highlight the drivers for substantial breakthroughs.**

***Index Terms*—Coilgun, compact pulsed power, PCSS, photoconductive semiconductor switch, pulsed power, repetitive pulsed power.**

I. Introduction

REPETITIVE pulsed power has been pursued at varying levels for nearly three decades, yet there is substantial room for growth. This paper examines two very different topics: 1) potential gains to be made in reducing the size or increasing the functionality of compact repetitive pulsed power system and 2) the prospects for a new generation of very high energy per pulse repetitive mass launchers. These topics represent a spectrum from the very small to the very large and cover a host of technologies. Yet, there are substantial similarities. In both cases, switching and dielectric systems are identified as technologies where leading edge developments can produce major gains. The example of high gain photoconductive semiconductor switching (PCSS) is highlighted. Issues of special interest to the design of repetitive systems will be emphasized. Examples include switch interpulse recovery, fault modes, pulse lifetimes, and dielectric issues. The objective is to identify a few high leverage areas where critical technology insertion could result in order-of-magnitude improvements in the state-of-the-art.

II. Enhancing the Capabilities of Compact Repetitive Pulsed Power Systems

Compact, repetitive systems are filling a rapidly expanding niche in pulsed power, including powering a variety of directed energy systems. Present systems perform admirably for their intended function; however, past experience indicates that future enhancements will be needed. Fortunately, this seems to be an area where order of magnitude improvements are indeed possible. These will probably include increasing the average power [i.e., increasing the pulse repetition frequency (PRF)], increasing the peak power, and reducing the size. Achieving these objectives will require technological advances. It will be argued that the potential for these order of magnitude advances exists.

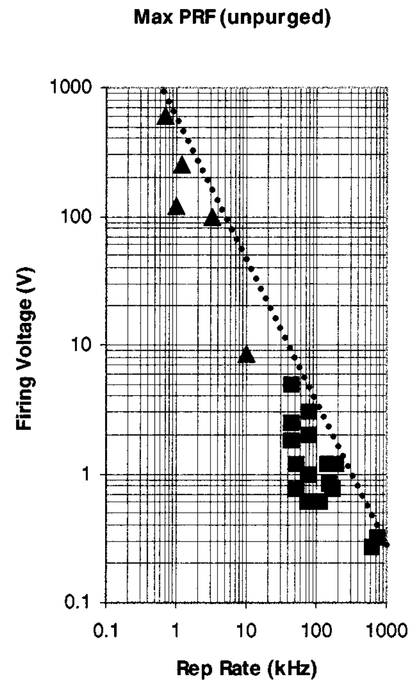

Fig. 1. The demarcation (dotted line) between free recovery of spark gaps and failure to recover over four orders of magnitude in PRF and switched voltage. Data from the Naval Surface Warfare Center (squares) and Sandia National Laboratories (triangles) [1].

Regarding PRF, Fig. 1 shows that over four orders of magnitude in switched voltage there is a reasonably clear demarcation (roughly the dotted line) between the area where stable free recovery has been observed (left of the dotted line) and where it has not. The dotted line in Fig. 1 and other observations are consistent with heat accumulation (density reduction) in the dielectric gas and electrodes limiting free recovery. Beyond free recovery, the alternative is forced recovery with purging gas. Purging mixes denser cool gas into the spark remnants and cools the electrodes, reducing the recovery time. Typically, several exchanges of the volume of gas in the spark region are required between pulses to enhance recovery. Particularly at high voltages and high PRFs, this can require an enormous quantity of gas. The hardware to pump gas through the switch(es) can make

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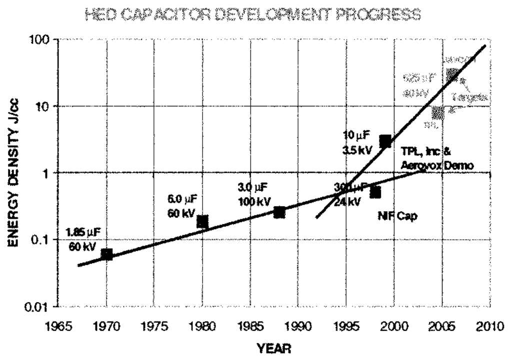

Fig. 2. The growth of capacitor energy density over several decades and a projected trend for the future [2].

the overall system impractical. To increase PRF capabilities by an order of magnitude may require a different switching technology. It will be argued that semiconductor switches are one plausible answer.

