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Pulsed Power:
Sandia's plans for the new millennium*

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Abstract Pulsed power science and engineering activities at Sandia National Laboratories grew out of a programmatic need for intense radiation sources to advance capabilities in radiographic imaging and to create environments for testing and certifying the hardness of components and systems to radiation in hostile environments. By the early 1970s, scientists in laboratories around the world began utilizing pulsed power drivers with very short (10s of nanoseconds) pulse lengths for Inertial Confinement Fusion (ICF) experiments. In the United States, Defense Programs within the Department of Energy has sponsored this research. Recent progress in pulsed power, specifically fast-pulsed-power-driven z pinches, in creating temperatures relevant to ICF has been remarkable. Worldwide developments in pulsed power technologies and increased applications in both defense and industry are contrasted with ever increasing stress on research and development funding. The current environment has prompted us at Sandia to evaluate our role in the continued development of pulsed power science and to consider options for the future. This presentation will highlight our recent progress and provide an overview of our plans as we begin the new millennium.

I. Introduction

The fast (submicrosecond) Pulsed Power Program began at Sandia over thirty years ago to test the response of components to hostile radiation environments. Pulsed power generators were developed to produce photons (from sub-keV to multi-MeV) and charged particle beams. The applications of fast pulsed power have grown to include indirect-drive Inertial Confinement Fusion (ICF) and Inertial Fusion Energy (IFE), industrial applications (e.g., materials processing and electromagnetic sterilization), and diagnostics development (e.g., radiography). The common element is efficient conversion of stored electrical energy into short bursts of radiation or charged particle beams.

Over time, pulsed power has achieved higher energy densities, driven by a variety of applications enabled by technological innovations. The international interest and investment has created a wealth of ideas and accomplishments. The driving force behind Sandia's pulsed power programs has been x-ray generation. The two major applications requiring high-energy-density x-ray sources are testing electronics for hardness against an intense x-ray burst and ICF. Recent successes with fast z pinches have exceeded the evolutionary improvement cycle with a revolutionary rise in the available x-ray energy and power. The possibility exists for a renaissance in pulsed power; we may, in fact, already be in the early stages of a new era

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in this technology. Such radical change in performance demands a rethinking of the strategy for developing these high energy density environments.

At Sandia, we have been engaged in outlining a strategy for the development and application of fast pulsed power for the Department of Energy's programs. In the near term, the strategy emphasizes the application of pulsed power to today's problems. The long-term goal is to achieve high-yield (~ 1 GJ) fusion in the laboratory to enable a substantially enhanced capability to understand and mitigate the effects of radiation on components and realize the potential of inertial fusion energy.

II. X-ray Generation and Applications

Recent advances in pulsed power have increased the capabilities of existing facilities and enabled a rapid growth in applications. Some examples are described below.

a) Z-pinch x-ray sources

Pulsed power accelerators driving fast z pinches now routinely produce x-ray power more than five times greater and energy one hundred times greater than any other existing laboratory device. Since 1995, radiated x-ray power and energy from fast z-pinch implosions have increased substantially [1]. Z, the most powerful and energetic fast z-pinch driver, has produced total radiated x-ray power of 250 ± 40 TW and total radiated x-ray energy of 1.8 ± 0.2 MJ. An x-ray source of this output enables a wide variety of applications. For example, the x-ray pulse can be used to heat hohlraums and create large-volume, long-lived sources of Planckian radiation for ICF studies. Alternatively, by placing an axial hole in the current conductor at the end of a z pinch, a hot, radiating disk region is created, and experiments requiring a high temperature but single-sided source can be fielded [2]. Besides ICF, this source has been used to create shocks in materials for equation-of-state studies [3] and to generate opacity data for astrophysical research [4]. Figure 1 shows the rise in x-ray power and hohlraum (volume)/radiation source (surface) temperature as a function of year.

