LLNL-CONF-655114

NIF Solid-State Switch Pulse Generator Optimization for Multi-Pulse Operation

G. F. James, G. B. McHale, A. S. Runtal, P. S. Cardinale, P. A. Arnold, L. S. Pades

May 30, 2014

IEEE International Power Modulator and High Voltage Conference
Santa Fe, NM, United States
June 2, 2014 through June 5, 2014

NIF Solid-State Switch Pulse Generator Optimization for Multi-Pulse Operation

G.F. James, G.B. McHale, P. A. Arnold, A.S. Runtal, P.S. Cardinale, L.S. Pades
Lawrence Livermore National Laboratory, National Ignition Facility,
7000 East Avenue Livermore, CA 94550

ABSTRACT

A solid-state high voltage pulse generator developed as part of the Advanced Radiographic Capability (ARC) mission for the National Ignition Facility (NIF) has been deployed. This paper will provide details of the pulser design and the upgrades required to achieve reliable operation for multi-pulse bursts for an ever-increasing mission space. The pulser design has been demonstrated to be robust, reliable and to meet all performance specifications as they apply to the Plasma Electrode Pockels Cell (PEPC).

This pulser is realized as a FET-driven twenty-seven stage magnetic adder operating with 700 volt primaries. It delivers a programmable multi-pulse burst of 18 kV, 3 kA pulses to a Plasma Electrode Pockels Cell (PEPC) at repetition rates up to 1 Hertz. The typical pulse widths are 200ns with 20ns rise-and-fall-times at the pulser. A capacitive load, significant cable lengths between pulser and Pockels cell, fast transition times, and the microsecond type delays between pulses lead to non-ideal interactions that must be addressed to limit pulse distortion and reduce stress on the pulse electronics.

In this paper we discuss the various options considered for resolving these issues, down-select decisions, and test results that demonstrate improvements.

1 BACKGROUND

The Plasma Electrode Pockels Cell (PEPC) is a key technology within NIF, working in conjunction with a thin film polarizer to create an electro-optical switch in the main amplifier cavity. This optical switch allows the optical pulses to be trapped and then released, permitting NIF to take advantage of a four-pass architecture in the main amplifier, thus reducing costs and minimizing the required size of the facility while maximizing performance. Now, this basic functionality has been augmented with requirements associated Advanced Radiographic Capability; the petawatt beams that will generate hard x-rays for diagnosing performance of the ICF targets as they compress.

Previously, we discussed the significant new requirements ARC placed on PEPC with the addition of a second pulse [1]. From further analysis it has been determined that a three-pulse burst is required. Specifically, the second pulse and third pulses are required to safely redirect, trap, and dump energetic reflections returning from the target. These reflections pose a threat to the low power "front end" of the laser. The concept is illustrated in the timing diagram Figure 1, Pass 1-4 represent PEPC standard operation, R4, 3, 2, and 1 represent the energetic reflections needed to be safely trapped in a beam dump.

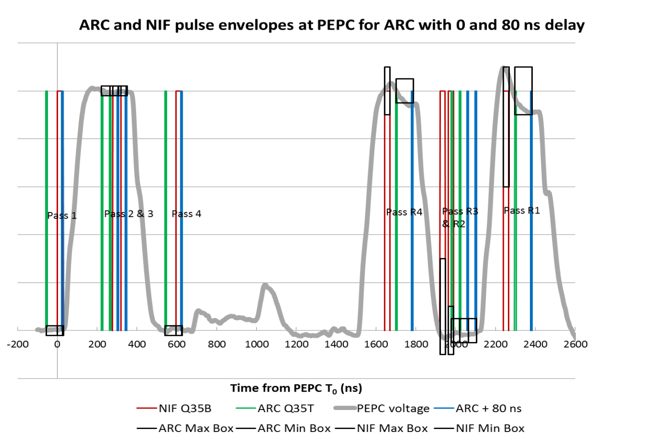

Figure 1. Relative timing of optical pulses and cell voltages. The boxes show allowable tolerances for the timing and voltage of the standard PEPC pulses and the ARC PEPC pulses.

2 SOLID STATE SWITCH PULSE GENERATOR

Solid-state switch pulse generators (SS SPGs) are well-suited for the task at hand: the FET-switched pulser offers many features including burst mode capability, variable pulse generation, frequency agility, variable pulse width, as well as fast rise and fall times. (For details of the design philosophy and implementation, see references [3] and [4], where double pulse operation is described.) The SS SPG has shown to perform reliably through millions of shots with double pulses (the first two pulses in Figure 1). It can be observed that intra-pulse period has a non-zero region and that the second pulse was somewhat distorted by the reflections generated when driving a reactive load such as the Pockels cell. However, this waveform met its original requirements.

