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Creating the Foundation of Next Generation Pulsed-Power Accelerator Technology

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Abstract

This SAND report covers the work performed under the “Creating the foundation of next-generation pulsed-power-accelerator technology” LDRD. This foundation consists of both foundational concepts and foundational components. Advances were made at both levels, with new machine concepts such as Thor and new machine components such has arc quenching charge resistors, laying a new foundation for pulsed power work at Sandia. This report attempts to summarize the numerous advances made at both of these levels under this LDRD over the last three years.

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1 Introduction

The intent of the LDRD entitled "Creating the foundation of next-generation pulsed-power-accelerator technology" is to develop those basic components and concepts from which our future vision of pulsed power will be built. Prototypes of several machine concepts were built and tested to evaluate their feasibility as the building blocks of more powerful, much larger machines in the future. Also, the present state of the art of the individual components, such as high voltage switches, capacitors, resistors, transmission lines and magnetic cores was advanced.

This report outlines six foundational machine concepts advanced under this LDRD and the numerous improvements made to the individual building-block components. These six machine concepts tie directly into our three main campaigns, which include radiography, material physics, and High Energy Density Physics (HEDP). Pluto and the advanced radiographic accelerator are directed at improving our country's radiographic capabilities. Thor and Neptune are proposed as new tools for exploring material physics [1, 2]. Z 300 and Z 800 are intended to advance fusion research, with Z 300 achieving thermonuclear ignition and Z 800 achieving high-yield fusion [3].

2 Pluto

2.1 Overview

Pluto is an LTD based machine design intended to improve our nation's radiographic capabilities. Some benefits of this advanced machine concept over conventional machines include a smaller footprint, simplified components, and safer operation. Pluto was designed with the intent of replacing Cygnus at the U1a facility in Nevada, and it was expected to achieve 100 times the dose of Cygnus within the same footprint. The machine design consists of 50 LTD cavities stacked in series driving a long coaxial impedance transformer which steps the voltage up to 12 MV on an SMP diode load. While Pluto was initially designed as an SMP diode driver for radiography, it could also be used to drive various loads.