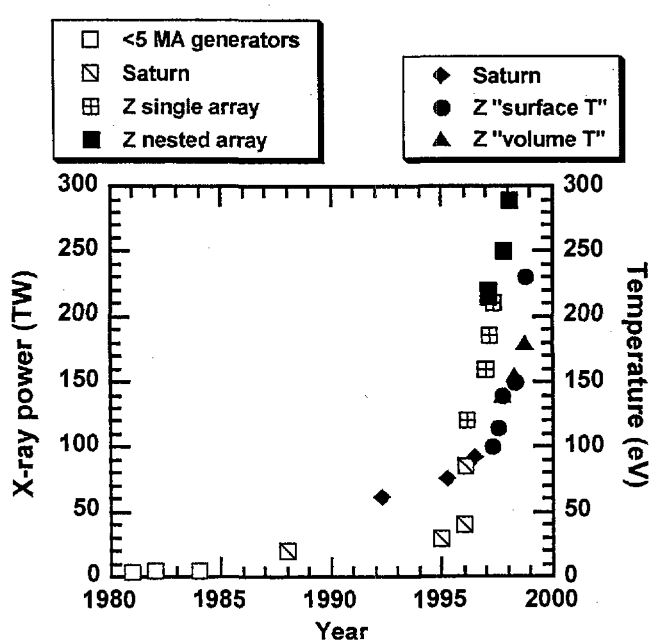

Figure 1. Increase in radiated x-ray power and radiation temperature vs. year

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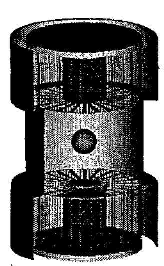
Some applications require non-Planckian spectra. Progress in increasing the K-shell yield from low-atomic-number plasmas has also been dramatic [5]. Radiated energy in the few keV part of the spectra has increased by over an order of magnitude in the past few years. The advance in x-ray power from z pinches has been documented extensively [6]. Research efforts are underway to increase our understanding of the physics that governs the pinch behavior. This work is being carried out in many institutions. In depth understanding of pinch initiation phenomena, implosion dynamics, and stagnation is being obtained in experiments that span the range from a few-wire implosions at a few kA to implosions of an array of 300-400 wires on the 20 MA Z accelerator. An example of this work is the study of wire initiation being done at Cornell University, Imperial College, and the Naval Research Laboratory.[7]. Complementary developments in diagnostics, analytic theory, and large-scale, multi-dimensional computer simulations are adding to our understanding of z-pinch physics.

b) Radiographic x-ray sources

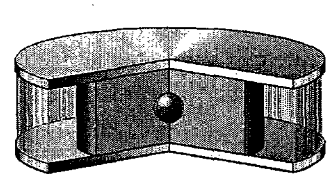
Fast pulsed power was developed by the British in the 1960s to provide a high brightness, penetrating flash radiographic capability. X-ray generation for radiographic imaging has also advanced recently with the achievement of sub-millimeter radiographic spot sizes using a carefully controlled electron beam diode [8]. The SABRE (10-MV, 250-kA, 40-ns) Inductive Voltage Adder (IVA) accelerator was used to demonstrate the proof-of-principle concept, producing a 1.5-mm-diameter x-ray source spot. The HERMES IVA (20-MV, 800-kA, 20-ns) accelerator was later modified to drive a 12-MV, 120-kA, 100-ns radiographic source that yielded a several mm-diameter source. SABRE has been modified to demonstrate radiographic technologies at 2.5 MV, 50 kA, 70 ns and has recently achieved a dose of > 1 rad at 1 m with a source spot diameter of < 1 mm and an end point energy of 2 MV. Further improvements at increased voltage are possible.

c) Inertial Confinement Fusion and Inertial Fusion Energy

The long-term goal of the US ICF program is to produce a fusion yield of > 200 MJ in the laboratory. Two-dimensional target design calculations have indicated that these yields can be reached in an x-ray-driven capsule that absorbs in excess of 1 MJ from a temporally-shaped x-ray pulse in a radiation environment that is spatially uniform to within 1%. A > 10 MJ x-ray source is required to drive a high-yield capsule. Multi-lab simulations and experiments have increased our confidence that pulsed power can provide a cost-effective path to high yield. The key next step to the z-pinch approach is to demonstrate adequate radiation symmetry to drive high-convergence-ratio capsule implosions in scaled experiments. Three different conceptual designs have been considered and two are are shown in Figure 2.[9]



Z-Pinch-Driven Hohlraum



Dynamic Hohlraum

Figure 2. Two concepts for driving ICF capsules with z pinches.

The baseline approach chosen is the z-pinch-driven hohlraum (ZPDH) concept. Design calculations predict that the required conditions can be achieved in a ZPDH configuration where the two opposed z pinches produce a total of 16 MJ of x-rays. Scaled experiments on Z have produced 1.0 MJ of x rays in 7 ns in a hohlraum containing the z pinch, demonstrated adequate x-ray transmission efficiency from the pinch-containing hohlraum to the hohlraum that would contain a capsule, and validated the energy balance in the hohlraums.[10)] The pulse shaping concepts has been demonstrated experimentally in principle.[11)] The fraction of the x-ray energy delivered to a diagnostic foam capsule within the hohlraum is in good agreement with code calculations. Furthermore, design calculations of the dynamic hohlraum (DH) configuration [12)] in which the capsule is embedded inside the pinch itself and the pinch material acts as the hohlraum (also shown in Figure 2), predict that high yield can be achieved with the energy equivalent of less than 10 MJ in the radiation field. The DH configuration is more efficient than the ZPDH configuration, because it relies on an integrated coupling of the capsule to the z-pinch implosion but, as a result, is subjected to asymmetries induced by the magneto-Rayleigh-Taylor instability of the imploding pinch. The research goal for both hohlraum concepts is scaled experiments that demonstrate adequate radiation symmetry for high-convergence-ratio capsule implosions. We believe that fusion energy, in particular IFE, will grow in importance with time. The IFE community is pursuing several different technologies for energy applications and, as yet, no specific driver has been chosen. The z-pinch approach provides a reproducible, energy-rich environment in support of IFE research. In June 1999, a two-week meeting dedicated to fusion energy issues and sponsored by the American Physical Society was held at Snowmass, Colorado. IFE concepts were presented by various institutions. Sandia's presentations utilizing repetitive z pinches attracted community interest.[13)]

