

Z : A Fast Pulsed Power Generator For Ultra-High Magnetic Field Generation

R. B. Spielman, W. A. Stygar, K. W. Struve, J. R. Asay, C. A. Hall,
M. A. Bernard, J. E. Bailey, and D. H. McDaniel
Sandia National Laboratories
Albuquerque, NM 87185-1194 USA

Abstract

Advances in fast, pulsed-power technologies have resulted in the development of very high current drivers that have current rise times ~ 100 ns. The largest such pulsed power driver today is the new Z accelerator located at Sandia National Laboratories in Albuquerque, New Mexico. Z is capable of delivering more than 20 MA with a time-to-peak of 105 ns to low inductance (~ 1 nH) loads. Such large drivers are capable of directly generating magnetic fields approaching 3 kT in small, 1-cm³, volumes. In addition to direct field generation, Z can be used to compress an applied, axial seed field with a plasma. Flux compression schemes are not new and are, in fact, the basis of all explosive flux-compression generators but we propose the use of plasma armatures rather than solid, conducting armatures. We will present experimental results from the Z accelerator in which magnetic fields ~ 2 kT are generated and measured with several diagnostics. Issues such as energy loss in solid conductors and dynamic response of current-carrying conductors to very large magnetic fields will be reviewed in context with Z experiments. We will describe planned flux-compression experiments that are expected to create the highest-magnitude uniform-field volumes yet attained in the laboratory.

Introduction

The generation of ultra-high magnetic fields necessarily leads to low impedance, pulsed current drivers.^{1,2} Current densities above ~ 10 MA/cm (magnetic fields > 1 kT) have dynamical time constants < 100 ns. The rapid development of pulsed power technologies^{3,4} has enabled the routine generation of magnetic fields above 1 kT. We describe the pulsed power design and performance of Sandia's Z accelerator as well as results from experiments in which peak currents of 15-20 MA are delivered to various low inductance loads generating magnetic fields of order 1 kT.

Accelerator Description

Z's pulsed power design⁴ is based on Sandia National Laboratories Marx-generator and water-pulse-forming technology developed over the last 30 years. (See Figure 1.) Z contains 36 nearly identical modules. In each module a Marx generator, with 60, 1.3- μ F capacitors charged to a voltage of 90 kV. The Marx generators store a total of 11.4 MJ. The Marx generator delivers its energy to a water-dielectric coaxial capacitor in 1 μ s. The coaxial capacitor reaches a

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, make any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

**Portions of this document may be illegible
electronic image products. Images are
produced from the best available original
document.**

peak voltage of 5 MV. A low-jitter laser-triggered gas switch is used to couple the energy into a second, lower-inductance coaxial water capacitor in 200 ns. Self-breaking water switches are used to transfer the energy into a 4.32- Ω constant-impedance water transmission line. The electrical pulse at this point has a voltage of 2.5 MV and a pulse width of 105-ns FWHM. The total power generated in the accelerator is 60 TW.

The water transmission lines are a biplate, constant-impedance, constant anode/cathode-gap designed to optimize the energy efficiency of the transmission lines and to maximize the coupling of the energy in the water transmission lines to an inductive load. The impedance of each of the 36 biplate lines was 4.32 Ω . The transmission line gap was fixed at 14 cm. We accurately measure the voltage and current and, hence, the power and energy in each water transmission line.

The insulator stack is the boundary between the water dielectric and the vacuum that is necessary to drive the z-pinch load. The insulators, nearly 4 m in diameter, are made from Rexolite™ (high-density cross-linked polystyrene). The voltages and currents were measured at each of the insulator stacks giving a very accurate measure of the power and energy through the insulator stack.

The MITLs consist of four separate, conical-disk feeds coupled together at the vacuum convolute. The upper two MITLs are 2- Ω impedance and the lower two MITLs are 2.75- Ω impedance. The MITLs operate successfully at a peak electric field of 2 MV/cm with vacuum gaps as small as 1 cm. We placed current monitors at two radial locations and 3-6 azimuthal positions in each of the four MITL anodes to better study vacuum power flow.

A critical point in the vacuum power flow is the double post-hole convolute that couples the four, conical-disk MITLs together. This is done in order to combine the current from each level and deliver the summed currents to a single z-pinch load. The baseline convolute on Z is a 12-post/hole design with 1.0- to 1.5-cm diameter posts and post-to-cathode gaps of 1-2 cm. A drawing of the convolute is given in Figure 3.