Increasing the energy density requires increasing the energy storage capability of two dielectrics, the capacitor films in the voltage multiplication stage (Marx or pulse transformer) and the dielectric in the pulse shaping stage. Fig. 2 illustrates the growth of energy density in capacitors suitable for this type of service. Two lines are drawn in the figure to guide the eye. The important feature is that the three highest energy density points (one achieved and the highest two projected) break the trend of the last two decades. Overly optimistic projections are to be avoided, but in this case, there is a basis for expecting the projections may be realistic. The two decade trend refers to improvements in capacitors built from carbon based films, a mature technology. The new trend is seen in new dielectric systems (silicon-based films or diamond). Often opening up a new developmental area creates new possibilities not achievable in a well-developed technology. System considerations imply that enhanced energy density needs to be accompanied by graceful degradation, as opposed to catastrophic failure, as capacitors age. This remains to be demonstrated. Finally, there really needs to be a testing procedure that can be used to prequalify dielectric systems. It has been suggested that partial discharge measurements are as good an indicator in pulsed power systems as they have proved elsewhere. This hypothesis also needs to be tested. If all of these requirements can be met over the next decade, there is the potential for an order of magnitude reduction in capacitor volume.

The dielectric volume needed to form the final pulse can be an even larger burden on system size and weight. A dielectric constant of a few hundred with the dielectric strength of a good plastic would achieve the order of magnitude improvement desired. Pulse forming dielectrics need to have high-energy density, good high-frequency properties, probably graceful degradation, and predictability. Ceramics seem to be the best candidates and there are several programs working on them.

The balance of the pulser system typically includes one other large item, either a dielectric fluid volume for a Marx generator or a pulse transformer. In these elements after accounting for capacitor volume, size is directly related to output voltage. The most direct approach to size reduction here is to eliminate half

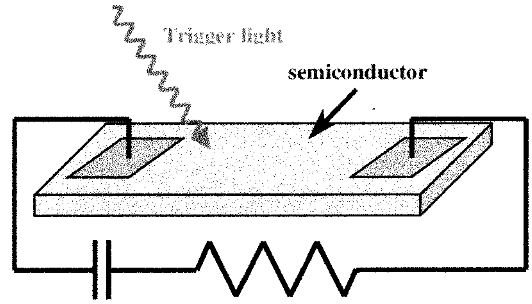

Fig. 3. Illustration of a PCSS. The basic building block is a piece of semi-insulating semiconductor with two contacts attached.

the system, either putting the pulse shaping into the Marx/transformer for longer pulses (above several hundred nanoseconds typically) or "Marxing" pulse forming elements for shorter pulses. The former solution is well known and tends to be limited by the inductance in the various pulse shaping elements. Marxing PFLs tends to be limited by certain intrinsic losses and by switching limitations. The intrinsic losses can be minimized with appropriate design. Switching is a critical issue. To divide a 50 Ω system into 10 stacked units, for example, implies that the individual units have an impedance of 5.0 Ω, which stresses switch inductance. Furthermore, the switches need to be synchronized (triggered) which is a problem given that some rise up as high as the output voltage as the Marx erects. The advantage of marxing in terms of achieving a size reduction can easily be lost in switching complexity. In essence, this concept enables a significant decrease in volume at the cost of switching complexity; by trading the size of a transformer or Marx system for a more complex switch and trigger. For that trade to be advantageous, it may be necessary to develop a new switching technology; ideally, based on light triggering of the upper Marx stages. One would want a switch that could enable both a higher PRF and smaller volume.

III. Photoconductive Semiconductor Switches (PCSS), a Possible Solution to the Repetitive Switching Challenge

For a variety of reasons, such as those previously discussed, several institutions have been investigating alternative switch systems. PCSS [3]–[5] presents an interesting example of what may be possible and where the challenges may be found. Fig. 3 is a drawing of a PCSS, illustrating its primary features. In its normal state, the undoped semiconductor is a reasonable dielectric for most purposes. With the application of sufficient light resulting in the production of electron–hole pairs, the semiconductor becomes conducting. This is the switching action. Both silicon and gallium arsenide (GaAs) have been investigated. A major system issue is the size of the trigger light source. A particular property of GaAs (and it is speculated of other direct band gap semiconductors) that allows carrier multiplication and reduces the light requirement is a probable enabler for the practicality of this switching system.

