Durable Solid State Pulsed Power for ArF Direct Drive Fusion and Other Fusion Concepts

White paper submitted by NRL Plasma Physics Division, Laser Plasma Branch.
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Executive Summary

We propose the construction and testing of a humble, yet vital, module in inertial fusion drivers that include lasers and ion beams. It delivers high cycle 10Hz pulsed power at the 0.2TW level, in modules that can be ganged to deliver >1TW. High cycle means $>>10^8$ pulses between failures and is delivered via the use of all-solid-state switches. Prior pulsed power has been limited in life to $<10^6$ pulses due to the degradation of gas discharge switches and cannot be projected forward to power station reliability. Building upon a proven 10Hz, $>10^7$ pulse NRL demonstrator we have designed a 10Hz generator at 500kV, 400kA, 200ns, delivering 40kJ at >90% efficiency in a rectangular pulse. This achievement is made possible through an innovation in electrical pulse compression. Parts for the prototype will cost $1.5m (small quantity costs) and the design, assembly and testing of #1 is planned to take 3 years at $2m/ yr, altogether totaling $7.5m. In production quantities the pulsed power module will cost from $1 -> 1.5m. When applied to the ArF driver, six modules will drive either of two types of 193nm ArF amplifier that can deliver a) 30kJ in 2ns (i.e. 15TW at 193nm), or b) 30kJ in 200ps (i.e. 150TW at 193nm). Combinations of these amplifier types can generate the compression and ignitor pulses to achieve high gain with direct drive spherical DT targets at sub-0.6MJ energy.

Background

The ArF laser emits at 193nm in the deep ultraviolet with a projected internal efficiency of 17% and an overall "wall-plug to target" system efficiency exceeding 10%. Its 10THz bandwidth is sufficient to suppress the most serious laser-plasma instabilities and it can be delivered in an ultra-smooth zoom-able beam profile onto a spherical direct drive capsule. Using D-T fuel high compression efficiency is projected to give gains of greater than 160 at laser energies as low as 600kJ [1,2,3], making laser fusion power plants possible at a much lower capital cost than before.

The ArF gas laser medium is immune to optical damage and is flowed to remove waste heat. Prior to the present proposal the Nike 60cm aperture laser has delivered 5kJ at the longer KrF wavelength of 249nm, operating reliably in "single pulse" mode for 26 years since its commissioning in 1995. Following Nike, the next phase of laser development relates to the ArF laser and the present proposal is to build a 40kJ, 200ns pulsed power system suitable to drive a 30kJ ArF laser (30kJ of output at 193nm) when arranged in a parallel group of six pulsed power modules.

For this purpose we are introducing a new architecture of durable pulsed power with all-solid-state design that satisfies the 10Hz, $>>10^8$ pulse requirement for a power plant. Initially we would test it at 1Hz in extended runs so as to establish viability without the complete thermal management that would be necessary at 10Hz. NRL has already taken a step in this direction [4] with a 10^7 pulse, 10Hz continuous demonstration at 200kV and relatively low energy (Figure 1, reproduced from [4]) in which the first failure was not in a solid state switch but in a capacitor, after 1.5 x 10^7 pulses. This and other related tests have verified the reliability of present-day silicon thyristor stacks in a Marx configuration at the required voltage and current regime for the new 40kJ pulser (in regard to the switch parameters).