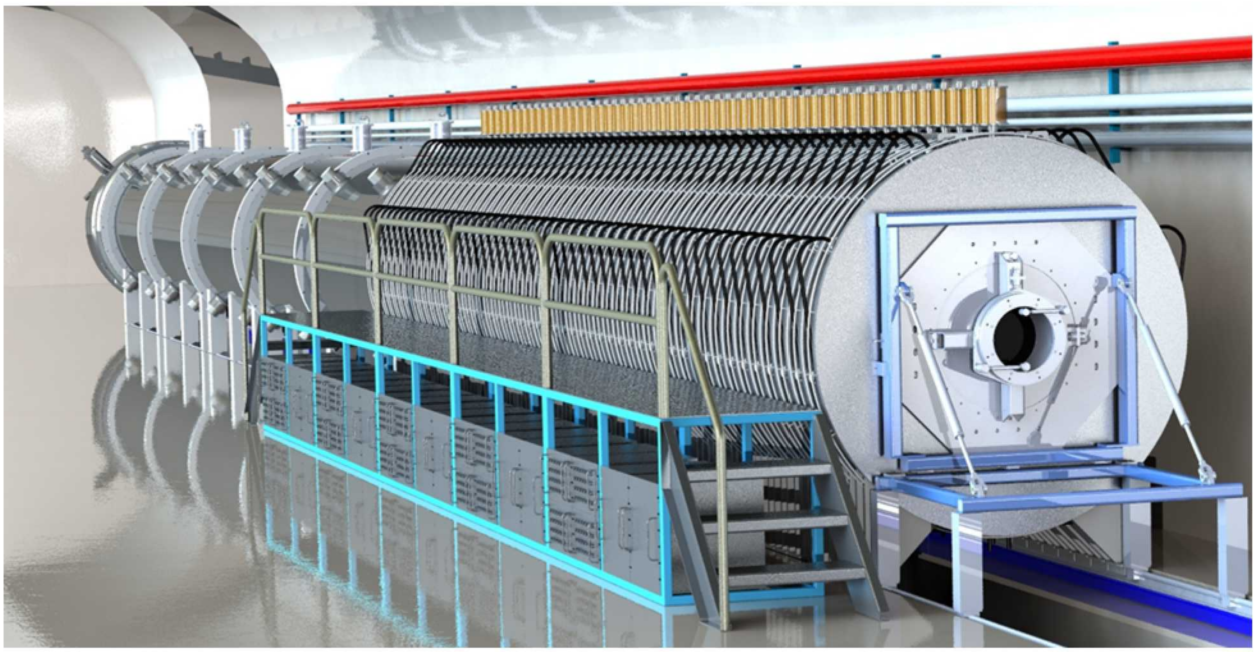

Figure 1. A rendering of the Pluto accelerator concept

2.2 Kinetech switch development

Switches are arguably the most foundational component of pulsed power machines, so naturally they were one of the first components we addressed in the LDRD. Kinetech LLC, ASR Corporation, and Sandia evaluated a new switch design for thousands of shots, reviewed its performance, and made changes as needed. Early switch designs exhibited reliability issues, such as loose electrodes, which were corrected in later versions. Following these corrections, the switch lifetime increased to approximately 10,000 shots. Several dozen switches were evaluated during this testing, but prefire rates varied considerably for reasons not uncovered during this test series. In addition to the switch improvements, the tests also measured the peak current and power output of an LTD brick. Waveform analysis of the discharges gave whole-brick inductance measurements. Besides the full-brick testing, another smaller test measured the inductances of individual brick elements. All these tests used a more inductive load configuration than would be found in a LTD-driven pulsed power machine, but the switch design improvements, discharge measurements, and component tests were all sufficient to provide a first-order estimate for LTD brick performance.

2.3 Arc quenching charge resistors

To achieve the high reliability needed for practical operation we must mitigate the consequences of a switch prefire. For example, a machine with 1,000 switches, each of which has a 1 per 1,000 prefire rate, almost guarantees that at least one switch will prefire and prevent useful operation. However, by simply increasing the resistance of our charge resistors from 1 kOhm up to >50 kOhms, we were able to quench the arc from a prefiring switch before the rest of the cavity discharged through it. Until now, two complications prohibited this simple fix. First, it's difficult to get a water resistor to work above 1 kOhm and still meet the spatial and current requirements of most pulsed power machines. Second, most machines use capacitors that store more than 10 kJ, which increases the energy handling requirement of the charge resistors.

Switching to solid-state resistors and using smaller capacitors which store less than 1 kJ makes this advance realizable. Using the new solid-state resistors and the smaller LTD capacitors, we can consistently quench switch prefire arcs and reduce the impact of this failure mode. Eliminating water resistors significantly reduces routine maintenance, as water resistors tend to have lifetimes of less than two years. Furthermore, the lack of water in the resistor eliminates the risk of spilling water into the oil-filled LTD cavity in the event of a resistor failure. The new resistor design has been submitted for patent.

2.4 Radial vacuum insulator stack

The Pluto concept requires the center stalk of the machine to be liquid-insulated up through the impedance transformer but the diode must operate in vacuum. Thus, a novel radial vacuum insulator stack is required for this concept to work. Radial vacuum insulator stacks have been built before, but this new stack would have to operate at a much higher stress in order to fit within the U1a tunnel. We designed a new insulator stack which uses dielectric lensing to distribute the field equally across the stack and increase its voltage hold-off. The effort was then shifted to program funds and a small-scale stack was built and tested for hundreds of shots, holding off higher field stress than expected from flashover scaling relations.

2.5 LTD IV testing and results

A Pluto prototype cavity was assembled from LTD III hardware and called LTD IV. We changed the capacitors to 40 nF capacitors and we changed all the switches from S^2 switches to Kinetech switches. The cavity was tested for over 100 shots to see if we could meet the switch prefire, no-fire, and jitter requirements needed to build Pluto. The relatively fast rising pulse of the Pluto design gives a narrower time window to close all the switches simultaneously. This was one of the primary concerns the LTD IV tests addressed, since correcting for this narrower time window can make balancing switch prefires and misfires more difficult. However, the testing was successful and we presented the results to NNSA.

3 Advanced radiographic accelerator

3.1 Overview

The advanced radiographic accelerator is a transmission line based accelerator concept intended to improve our nation's radiographic capabilities. The machine uses switched transmission lines to generate individual square electrical pulses that generate time-adjustable x-ray pulses. The transmission lines and switches used are the heart of the machine and thus are worthy of our best development efforts. The design and component development was solid enough that it has become the chosen concept for Sandia's radiographic development has been transferred over to campaign 3 (C3).

3.2 Switch loss measurements

In order to generate a square pulse with a fast rising edge and a flat top the pulse controlling switch has to rapidly transition from an open to a closed state. How a switch arc's resistance changes over time is a key pulsed power question which has been studied over many decades. It is especially germane to radiographic machines since the switch resistance heavily influences the rising edge. Interestingly, even though the question has been around for many decades, the vast parameter space of operating voltages, gap distances, insulating gases used, switch pressure, driver impedance, available current, and rise times requires empirical testing to verify driver performance.

To this end, a number of switch prototypes were built and tested which covered a wide range of parameters. Switch gaps, switch pressures, and charging voltages were scanned over a wide range. Transmission lines were tested with a wide range of impedances, and various switch gases were tested; air, argon and air mixtures, and sulfur hexafluoride. In summary, we found that minimizing the switch gap and operating at the highest possible voltage yielded the fastest rising edge and flattest top. For most switch configurations of interest, Tom Martin's switch arc resistance model gives an accurate prediction of the arc resistance.