III. Other pulsed power applications at Sandia

Sandia's pulsed power facilities have been used in a variety of other applications. The large current available on Z, for example, has been used to create a magnetic-field-produced pressure pulse of 130 kbars in copper and 300 kbars in iron.[14)] More recently, we achieved 1.5 Mbar in aluminum. Since the current rises over the 100 ns of the Z pulse, this technique allows for isentropic compression experiments (ICE) on a variety of materials. The magnetic field has also been used this year to accelerate flyer plates to velocities in excess of 10 km/s, above that achievable with conventional gas guns [15)]. This development enables shock wave studies at pressures > 1 Mbar with accuracy of a few percent. Electron-beam-based heating to increase the enthalpy and, thus, the effective velocity in a hypervelocity wind tunnel is being pursued in partnership with Lawrence Livermore National Laboratory, Princeton University, and MSE Inc., and is funded by the Air Force hypervelocity wind tunnel program [16)]. Pulsed power driven lightning simulators are being used for a wide variety of lightning safety and lightning effects work.

The Repetitive High Energy Pulsed Power (RHEPP) program provides a technology base for both IFE and commercial applications of pulsed power technology. RHEPP-1 demonstrated the HELIA-, SABRE-, HERMES-style IVA architecture at 250 kV per induction cell, providing 500-kV, 10-kA, 100-ns pulses at < 5 Hertz. RHEPP-2 extended this approach to 2.2-MV, 25-kA, 60-ns pulses at 120 Hertz, and has demonstrated component lifetimes of several million shots. Repetitive pulsed power systems, which typically operate at 1 to 100 Hz at a high average power (300kW), have been used as electron and radiation sources for industrial processing, including polymers, elastomers, and surface treatment. Surface treatment could reduce the electron emission on surfaces for the next generation of pulsed power devices. High radiation dose rates have been used to study the radiation rate effects on the pasteurization of food. A repetitive, large-area electron beam source is being developed for the KrF laser ICF program.

IV. Future Plans for Pulsed Power at Sandia

a) Z-Beamlet

The next major facility being added to the pulsed power program at Sandia is actually a new diagnostic for the Z accelerator. The Z-Beamlet laser will provide an intense x-ray source, as either a point or a diffuse backlighter, to image the z-pinch source and the hohlraum environment on Z. X-ray backlighting has been used successfully for high-energy-density experiments on other facilities, such as Nova and Omega. When operational, Z-Beamlet will be the third largest laser in the world, producing over 2 kJ of laser light that can be used in a single pulse or as a series of smaller pulses in a picket-fence configuration. Z-Beamlet is based on components from the 100-foot-long Beamlet laser built at LLNL in 1994 to serve as a prototype of one of the 192 beamlines of the National Ignition Facility (NIF). As a diagnostic, this will be a complete system with careful attention to synchronizing the backlighter to the z pinch and providing a high precision x-ray imaging system to match the backlighting capability.

b) Value of increasing current

The pulsed-power applications mentioned above drive development of the technology. As an example, applications of short-pulse, high-current accelerators such as Saturn and Z have driven the demand for higher-current accelerators because doubling the current increases the radiated energy by a factor of four. Using some important parameters as examples, Table 1 illustrates the advantages of scaling the current on Z to proposed future drivers.

Current	**Z** (20 MA)	**Z Mod** (28 MA)	**ZX** (50 MA)	**X-1** (2 x 60 MA)
Total Radiated Energy	1.8 MJ	3.6 MJ	11 MJ	32 MJ
Radiation Temperature in ZPDH	80 eV	100 eV	145 eV	220 eV
Radiation Temperature in DH	180 eV	225 eV	280 eV	310 eV
Peak Pressure for ICE	2.5 Mbar	5 Mbar	15 Mbar	22 Mbar
Peak Pressure with Flyer Plates	30 Mbar	65 Mbar	200 Mbar	300 Mbar