The addition of a third electrical pulse only slightly delayed from the second pulse (Figures 1and 2) introduces all new reliability, and performance challenges. In particular, the third pulse experiences severe distortion due to cable reflections, produced more stress on the free-wheeling diodes, and produced arcing in the PEPC gas system due to the prolonged time at elevated stresses.

3 TRIPLE PULSE CHALLENGES

3.1 CABLE REFLECTIONS

As illustrated in the three-pulse burst of Figure 2, the electrical cable reflections arrive 600ns after the rising edge of the first pulse. The 600ns delay is due to the 60 meters of RG-217 cables (8 in parallel) between the pulser and the capacitive load (the Pockels cell). This same waveshape shows up once again 600ns after the beginning of the third pulse. The secondary reflections return with lower amplitude another 600ns later. The reflections from the first pulse ride on the second pulse and the first reflection of the second pulse rides on top of the third pulse producing substantial distortion. Currently the triple pulse waveform barely meets the requirements as defined by the boxes. There is a desire to improve performance.

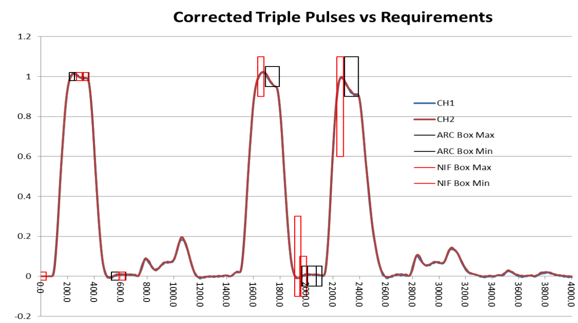

Figure 2 Expanded view of triple pulses and associated reflections. The units on the horizontal axis are in nanoseconds.

We are considering the following approaches to reduce the reflection effects on the waveform at the Pockels Cell.

3.1.1IMPEDANCE MATCHING

Attempts at only matching the load to the drive circuit met with limited success. More recently, it has been determined that a better method entailed adding a shunt impedance at the driver. (Note that the pulser looks like an open circuit to a reflection when the FETs are turned off, and looks like a low impedance if/when the FETs are on.) The location of this resistor, with respect to the pulser and transmission lines, is shown in the PSPICE model of Figure 3. In this model the SS SPG is represented by 3 ideal pulse generators; one for each pulse in the burst. The model captures the binary impedance behavior of the pulser via switch S1. When any of the three generators is on, the switch closes making the pulser look nearly like a short circuit. When all the three generators are off the pulser output looks like an open circuit.

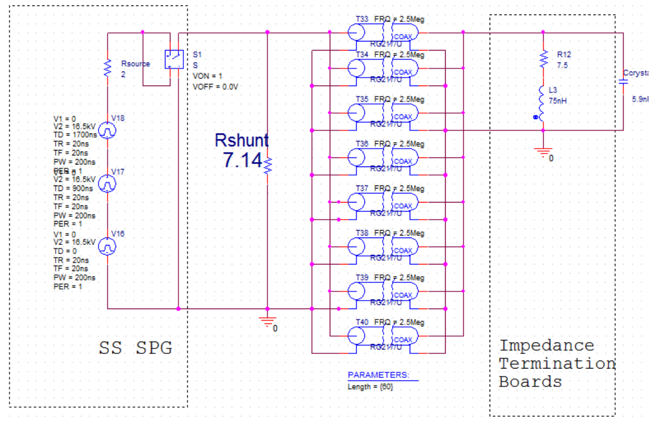

Figure 3 PSPICE model provides a simplified schematic of the SS SPG, the added shunt resistor, 60 meter transmission lines (8 each in parallel), termination board, and the capacitance of the Pockels Cell crystal.

The value of R_{shunt} was determined through a combination of PSPICE simulation runs and empirical tests using a pair of SS SPGs. A comparison of the waveforms with and without the shunt impedance is shown in Figure 4. The green trace illustrates the simulated performance without the shunt impedance. The red trace shows the effect of absorbing the load reflections at the driver. As a consequence the second and third pulses are much flatter and the intra-pulse regions are much quieter. Note that initial testing was limited to half voltage. Through modeling and testing we will pursue simultaneous optimization of the termination impedances at both the pulsers and the LRU to permit operating at full voltages while satisfactorily controlling reflections.