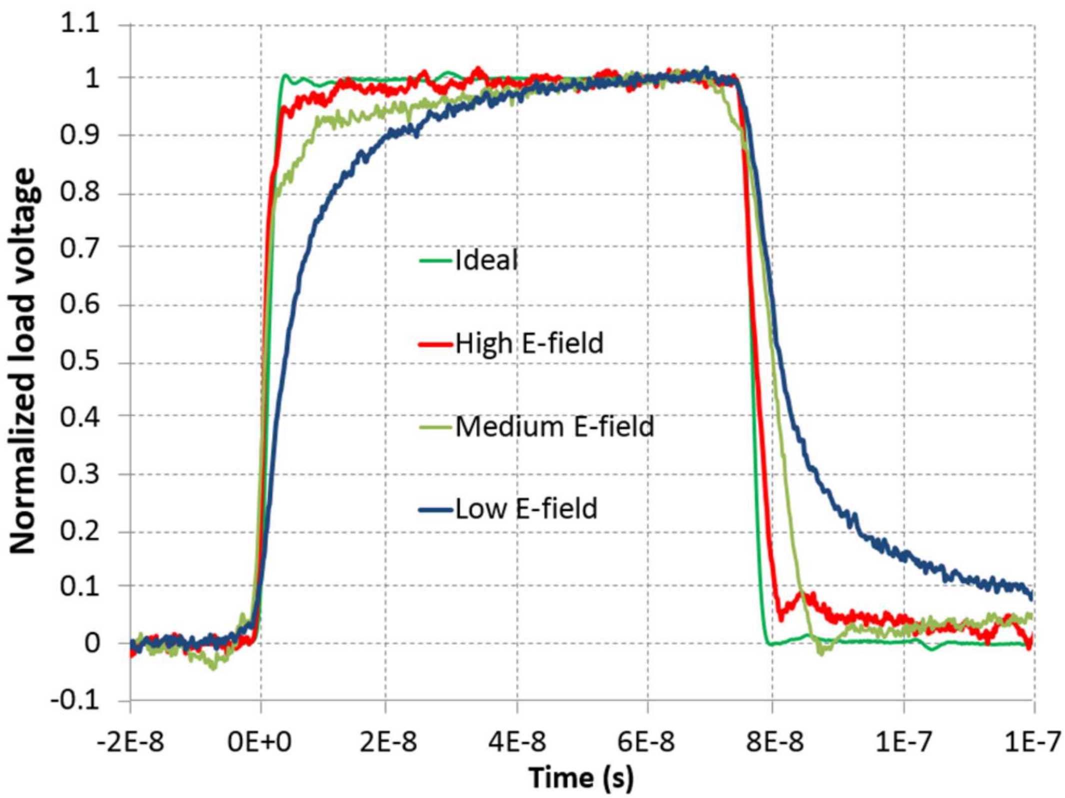

Figure 2. Switch arc formation affects output rise time

3.3 Cable attenuation and dispersion measurements

In addition to the pulse distortion caused by the switch arc formation over time, the transmission lines add two more effects: attenuation and dispersion. These are two critical parameters which significantly impact the accelerator's design. We sampled a variety of commonly used cables to better understand how to design a custom transmission line for this application. For instance, many cables rated for voltages above 100 kV have a semiconducting layer around the inner conductor to make a smooth bond with the insulator to decrease its probability of breakdown. However, this layer could also increase transmission line attenuation and dispersion so it was important to measure its impact on a representative pulse.

3.4 Diagnostic development

Due to the relatively fast rise time of the pulses measured for this machine and the 1% accuracy requirement, it was important to ensure we were using the best diagnostics possible to measure driver performance. Unlike the previously conducted LTD work on Ursa Minor, these new signals have much higher frequency content and signal cable compensation had to be added to get the accuracy we needed. We evaluated several alternative configurations of b-dots, v-dots, CVRs, and Pearson coils to select which proved most accurate. Based on what was available at the time, the CVRs made by T&M research seemed to be the most reliable, consistent, and accurate for recording these pulses. Testing and diagnostic improvements will hopefully continue under C3.

4 Thor

4.1 Overview

Thor is an LTD brick-based machine concept intended to improve our nation's material-physics programs. The basic concept is to use individual bricks to drive cables, which transit time isolate the individual bricks. This timing separation allows for arbitrary pulse shaping within the transit time isolation window, ~500 ns for the present Thor configuration. The current from all of the cables is then combined in the water-filled Central Power Flow (CPF) and fed into a single pair of plates insulated by a solid dielectric. This final solid-insulation radial transmission line then feeds the simple strip line load where the magnetic pressure can reach ~1 Mbar. Shaping the current pulse by shifting the brick timing allows for shaping of the pressure pulse and thus opens up a new range of shockless material-physics experiments. The machine design is more thoroughly explained in a recent publication [D.B. Reisman, *et al.,* Phys. Rev. ST Accel. Beams **18**, 090401 (2015)].