The advantages expected from PCSS include:

1) very fast interpulse recovery (high PRF capability);
2) simple, precise triggering;

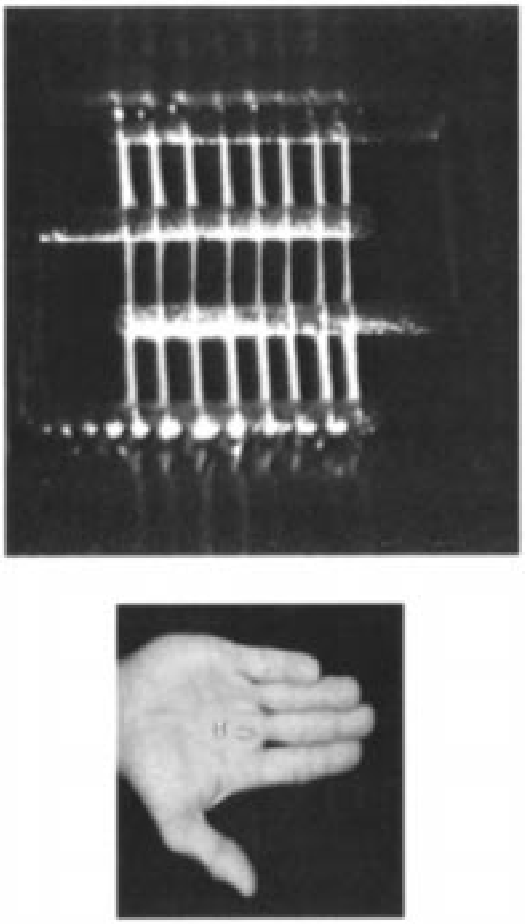

Fig. 4. A pair of interdigitated (U-shaped) electrodes with 24 filaments struck in parallel (upper photograph) and a photograph illustrating the size of the switch (center of hand) and laser (right of the switch).

3) optical isolation;
4) good current and voltage handling capability;
5) good "multichannel" capability.

Interpulse recovery is expected to be dominated by fast recombination of carriers (on the nanosecond scale for GaAs) and by conduction of heat from the switching event into the crystal, a good thermal conductor. Kilohertz PRFs are routine and two pulse recovery above 1 MHz has been observed. Good control comes from the very rapid and predictable response of the crystal to absorbed light. Good voltage and current handling come from the ability to scale the switch dimensions. Increasing the spacing between contacts increases the voltage hold-off (there are no junctions to contend with). Increasing the transverse dimension of the contacts accommodate more current and dI/dt. Each of these advantages has been confirmed to some extent. The disadvantage of the photoconductive process with gain is that the current is conducted in constricted channels. This is somewhat moderated by the observed propensity for PCSS to multichannel. Still filamentation leads to contact degradation and lifetime issues. Fig. 4 illustrates this filamentary nature of the discharge. This is an open shutter IR photograph of a PCSS after a high-gain switching event. The camera is recording recombination light. Since the carriers do not move significantly during the switching event, this

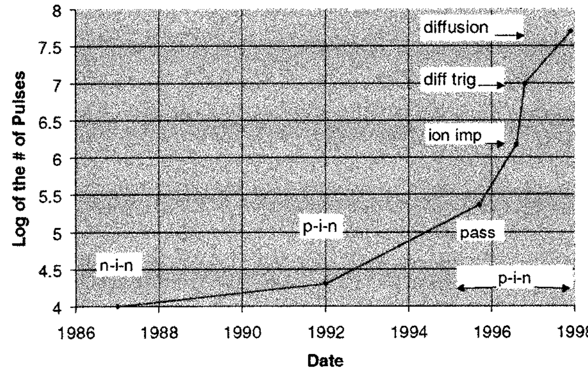

Fig. 5. Improvement of PCSS pulse lifetime as a result of improved contact design.

TABLE I
HIGH GAIN GAAS PCSS, SUMMARY OF RESULTS

Parameter	Simultaneous Results	Extremes(not simultaneous)
Switch Voltage (kV)	100	210
Switch Current (kA)	1.3	8
Peak Power (MW)	48	780
Rise Time (ps)	430	370
Trigger Energy (nJ)	180	2
R-M-S Jitter (ps)	150	50
REP. Rate (Hz)	1,000	1,000
Device Life (# of Pulses)	50,000 at 77 kV	>100,000,000

light faithfully replicates the current path through the switch. A solution to contact degradation has been pursued for over a decade, as illustrated in Fig. 5. The primary approach has been to terminate the filament before it enters the semiconductor-to-metal contact region, resulting in a much-reduced current density and deposited energy density under the metallization. Improvements have been very promising, but more remains to be done. It is instructive to estimate the upper limit this heating mechanism imposes on the discharge parameters per filament. A simple calculation indicates that perhaps several hundred microcoulombs could be safely conducted per pulse. Since the best results to date are at a few percent of that level, there may be considerable room for improvement, and further research is justified.