Sandia has begun to investigate designs for these higher-current drivers. The ultimate technological step would be to reach 60 MA into two z pinches and high fusion yields of > 200 MJ. This high-current driver, X-1, would have over twelve times the energy of the present Z machine, requiring both increased energy per module and improved efficiency. As early as 1997, it was clear that a path to high-current drivers was possible, and we defined the needed research and development to double the energy, increase the x-ray production efficiency (the ratio of stored electrical energy to radiated x-ray energy) from the demonstrated 15% on Z to 20%, improve component reliability by a factor of five, and keep the total project cost of the pulsed-power-driver component of a high-yield facility at $400M. A previous X-1 study suggested that the total cost for such a facility, including containment and waste stream management, would be > $1B. These goals are believed achievable with a reasonable research program in pulsed power technologies.

c) Z Mod

The success of Z has led its users to request facility enhancements and an increase in the number of experiments conducted each year. In modifying PBFA II to Z in 1996, only the central hub of the machine was changed. The rest of the facility has been in operation since December 1985. All active components are over fourteen years old. The present Z water-pulse-forming section is optimized to produce a 20-ns power pulse for our previous ion diode program and is no longer needed.

The requests for improvement to Z include reduced operational cost, increased reliability and shot rate, and more precision in timing and diagnostics. Research is being performed to increase the reliability and energy-handling capability of critical pulsed power components. This research suggests we can modernize Z (Z modernization, or Z Mod) so that the radiation produced by the z pinch is doubled, the reliability and the shot rate increased, and the cost of operation reduced. To cost effectively extrapolate the present technology on Z to a high-yield facility requires increasing the energy efficiency to 20% and doubling the energy of each pulsed-power module. The primary technology objective of Z Mod is to demonstrate these improvements. The proposed Z Mod will include improved reliability of the high-voltage intermediate-store gas switching, Marx gas switching, and other limited-lifetime components.

d) New Technology

In addition to evolutionary approaches to improving the performance of the pulsed-power components in existing accelerators, different technological approaches are receiving considerable attention. The international community has recognized the results achieved with z pinches at the 20-MA level, and new or renewed efforts in pulsed power are growing. France and Russia are actively pursuing programs to drive z pinches at higher currents.

Russia has a long history of pulsed power successes and has contributed significantly in the area of z-pinch physics, both theoretically and experimentally. France began studying pulsed power systems to drive z pinches about five years ago. In a short period of time, the French have built two modules capable of supplying 2 MA to an inductive energy store. One of these devices, the Linear Transformer Driver (LTD), has proven very successful. This technology has the promise of decreasing the complexity, and the construction, operating, and maintenance costs of future drivers. In particular, pulsed-power driver cost could be reduced by a factor of two. Sandia plans to build and evaluate a pulsed power module for a high-yield facility based on this technology. The goal is to produce a single physics module of a high yield facility, similar in concept to the Beamlet prototype laser built by LLNL for the NIF project.

A new technology under development uses low inductance capacitors and switching to drive an inductive-energy-store plasma opening-switch configuration. Another concept employs technology to drive 120-ns plasma implosions directly. The plasma opening switch approach would require no water, oil, or high pressure gas (SF_6) systems. The direct drive approach would require no SF_6 system and would reduce, by several orders of magnitude, the amounts of oil and water required. Both approaches eliminate the need for intermediate stores, high-voltage laser-triggered gas switches, low inductance water or gas switching, and water pulse forming lines. Either architecture would require fewer maintenance personnel than today's technology. We have been pursuing these technologies through cooperative research with the French DGA laboratory, CEG, in Gramat, France and through direct contracts to the High Current Electronics Institute in Tomsk, Russia. Proof of the physics of both approaches will be completed in FY01.

e) ZX / High Yield Facility

The path we are pursuing capitalizes on maximizing the use of existing facilities while keeping high fusion yield as our long-term goal. In the near term, we will invest in a modernized Z facility using improved conventional pulsed power elements and, in parallel, we will contribute to research in new pulsed power technologies through a pulsed power development laboratory. At some future date, we will be able to decide whether an intermediate step is required before committing to a high-yield facility (X-1). If risk reduction experiments are recommended, we may require an intermediate pulsed power accelerator (ZX) that delivers approximately 40 MA to a single z-pinch load and/or approximately 30 MA to each of two z-pinch loads. At these current levels, physics issues of power flow, z-pinch x-ray production, hohlraum energetics, radiation flow, radiation pulse shaping, radiation symmetry, and capsule implosion physics for high-yield target configurations can be addressed. The decision (ZX first or straight to X-1) will be determined from the research on Z Mod and the international successes in developing advanced pulsed power technologies.

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It is impossible to put a price tag on the value of the interactions we enjoy with our pulsed power colleagues around the world. Sandia has benefited greatly from their creative ideas and approaches when applied to our mission-oriented problems, and it is clear that, without national and international interactions, the outstanding rate of progress would not have been possible. To maintain and enhance the rate of progress in pulsed power, it is essential to have a healthy and vigorous international collaboration program.

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