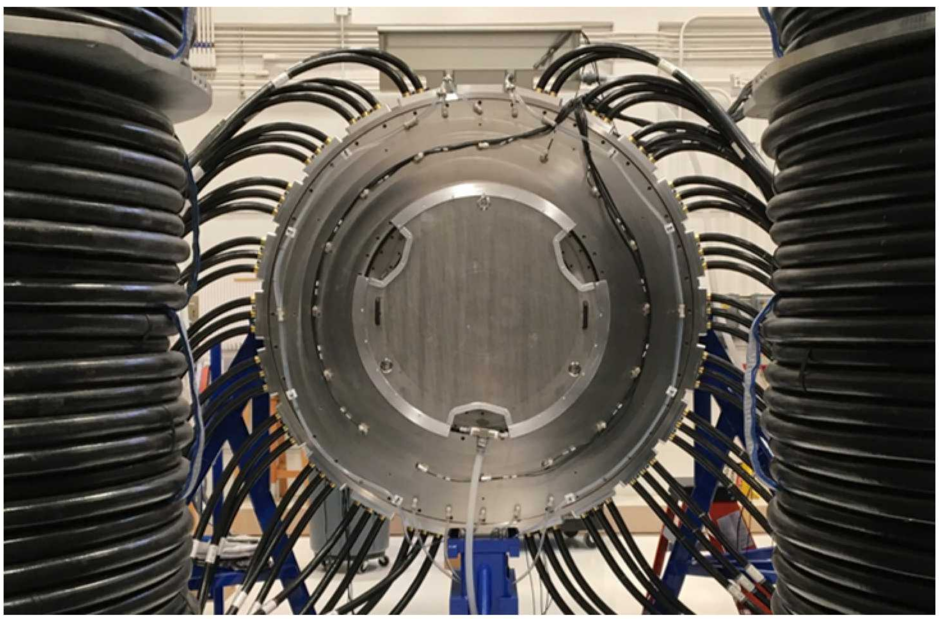

Figure 3. A rendering of the Thor concept

Reisman et al., "Pulsed Power accelerator for material physics experiments" 10.1103/PhysRevSTAB.18.090401 (2015)

4.2 Cable development

The key concept that makes Thor stand out amongst other similar machines is transit time isolation of the switched components, and the component that enables this feature is the cable. At present, using conventional cable designs, transit time isolating the bricks by 500 ns, which requires at least 250 ns of cable, means the cables have to be at least 140' long. This value is set by the propagation velocity of an electrical wave in the cable which is driven by the dielectric constant of the cable's insulating material. If this dielectric constant can be increased, then the wave can be slowed, and the cable can be shortened proportionally while still achieving the desired time isolation. One additional benefit to increasing the dielectric constant of the insulation is that it also reduces the impedance of the cable. Reducing the impedance by a factor of two allows us to use half as many cables, which in addition to the length reduction has a dramatic impact on the size of the Thor machine.

David Reisman has been working with Dielectric Sciences to develop cable insulation with a higher dielectric constant, which would allow us to realize these benefits. Under funding from this LDRD Dielectric Sciences was able to mix nanoparticles in with polyethylene and bump the relative dielectric constant up from ~2.3 up to 10. The new material still had a reasonably high dielectric strength, was reasonably flexible, and could be extruded onto a wire. Based on these positive results, testing will continue after the closing of this LDRD, and we will attempt to field a cable made from such material on Thor.

4.3 Drywell connection development

In an effort to make Thor a user friendly and maintainable machine, we attempted to use a "drywell" connection on both the water filled CPF and the oil filled brick towers. This "drywell" allows us to pull cable, replace cable, or reconfigure without draining either the oil in the brick towers or the water in the CPF. Also, this barrier protects the cable from interacting with either the oil or the water, which would damage the cable over time.

The most significant problem with a drywell connection is that, given the same dimensions, it is electrically weaker. During testing on Thor 1, we would consistently "flash" the drywell surface when shooting at 100 kV with 50% reversal. It's believed that charge is emitted off of the high E-field regions of the electrodes during the initial pulse and deposited on the insulator surfaces. The total track length is long enough that this charge doesn't result in a breakdown, but once the pulse reverses the resulting E-field is even higher as a result of the charge stored on the insulator surface and a breakdown occurs.

The solution to this problem was to install a thin semiconducting layer on the cable down the length of the drywell. This semiconducting layer seems to allow the initial deposited charge to move and redistribute in such a way that a breakdown is prevented once the polarity flips from the reflection.

4.4 Oil diverter

Another issue with the Thor design is that large capacitor reversals on the late fired bricks are possible when pulse shaping. Capacitor voltage reversals on the order of 100% are possible, which would certainly result in unacceptable capacitor failure rates. One solution is to use an oil diverter at the brick's output. Testing was conducted on Thor 1 using a 1 mm oil gap, a 5 Ohm dump resistor, and a point-plane geometry. It was found that, with these settings, we could consistently clear the main drive pulse yet have the oil gap close upon reversal. A system like this could clearly work to protect the late time capacitors from high voltage reversals. Future brick tower designs will likely include such a feature.

4.5 Thor 1, Thor 8, Thor 16, and Thor 24 testing

Thor 1 was completed in May 2015 and has tested the first eight bricks installed in Thor 8 for over 1,000 shots each. This initial testing provided us a measurement of the infant mortality, random, and end of life failure rates for the switches, capacitors, brick towers, and cables. We were also able to use it to develop the drywell sockets and the oil diverter. As a result of this successful testing, the Thor concept was transferred over to program funds. The following comments related to Thor 8, Thor 16, and Thor 24 work, though they were conducted using program funds, are presented to show the impact of the Thor LDRD work.