Beyond the issue of injecting current from the contact into the GaAs, PCSS tend to be quite benign. Table I shows switching parameters that have been obtained, either with a single switch design (simultaneous results) or over the whole set of experiments conducted to date. These data confirm the properties of PCSS listed earlier.

The discharge in Fig. 4 is on the order of a kilovolt and 1 Ω, that is, on the order of megawatts. For most repetitive, compact pulsed power applications, the voltage will be higher, on the order of 100 kV. Increasing the voltage involves making a larger switch and increasing the trigger light accordingly. Powers in the 100-MW range should be straightforward. Beyond that, it may be most convenient to replicate a single switch design for series/parallel operation. Most of today's compact repetitive pulsed power applications require peak powers in the range from a few gigawatts to perhaps 100 GW. This corresponds to several hundreds of these switches at most, a number thought to be reasonable.

The bottom line seems to be that the combination of advanced switching (PCSS or something even better) plus new high-energy dielectrics offers a credible option for increasing the parameters of compact repetitive pulsed power units by at least an order of magnitude over the next decade.

IV. High Energy, Repetitive Mass Launchers (Coilguns)

At the opposite end of almost every axis of the parameter space from compact repetitive systems is a new generation of very high-energy mass launchers. Applications include electromagnetic guns with ranges up to several hundred miles and their extension even to putting small objects into low earth orbit.

To launch a projectile to a maximum range around 500 km requires a muzzle velocity around 2.5 km/s, depending on the ballistic coefficient of the projectile. To go to orbit requires 5 to 7 km/s. The masses needed for the various applications range from tens of kilograms to many hundreds of kilograms. The corresponding per pulse energies required to be supplied to the launcher (i.e., accounting for the launch efficiency) are from the hundreds of megajoules to tens of gigajoules per pulse. Some of the applications require several launches per minute and average powers in the tens of megawatts. This is truly an extension of the state-of-the-art parameters in launchers by orders of magnitude along several axes in the parameter space. New technology will be needed to enable these order of magnitude improvements.

A leading technology for this application is the coilgun [6], an extension of a fairly common demonstration experiment where a conducting slug is placed off center in a solenoid and a pulsed magnetic field is applied. The slug is ejected from the solenoid by the interaction of the rising magnetic field with the eddy currents that it induces in the base of the slug (armature). The coilgun repeats this process as the armature moves through a series of coaxial coils. The rising magnetic field in successive coils is timed to give the armature maximum acceleration per coil. In principle, this can be carried on for an arbitrary number of coils up to the point where the eddy-current heating causes melting in the armature.

There are two distinct systems requirements here which tend to favor coilgun technology. The first is predictability, pulse-to-pulse reproducibility. The second, strangely enough, is complexity (modularity). As far as has been established to date, the behavior of the coilgun is predictable in a straightforward manner from first principles. If this continues to be true at higher speeds and masses, it greatly simplifies the development process for the very large systems envisioned above. It seems likely that in the pulse energy regime envisioned here, any successful system will be modular to allow for prototyping, maintenance, and graceful degradation, if necessary. The coilgun has the advantage of being intrinsically modular.

To illustrate predictability, Fig. 6 compares coilgun simulations with data up to the maximum (funding limited) speeds achieved to date. The point of the figure is that for two events at somewhat different conditions the model predicts the behavior of the coilgun from first principles (no adjustable parameters).

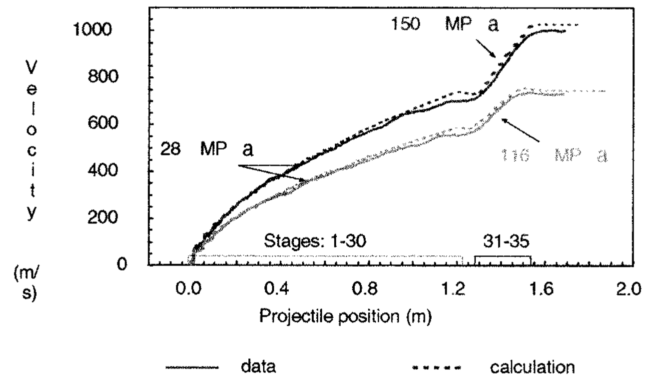

Fig. 6. Comparison of projectile velocity through the barrel, both data (solid line) and calculation, for two events. The horizontal axis is the position in the launcher. The vertical axis is the projectile velocity (m/s). The calculations were done without adjustable parameters.

A critical next question is whether predictability continues to higher armature speeds.