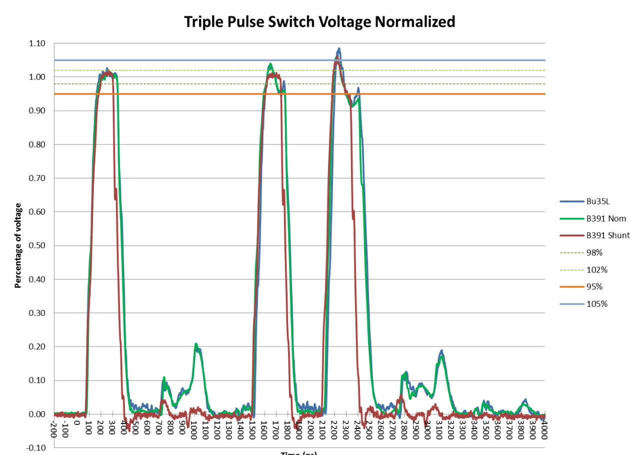

Figure 4 Having the matched impedance located at the pulser substantially reduced the reflected waveform amplitudes and reduced the distortion on the second and third pulse. The second pulse is the most critical to the mission. The red trace illustrated matched performance.

Note that we have also considered other following ways to reduce the reflection amplitudes:

- Increase cable length between the driver and load. The cable lengths could be increased eliminating the effects of load reflections at the pulser. Each of the cables would have to be increased by tens of meters. The packaging of the cable reels for 8 parallel cables would be very costly and very sizeable. In addition, the cable losses are significant enough to require more stages added to the pulser.
- Slowing the rise and fall times of the pulsers. Discussed in the next section.

3.2 DIODE FAILURES

In order to meet current timing requirements, the SS SPG turns on for the third pulse as a full amplitude reflection from the second pulse arrives. Measurements indicate that this can lead to free-wheeling diode failures. The free-wheeling diodes function is described in Figure 5. The diode failures have been traced to overvoltage stress from the reflected waveform transmitting through the transformer to the primary while the FET switches are turning on.

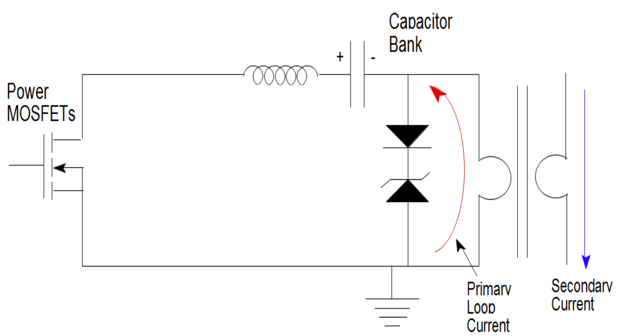

Figure 5 Simplified circuit of one of 27 stages shows the free-wheeling diode in series with a 38V transorb. The diode provides a path for induced current from the secondary, transformer leakage path, and a path for magnetization currents. The capacitor is typically charged to 700Vdc.

To protect the diodes, capacitive snubbers were soldered across each free-wheeling diodes as shown in Figure 6. These are ceramic disk capacitors with X7R dielectric.

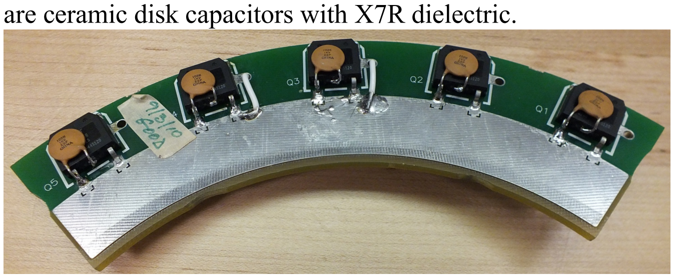

Figure 6. Free-wheeling diode boards; 5 diodes per board; each with snubber caps connected in parallel with the diodes. 4 of these boards are in connected in parallel for every stage.

The ESR of each capacitor is approximately 1 ohm. That spoils the Q of the circuit. The test results show that snubbers decreased the transient amplitude by almost 3 to 1, keeping the transient voltage below the 1200V rating of the diodes. Snubbers were implemented on all four pulsers and tested for over 100,000 triple pulse bursts without failure.

Other protection mechanisms that were considered:

- High Q mica capacitor with a separate damping resistor. However, the series connection of the resistor appeared to add too much inductance.
- Avalanche diodes with a 20 mJ rating were recommended by the diode manufacturer. We performed pulse testing that showed that they failed at energies lower than their 20 mJ rating but higher than the non-avalanche diodes.
- Transorbs with a sharp enough knee to keep the voltage below the rating of the diodes were quite expensive. Preliminary tests results showed some overshoot prior to the clamping action that could exceed the voltage rating of the diodes.
- Slowing rise and fall times of the SS SPG by increasing the gate drive resistance was tested on the bench for a single channel. The reflection amplitude could be reduced with slower rise and fall times. However this effort would require changing 5000 resistors.