Thor 8 was completed in May 2016. These were the first shots taken with multiple bricks inhabiting the same tower. These were in the full experimental configuration consisting of brick towers, cables, central power flow, and a representative ICE strip-line load. The shots went well and the output was as expected. We took about 50 shots with limited diagnostics on the load and CPF.

Thor 16 was completed in August 2016. These were the first shots taken with a PDV diagnostic and the full complement of CPF voltage and current monitors. The shots went well and the output was as expected.

The 24-brick version of Thor (Thor-24) was commissioned on September 22nd. The experiment was fired at +/-50 kV (half-voltage) in the full experimental configuration. 100% data return was obtained from current and voltage monitors. PDV data was returned from the load. All data was consistent with circuit modeling, thus validating all major elements of the Thor design.

5 Neptune

5.1 Overview

The ZR machine uses conventional, state-of-the-art, pulsed power technology to achieve high pressures. Recently, we have developed the "current adder" architecture to overcome some of the limitations of standard pulsed-power machines. One of these limitations is the difficulty in producing tailored pulses with internal voltage reflections from the closely coupled Marx banks. Another limitation is the energy delivery inefficiency caused by the need for multiple stages of pulse compression.

We have extended the current adder concept to design a machine capable of 1 TPa (10 Mbar) level performance. This machine, called Neptune, consists of N=600 independent impedance-matched bricks. Each brick is an 8-stage Marx generator (the case of m=8 in Eq. 2 and 3) which produces a 52 kA current pulse with a rise time of 100 ns. Neptune stores 4.8 MJ of electrical energy in its brick capacitors. A τ=450 ns long water insulated coaxial transmission line transports the power generated by each brick to a system of 12 electrically parallel water-insulated conical transmission lines. The coaxial lines ensure that transit-time isolation is maintained for the clear time of τ=900 ns. Impedance matching is maintained between the bricks (Z_B) , the coaxial lines (Z_1), and the system of conical lines (Z_W). This can be expressed as

$$Z = \frac{Z_B}{N} = \frac{Z_1}{N} = Z_W$$

where Z is the effective impedance.

The conical water lines are connected electrically in parallel by a water-insulated convolute. The convolute sums the electrical currents at the conical lines, and delivers the combined current to a single solid dielectric insulated radial transmission line, called the central power flow (CPF). The radial line in turn transmits the combined current to the physics load.

The intent for Neptune is to be able to off-load material-physics shots from Z and field them less expensively on a smaller, yet more capable machine. The design is thoroughly explained in a recent publication [W.A. Stygar, et al., Phys. Rev. Accel. Beams **19**, 070401 (2016)].

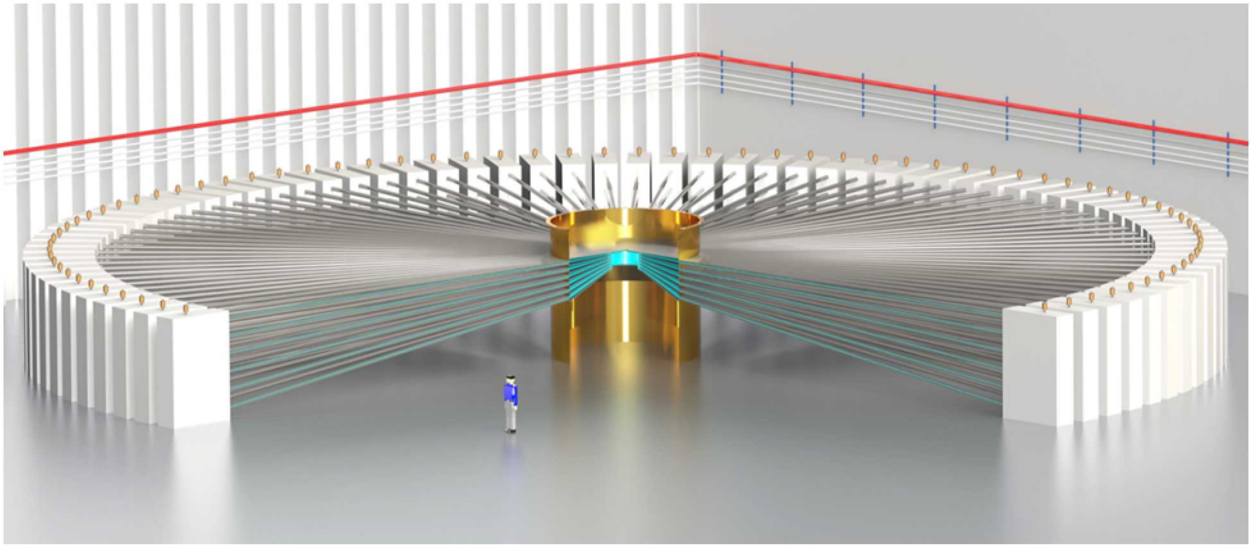

Figure 4. A rendering of the Neptune accelerator

Stygar et al., “Conceptual design of a 1013 W pulsed-power accelerator for megajoule-class dynamic-material-physics experiments” Phys.Accel. Beams 19, 070401 (2016)

6 Z-next LTD cavity and Z-300

6.1 Overview

The Z-next LTD cavity is the foundational component of Z 300, which is a ~300 TW accelerator concept capable of thermonuclear ignition and the planned successor of the Z machine. As the foundation of this enormous machine, the Z-next LTD cavity must be reliable to the extreme and as electrically and spatially efficient as possible. A number of advances were made under this LDRD which impact reliability and efficiency at the LTD cavity level and they are listed below.