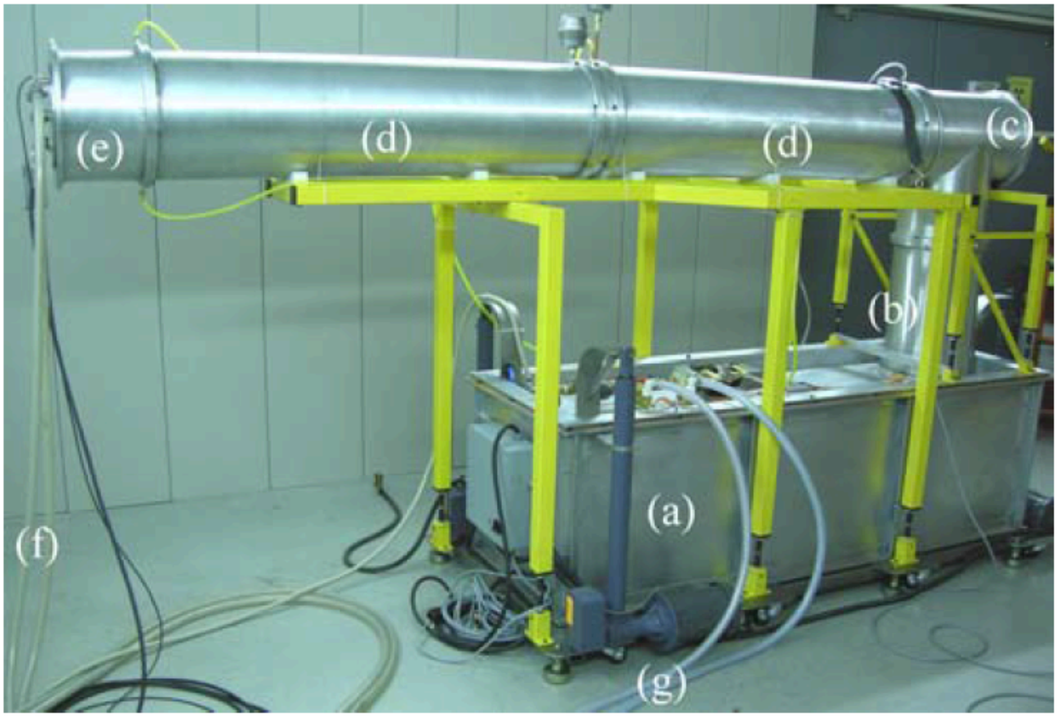

Figure 1. A compact gigawatt class solid state pulsed power system. (a) Marx tank, (b) main magnetic switch, (c) oil-filled T-section that houses a inner conducting elbow and the output voltage probe, (d) a 2-section compact pulse forming line with a total length of 2.5 m, (e) resistive load with reset isolation inductor, (f) water/soap solution recirculation lines, and (g) water cooling lines for the Marx oil heat exchanger.

(figure reproduced from [4]

We have chosen a 30kJ (193nm) ArF amplifier as the flexible basis of a program aimed at ignition and high gain. This will have a laser gas volume of 3m x 0.9m x 0.9m and be pumped by six pulsed power modules of the design to be prototyped under this effort. The six modules deliver 240kJ to 500kV electron guns with segmented cathodes that collectively deposit at least 180kJ into the laser gas. At 17% intrinsic efficiency the nominal output at 193nm is 30kJ. ArF amplifier design in regard to the electron beam, gas deposition and laser kinetic simulation is well advanced at NRL, with a single cathode segment at the final scale under test on the Electra laser [5].

Development of the 40kJ module

The 40kJ pulsed power test device is drawn schematically in Figure 2, not to exact scale. It comprises a DC power supply, Marx generator, pulse shaper, two pulse compression stages, resistive load and core reset pulse generator. The Marx tank has a footprint of 1m x 2.5m, height 1.4m, and the balance of the system is contained within 1m outside-diameter steel pipes that may be disconnected from each other and moved horizontally on rails.

The pulsed power test module will be developed in two sequential parts:
1) Subscale tests of a Marx generator module of 3 stages, with parallel low voltage tests of a full-scale pulse shaper.
2) Build-out of the Marx generator to 15 stages and integration at full voltage with the pulse shaper, two pulse compressors and a resistive load.