3.3 HV ARCING

Discharges in the plasma between the PEPC cathode the grounded vacuum system were observed while triple pulsing. The HV discharges were occurring for approximately 1 in 10 pulses. This discharge results in collapse of switch pulse waveform (Figure 7) that fails to meet requirements and waveform analysis.

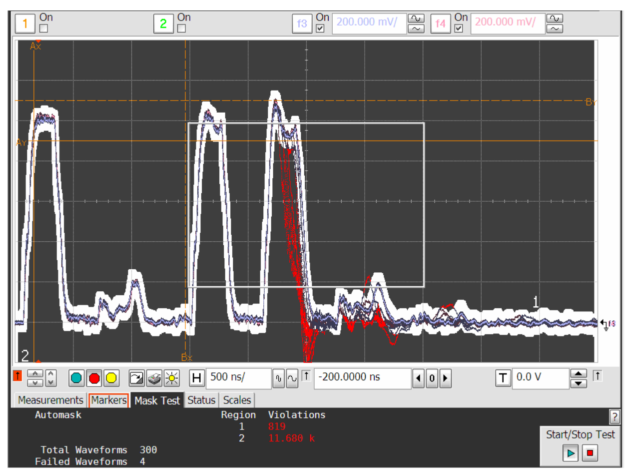

Figure 7 Overlay of thousands of shots shows the collapse the trailing edge of the third pulse in red.

The discharge is due to the cathode being at HV for an extended time allowing the plasma in the cell to migrate to the grounded vacuum system. The arc rate was reduced to an acceptable level by extending the path through the existing gas baffles and providing a ceramic vacuum insulator break in the gas line to ground, as illustrated in Figure 7. In addition, a HV conditioning procedure was developed to reduce the incidence of breakdowns.

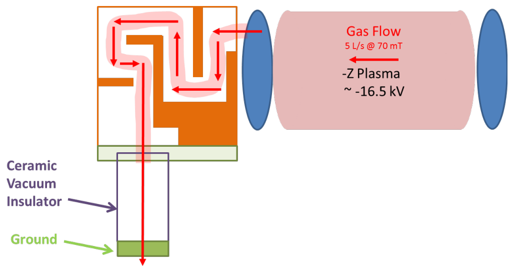

Figure 8 The Baffle path was extended and the ground was further isolated through a ceramic insulated gas line break.

4 SUMMARY

The component and HV break down solutions have been implemented and tested and have shown to work reliably.

- The capacitive snubbers have shown to be a very cost-effective solution in protecting the freewheeling diodes.
- The baffles, break, and conditioning procedure adequately reduces the HV arcing rate in the cell.
- Continue to look into improving the pulse wave forms by reducing the reflection amplitudes.
    - We are currently investigating the optimization of the impedance matching at the LRU to boost the signal amplitude.
    - We will be developing a more detailed model to understand the switching action effects on reflections.

ACKNOWLEDGMENT

Acknowledgements to Ed Cook for developing a pulser with the agility to accommodate the expanding mission space and Bernie Merritt for technical guidance and authorization of our testing effort. We also want to acknowledge Kenn Knittel for performing tolerance analysis of the triple pulse waveforms.

REFERENCES

[1] F. Barbosa, P.A. Arnold, G.B. McHale, G. James, G. Brown, E.G. Cook, B.C. Hickman *Development of Solid-State Drivers for the NIF Plasma Electrode Pockels Cell*, Proceedings of the IEEE International Power Modulator Conference, Las Vegas, NV, United States, May 2008.

[2]. F. Barbosa, P.A. Arnold, A.F. Hinz, C.W. Ollis, R.A. Zacharias, E.S. Fulkerson, C.L. Bishop, *Plasma Electrode Pockels Cell Subsystem Performance in the National Ignition Facility,* Proceedings of the 16th IEEE Pulsed Power Conference Albuquerque NM, 2007.

[3]. P.A. Arnold, F. Barbosa, E.G. Cook, B.C. Hickman, G.L. Akana, C.A. Brooksby, *A High Current, High Voltage Solid-State Pulse Generator for the NIF Plasma Electrode Pockels Cell*, Proceedings of the 16th IEEE Pulsed Power Conference Albuquerque NM, 2007.

[4] E.G. Cook, et al., *Solid State Modulator R&D at LLNL*, 1st International Workshop on Recent Progress in Induction.

This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344. This document has been released under LLNL-ABS-648506.