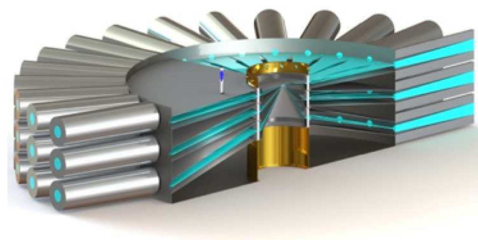

Figure 5. Rendering of the Z-300 accelerator

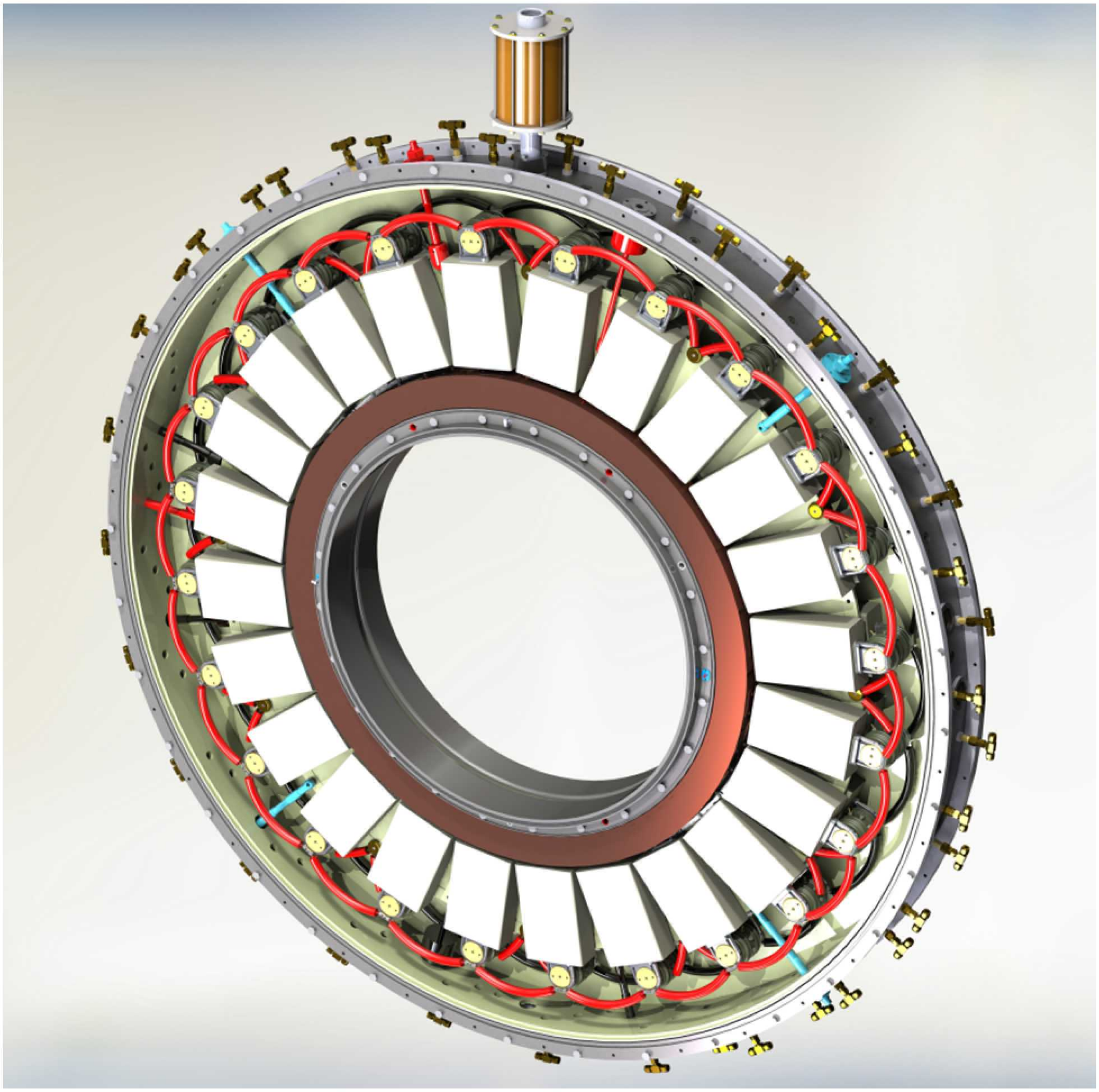

Figure 6. Rendering of the Z-next LTD cavity

6.2 Thin solid insulators developed

In the effort to reduce the brick inductance and also the overall size of the cavity, the space between capacitors and the distance between switch electrodes has been reduced. However, we're still charging to 100 kV, so the electric field stress has increased and yet we still need to achieve the same reliability. One solution to this problem is to not rely on the oil's dielectric strength alone, but rather to add a thin solid insulator to the stressed area.