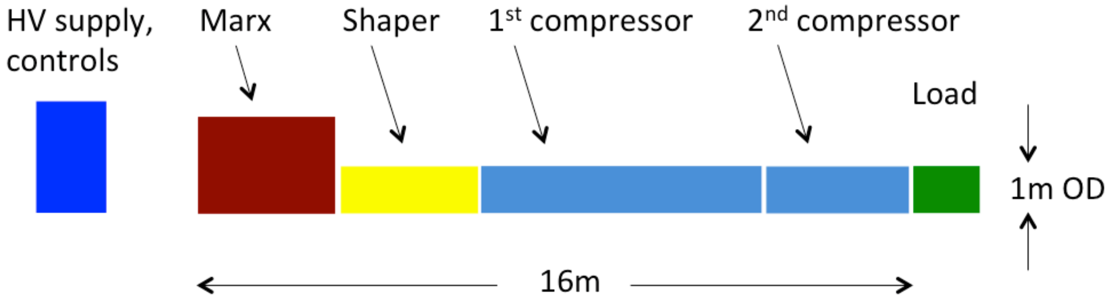

Figure 2. Sketch of 40kJ module with output 500kV, 200ns, 1.25Ω (0.2TW)

Within the Marx generator, which has 15 stages, each at 67kV, it is desirable to perform an initial test with only 3 stages so as to verify the stage design and the performance of the main sub-components:
1) silicon thyristor switch stacks
2) rapid discharge capacitors
3) saturable magnetic cores.
Although these items are each very close to existing commercial designs that have been proven in operation, the precise component parameters and any more recent improvements need to be checked against the rigorous requirements of the present project. The achievement of reliable 3-stage Marx operation at 1/5 voltage (200kV in 3 stages vs 1MV for 15 stages) is a key milestone. Minor design details can be ironed out before extended manufacture of the full 15 stages. As an example, it is intended to design a plug-in switch + capacitor module for easy change-out and subsequent easy upgrade if and when SiC and GaN switches overtake the

performance of silicon at high voltage (they are currently only competitive up to about 1kV). The initial medium-scale purchase orders for switches, capacitors and cores will be augmented by the purchase of any additional development, verification and manufacturing readiness that is needed from the commercial vendors of these items.

In a parallel first step it is proposed to test a first design version of the pulse-shaper circuit that is fed by the Marx stack. This circuit follows a well-established principle that is all passive, converting the Marx output into a 500kV, 850ns, 5Ω rectangular pulse that is suitable for subsequent compression. The shaper circuit is adapted to the scale of the 40kJ system and it has a new configuration that is simple and inexpensive. This is built in the first program period so as to do fine tuning in preparation for full voltage work.

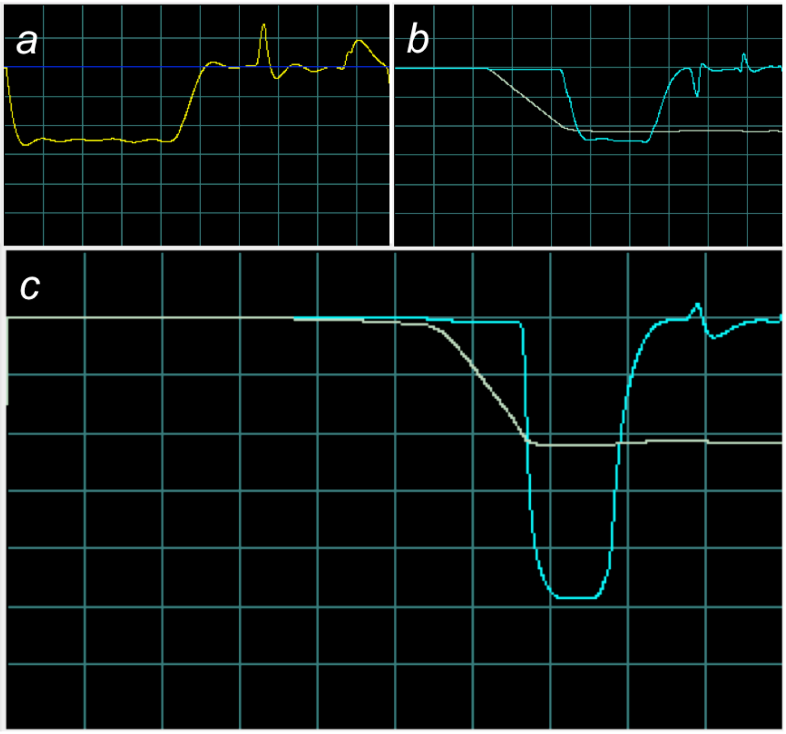

Figure 3. All traces 200ns/div. a) Waveform at output of pulse shaper (200kV/div.); (b) waveform at output of 1st compressor line (200kV/div.); (c) waveform at output of 2nd compressor line (100kV/div) into 1.25*Ω* resistive load. The white traces in (b) and (c) (arbitrary voltage) are monitors of core status, showing the transitions occurring prior to compressor output.