As with the compact repetitive pulser work, the two pulsed power issues for the coilgun center on switching and dielectrics. They are coupled. For a design with constant average pressure through the launcher, the current–voltage product is roughly fixed by the relation

$$\text{Pressure} \sim \frac{\text{Voltage} * \text{Current} * \text{Coil Charge Time}}{\text{Magnetic Field Volume}}.$$

According to this relation, it follows that one can, in principle, tradeoff between current and voltage (by a choice of the number of windings in the coil, inductance). The objective is to maximize system pulse lifetime, given a constrained size, mass, and/or cost. Currents in the higher mass launchers can reach into the multiple megamperes, pushing repetitive switching, and switch lifetime, into a new regime. Lower current is better from the switching point of view. On the other hand, the coils, being very complex wound structures containing insulation, conductors and cooling channels, are easier to design at lower voltage. They must be designed to withstand combined pressure, thermal and electrical stress. Today's designs work at 40 kV. An increase to the multiple hundreds of kilovolts will require substantial technology advancement. Precisely where the optimum choice between current and voltage will be found is not clear, but it is clear that the new generation of launchers will stretch the technology for both the switching and dielectric systems.

A logical approach to coilgun development can be structured around 1) demonstrating predictability at low mass and high speed, followed by 2) demonstration of the pulsed power for high speed, high mass. Along this line of reasoning, initial experiments have been suggested at 0.2 kg and 2.5 km/s, to be followed by experiments at several tens of kilograms and the same speed. Assuming success, it is reasonable to project a follow-on small mass experiment at the 5 to 7 km/s followed by a hundreds of kilogram experiment at this higher speed. The technology in hand seems sufficient for the low mass demonstrations of predictability, even at the highest speeds. At issue is the technology for the pulsed power experiments at high mass, high energy per pulse.

The complexity of the coilgun is critical to the success of this endeavor. It is naturally modular, that is, the pulsed power system is divided into multiple units, one per coil. For some applications at lower projectile energy, it may be advantageous to have all the pulsed power drawn from one source, e.g., a single capacitor bank or rotating machine. However, at the energies considered here, there are strong advantages, probably an absolute requirement, to divide the energy into smaller units for the sake of reliability, system development, and fault tolerance. The prerequisite for successful modularization is very reliable modules. Modularization was faced and overcome in multiple tens of terawatt simulation sources two decades ago, and it is common to a host of other systems that stretch the limits of technology. It will be addressed in launcher pulsed power systems over the next decade.

The prospects for high-mass, high-speed launchers rest on order of magnitude increases in pulsed power capability, both in switching and in dielectric systems. Fortunately, there are no apparent show stoppers, and the prospects for success seem excellent.

V. Conclusion

This paper has addressed some of the challenges in building compact repetitive pulsed power systems that are an order of magnitude smaller than today's systems and in building launcher systems orders of magnitude bigger than the current state of the art. Switching and dielectric systems have been identified as areas for technology development over the next decade as these systems move toward being fielded. This is no surprise. For compact high PRF systems the switching limitations arise at the interface where current is injected from the metal electrode into the switch dielectric (gas or semiconductor). Going to very high PRFs or very compact systems would be much more likely to succeed when a new generation of semiconductor devices (or their equivalent) comes of age. A critical dielectric issue for compact short pulse systems is the development of high-energy density (ceramic) dielectrics for pulse forming lines. For the very large coilgun systems there is a tradeoff between designing higher voltage coils and higher current repetitive switches. The product of current and voltage is fixed. A challenge for the next decade will be to find an optimal voltage and current for the most stressing elements (the muzzle coils) of the high-speed launchers. Fortunately, we have built a large community experience base to address these issues over the past few decades; so their resolution seems reasonably certain of success.

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[1] Unpublished data courtesy of the Naval Surface Warfare Center (S. L. Moran) and Sandia National Laboratories (L. F. Rinehart).

[2] Unpublished data from TPL, Inc, Albuquerque, NM.

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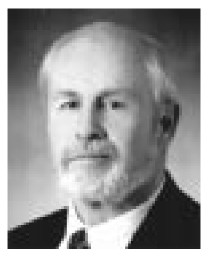

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Dr. Buttram is a member of the American Physical Society. He received the 2000 Germeshausen Award from the 24th International Power Modulator Symposium for "Contributions to Power Modulator and Radar Transmitter Technology." He also received the Erwin Marx Award from the IEEE and the 2001 Pulsed Power Conference for "Outstanding Achievements in Pulsed Power Technology over an Extended Period of Time."