This thin insulator has a higher dielectric strength than the bulk oil, but also, it is a barrier to the flow of oil caused by charged trapped in it. Inhibiting this flow seems to significantly reduce the probability of rare, abnormally low voltage breakdowns. The thin insulator, made of Mylar or some similar material, isn't intended as a means to increasing the average voltage hold off of an oil filled gap, but rather as a means of reducing the probability of rare "low stress" breakdowns which seem to occur in oil even at stress levels <50% of the average breakdown stress.

These thin solid insulators, or "skirts" as we refer to them, have been fielded on the single-brick tester and we've noted a reduction in the rate of oil arcs near the switch and capacitors. Presently, we've built the Z-next LTD cavity using these skirts on all of the switches and we'll soon learn how they perform in a full cavity.

6.3 Core material development

As part of the LDRD, department 1132 "Nanosystems Synthesis/Analysis" worked on developing a new nanocomposite material for magnetic cores using superparamagnetic nanoparticles. One benefit of this new material is that it has a high susceptibility yet is remanence-free, which means that it provides a large blocking inductance yet it doesn't have to be reset after each shot. If a machine could be built using this new core material, there wouldn't be a need for pre-magnetization generators to flip the magnetic domains back after a shot. Interestingly, these new cores could have a huge impact on multi-pulse LIAs if the magnetic domains could randomize before the second pulse arrives. This feature could result in huge cost reductions for such a machine. As of the close of the LDRD, department 1132 had successfully built a small scale core and was working to refine the technique needed to build larger scale cores. As a result of their success, their work will continue under project funds moving forward.

6.4 2D LSP particle-in-cell switch model

As part of the LDRD, Voss Scientific ran the first ever 2D LSP particle-in-cell switch simulations to better understand how the switch functions in the first phases of triggering and arc formation. The model included processes like photoionization and could make predictions for the voltage and current across the switch gap over time. The work conducted by Voss sets us up well if we wished to further develop the model moving forward.