In the second and main phase of development the 15 stage Marx together with pulse shaper will be connected to pulse compressors [6] that ultimately produce an output of 500kV at 200ns duration and 1.25Ω impedance into a matched resistive load. The pulse shapes at different positions within the system have been simulated using "Spice" circuit software, with results shown in Figure 3. A final pulse rise-time of 20ns is projected, which represents a dI/dt value of 400kA/20ns, or 20MA/µs.

The system will be tested in long duration runs up to approximately 1Hz, which demands a 45kW, 70kV single polarity DC supply and associated charging controls. From DC to the 200ns pulse the calculated efficiency is >90%. The measured efficiency will be compared to theory. The goal of this pulsed power program will have been achieved when the system has a reliability consistent with its use in, for example, a group of six such modules driving the electron beams of a 30kJ, 193nm laser for an extended experimental campaign, for example, years at 0.01 – 1Hz.

Across-field applications

Pulsed power of the generic type proposed here would be of great utility in many fusion energy contexts beyond ArF direct drive. The design has great flexibility of pulse duration down to less than 100ns by utilizing variable numbers of compression stages. Some applications are:

a. Repetitive >10^8 pulse, 10Hz driver for mega-ampere pinch plasmas, e.g. sheared flow Z-pinch, magneto-inertial fusion,
b. Plasma jet acceleration in plasma jet driven magneto-inertial fusion
c. Pulsed ion acceleration in heavy ion fusion
d. MAGLIF drivers, for an ArF laser heating driver or Z-pinch driver

Low component counts

Relatively small quantities (Table 1) of the main components are required to build a single 40kJ pulsed power module. The main structures, which are the shaper and pulse compressors utilize stainless steel pipes of standard diameters.

Design, assembly and checkout of the first module costs considerably more than the parts. A very rough estimate of the team would be (full time):

2 engineers, 4 technicians, 1 director. A space of ideally 4,000 square feet, with high bay and traveling crane is required. For initial 1Hz work an electrical power of 50kW is needed. Parts for the prototype will cost approx. $1.5m. The balance of costs will be approx. $2m per year for 3yrs, altogether totaling $7.5m. The cost of modules in quantity will be between $1m and $1.5m each.

Table 1. Parts count for a 40kJ 0.2TW pulsed power module

Item	Number
67kV, 30kA Silicon thyristor stack	**60**
Primary plastic capacitor	**60**
Output plastic capacitor	**60**
Marx cores	**15**
Compressor cores	**2**
Misc. other parts	**lot**

Schedule

Briefly, the 3-stage Marx completion and testing together with the pulse shaper development will take 18 months. Construction and testing of the balance of the 15-stage Marx, integrated into the whole pulsed power system, will take an additional 18 months. The program will take 3years

References

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2. L. John Perkins, "And Now on to Higher Gains: Physics Platforms and Minimum Requirements for Inertial Fusion Energy". IFE Strategic Planning Workshop Kickoff Meeting Nov 16th 2021.

3. S. P. Obenschain, NRL white paper "Path to reduced-size laser fusion power plants with direct-drive using the argon fluoride laser"

4. F. Hegeler, M. W. McGeoch, J. D. Sethian, H. D. Sanders, S. C. Glidden and M. C. Myers, "A durable gigawatt class solid state pulsed power system", IEEE Trans. Diel. Electr. Insul. **18**, 1205-1213 (2011). Doi: 10.1109/TDEI.2011.5976117

5. Internal program at the US Naval Research Laboratory.

6. The pulse compressor passively converts a rectangular pulse to half-duration and half-impedance, maintaining constant voltage (M. W. McGeoch, unpublished).

Contact information:

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