Pulsed-Power Innovations for Next-Generation, High-Current Drivers

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Recent proposals to build larger high-current drivers to be used for high-energy-density physics, inertial confinement fusion, radiation effects testing, and basic science will present challenges.[1] Drivers significantly larger than the Z Machine at Sandia National Laboratories encounter increasing difficulties in water power flow, insulator performance, and vacuum power flow. The physics requirements of imploding loads limit a designer's flexibility in choosing machine parameters such as current rise time, driving impedance, and total inductance. This summary enumerates these physics constraints and shows how they impact driver design. This leads to the conclusion that advances in pulsed-power understanding and pulsed-power capabilities are needed to control risk and to build a cost-effective driver at peak currents of ~60 MA.

The Z machine, driving an imploding load, requires a peak insulator voltage of ~4 MV while delivering up to 25 MA to the load.[2] The current rise time is ~100 to 110 ns and the overall implosion times are 100 ns to 120 ns (Refs. 3–5). Scaling Z today at 25 MA to a new next-generation pulsed-power facility (NGPPF) at 60 MA requires that the driving voltage scale proportionally with the increased peak current (other parameters held constant). This results in a driver with a peak voltage at least ~2.4× larger than Z.[6,7] These scaled voltages will exist at all locations in the driver for all times during the pulse. This summary describes the physics constraints on driver parameters, discusses the pulsed-power impact on the pulsed-power design, and finally asks if advances in pulsed-power physics understanding and pulsed-power engineering can reduce the risk and cost of an NGPP driver.

Magneto-Rayleigh–Taylor (MRT) physics drives *Z*-pinch drivers to implosions times of 100 ns or less.[2,8,9] In the case of an NGPPF driver, implosion quality is paramount. It becomes difficult to justify a significant increase in the implosion time (current rise time) to reduce the voltage (and power) risk beyond 100 ns unless MRT can be stabilized to some extent.

Electrical coupling efficiency to the load is a huge part of driver optimization. Simplistically, the electrical coupling (to stored magnetic energy) is optimized when $L/Zt \sim 1$, where L is the total inductance of the load, Z is the impedance of the driver, and t is the rise time of the current. Given from MRT consideration that the current rise time t is constrained, we see that increases in the load inductance L must be accompanied by an increase in driver impedance Z. However, the coupling efficiency to the load is $\sim\Delta L/L$, where ΔL is the change in inductance due to the dynamic load and L here is the total final inductance. For a convergence ratio of ~10:1, the change in inductance of a 2-cm-long load is ~9.4 nH. We see that coupling to the load is optimized for lower total inductances. As a result, the overall coupling efficiency from available driver energy drives us to a lower inductance and lower impedance driver. The driver inductance and impedance are not free parameters.

Higher-voltage NGPP drivers force larger gaps in the water section of any driver because, for a voltage rise time of ~100 ns, the threshold for electrical discharges in water is 300 kV/cm. The only ways to increase the gap in the water section near the load are to increase the radius of the insulator stack (height scales with radius at constant impedance) and increase the impedance of the water lines. Both of these approaches will be required.

The largest-diameter parts that can be built and shipped across the country are roughly 6 m in diameter. With this assumption, the only additional way to increase the driver voltage is by using multiple levels of insulators and magnetically insulated transmission lines (MITL's). (See Fig. 1 for a four-level example.) The key advantage of increasing the number of MITL levels is an increase in the water transmission-line gap for a given insulator stack radius because the levels are driven in parallel. A secondary impact is the paralleling of the MITL inductances at the post-hole convolute. Inductance is a secondary impact because the reduced current per MITL level forces an increase in MITL inductance to hold the electron vacuum flow nearly constant. The number of MITL levels and the insulator stack radius effectively determine the maximum current for a given design.

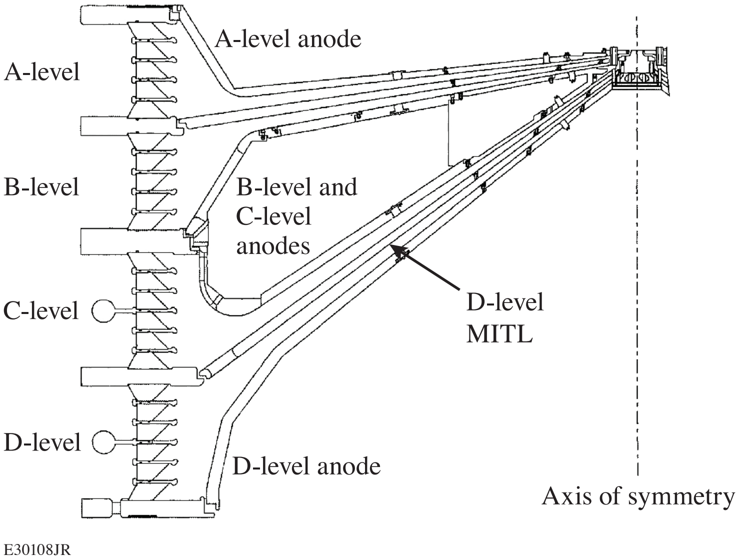

Figure 1
Schematic of a double-disk MITL that shows the insulator stack, the vacuum flare region, the MITL's, the post-hole convolute, the inner disk MITL, and the load region.

An impedance of $Z = 6.67\ h/r\ \Omega$ per level for a four-level MITL is used to estimate the peak current of a Z machine–like design. One potential design impedance is 0.180 Ω, so the individual level impedance is now increased to 0.72 Ω. This results in a water-transmission line gap of 32.4 cm at a radius of 3 m. Following the arguments of maximum electric field above, the peak allowed voltage is ~4.8 MV and the peak current is ~50 MA. Higher-current drivers will require a larger-radius insulator stack, a higher driving impedance, and/or more MITL levels.

The increased voltage on NGPPF (everywhere and at all times) will create difficulties in pulsed-power design and result in increased current losses and reduced coupling efficiency to dynamic loads. Mitigating losses by increasing physical gap results in an increase in inductance that reduces peak current and decreases coupling efficiency. Further increases in driving voltage are required to obtain the design load current. This is a strong feedback effect that can limit the overall magnitude of a potential NGPP driver. Kinetic energy delivered to a relevant load becomes the key metric for comparing various driver designs. It is possible to design a pulsed-power driver that achieves 60 MA at the load that couples insufficient energy to a dynamic load.

It is likely that there is an effective limit to the peak current and kinetic energy of a pulsed-power driver that is based on cost, shot rate, and programmatic impact. A 60-MA-class driver can be built but such a driver, based on today's pulsed-power understanding, will be costly and inefficient.

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