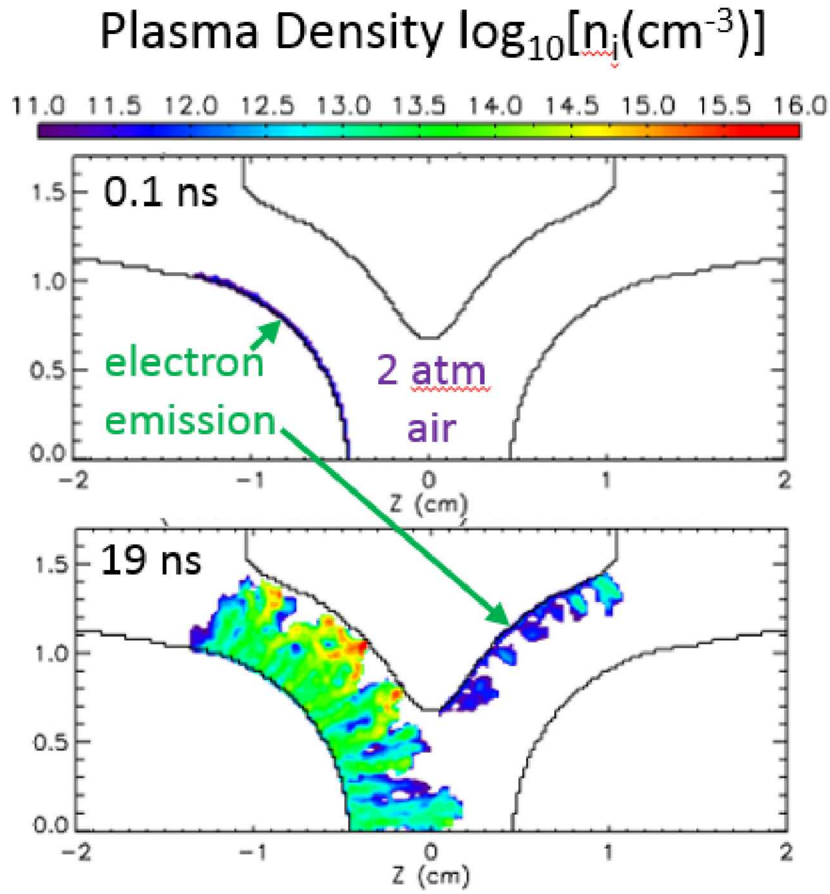

Figure 7. Plots of electron density in a gas switch at 0.1 ns and 19 ns

6.5 Switch testing on the single-brick tester

Over the past 3 years, in addition to the Kinetech switch development performed at ASR, we've conducted switch testing on our single-brick tester and have logged something over 100,000 shots. One goal of these tests is to consistently demonstrate a switch prefire rate of <1 in 1,000 shots. We achieved this goal by increasing switch purge time, improving switch air quality, and specifying the machining and handling procedures for the switch electrodes at a level similar to that used on the Z load hardware. Early switch testing at ASR purged the switch for 1 second, but by increasing purge time to 10 seconds, and adding an ultra-high-purity filter in the switch air inlet, the prefire rate improved from about 3 per 1,000 shots to <1 per 1,000 following a 100-shot conditioning period. Furthermore, the oils used to machine the parts, the cutting speed, the post-machining cleaning protocols for the electrodes, and switch assembly procedures were all explicitly called out. These improvements will yield more repeatable and reliable switches. Going forward, we will continue to explore the causes of switch prefires and how to mitigate them further.

6.6 Developed capacitor vendors NWL, GA, CSI

In an effort to strategically set Sandia up for a major project like Z 300, we engaged with three capacitor vendors to evaluate and improve their present capacitor products. To that end, we have purchased and tested capacitors from NWL Capacitors, General Atomics, and CSI Technologies.

Additionally, we have collaborated with them to develop their own in-house LTD brick test stands where they can rapidly evaluate new designs without needing to rely on Sandia for feedback. We have also developed a low-voltage, standard method for measuring capacitor inductance when assembled in the LTD brick geometry (i.e. two stacked capacitors surrounded by a nonconductive material). We did this because each vendor's inductance test method is unique, which complicates product comparison and benchmarking. We intend to use this new measurement method to compare capacitor inductances, since it is most applicable to our end use and ensures an objective comparison.

6.7 Cavity testing

In addition to the smaller component testing mentioned above, a full scale cavity was designed, fabricated, and assembled. The new cavity design is the most energy- and power-dense design to date and it includes a few new features. For instance, the new cavity has built-in voltage and current monitors embedded in the output electrodes such that the cavities can still be stacked in a module without sacrificing the diagnostic. These monitors should return the best individual cavity output signals to date.

Also, we have created a novel tapered middle insulator, which is designed to reduce inter-capacitor gap inductance without sacrificing voltage hold-off. This new insulator is the first of its kind, and it has the potential to become the new standard.

Finally, the control system of the cavity test stand is the most advanced to date. A National Instruments cDAQ control chassis is the heart of the control system, and automatically manages pressurization, charging, triggering, data acquisition, switch purging, and shutdown. The software monitors and records the charge voltages and switch pressure during the charge sequence, which provides an additional pre-shot diagnostic. The software architecture is the same as that of the single-brick tester and Thor, making this software highly portable and easy to use across all these next-generation pulsed-power facilities.

The first shots on the new cavity should be conducted in early October, 2017.

7 Z-800

7.1 Overview

The Z 800 is an ~800 TW accelerator concept capable of achieving high-yield fusion. As can be seen from the image, it is simply a scaled up version of Z 300, and as such, everything learned from Z 300 will directly impact the design of Z 800. Like Z 300, Z 800 is driven by 90 LTD modules, but each module now consists of 60 cavities in series (up from 33) and each cavity now has 30 bricks (up from 20). The design is more thoroughly explained in the following reference: Stygar et al., PRSAB 18, 110401 (2015)

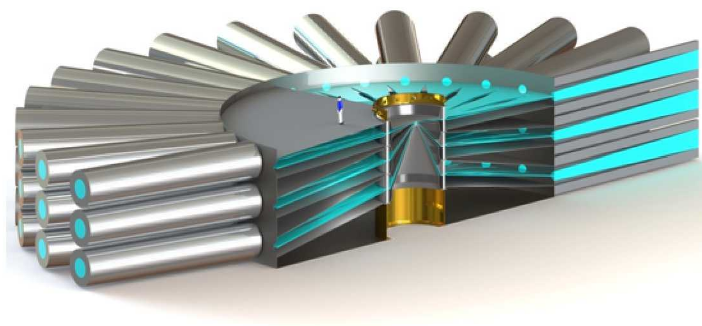

Figure 8. A rendering of the Z 800 accelerator capable of high-yield fusion

8 Summary

This LDRD was very successful as evidenced by the number of LDRD machine concepts transferred over to project funds. This investment in foundational machine concepts and components is certain to impact the future of pulsed power at Sandia. Three peer-reviewed journal articles and two patents have emerged from the vast body of work completed over the past three years of funding under this LDRD.

9 References

1. Reisman et al., "Pulsed Power accelerator for material physics experiments" 10.1103/PhysRevSTAB.18.090401 (2015)
2. Stygar et al., "Conceptual design of a 10^{13} W pulsed-power accelerator for megajoule-class dynamic-material-physics experiments" PRAB 19, 070401, Jul (2016)
3. Stygar et al., "Conceptual designs of two petawatt-class pulsed-power accelerators for high-energy-density-physics experiments" PRSAB 18, 110401 (2015)

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