Load Design

The generation of magnetic fields with these large pulsed power drivers can be direct, in which current flows in a conductor (typically a coaxial arrangement), or indirect in which a seed magnetic field is inserted then compressed by the main current. Both configurations have advantages and disadvantages. The primary problem with directly driven systems is the non-uniformity of the magnetic field. In a coaxial geometry the azimuthal magnetic field falls off as $1/r$. The peak field is on the inner conductor and may be unusable for most experiments. In flux compression schemes the B_z magnetic field is uniform over the volume being compressed but the fact that the conducting plasma shell is moving and radiating strongly can compromise many potential experiments. We describe two such load designs for the Z accelerator.

The actual load to which current is delivered is relatively small in size. The load dimensions are limited by the driver energy (or, equivalently, the load inductance). Our directly driven load is coaxial with a 6-mm inner conductor diameter and a 12-mm outer-conductor inner diameter. The length is 1 cm. (See

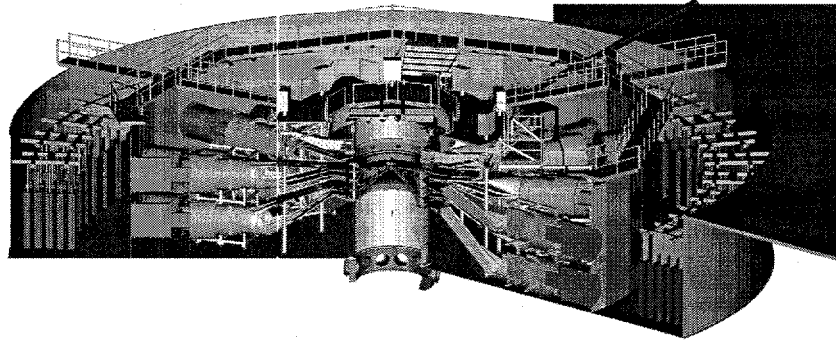


Figure 1 A schematic of the Z accelerator showing the pulsed power layout. The diameter of the outer oil tank is 33.5 m.

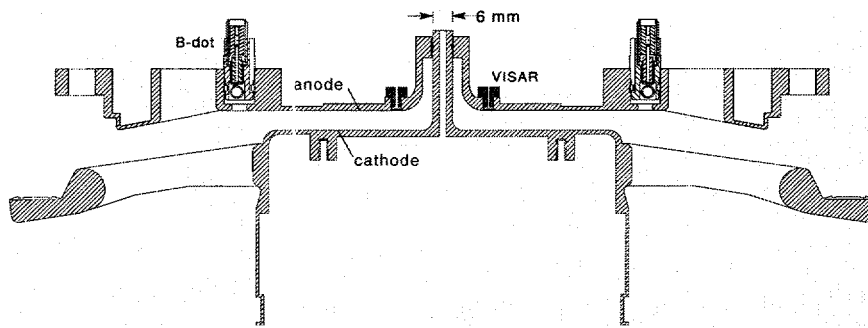


Figure 2 A drawing of a coaxial load in which azimuthal magnetic field is generated in the volume surrounding the inner conductor. The locations of the B-dot current monitors and the VISAR probes are shown.

Figure 2.) The inductance of this load is 1.38 nH. All materials for this experiment were 304L stainless steel. We examined the hydrodynamic motion of the inner conductor due to the magnetic forces. With a peak current of ~ 20 MA and a diameter of 6 mm the motion of the inner conductor is small in 100 ns. Increases in magnetic field (reductions in conductor diameter) are possible if higher density materials are used for the conductors.

Magnetic Field and Current Diagnostics

One of the greatest challenges of high magnetic field experiments is the measurement of the magnetic field itself. We describe two methods that are used to infer the magnitude of the magnetic field on Z. First, we use B-dot current probes.⁵ On Z we used four of these current monitors located 6.0 cm from the

probes.⁵ On Z we used four of these current monitors located 6.0 cm from the load. At this position the current density is < 1 MA/cm and the current monitors work well. Thus, we have a direct measurement of the magnetic field from which we infer the local current. Typically we assume that this current flows through the load itself without losses. Second, we have used VISAR techniques⁶ to measure the magnetic pressure on the conductor itself near the load. This technique uses laser interferometry to directly measure the rear surface velocity of a small piece of the electrode. The magnitude of the driving magnetic field is then inferred from the velocity history of the electrode.

Our B-dot current monitors have 1-mm diameter loops aligned with the magnetic field. Copper sleeves surround the detector to minimize the diffusion of current in nearby conductors and, hence, minimize changes in the detector sensitivity to the local fields. The B-dot current monitors are calibrated in a fixture in which a current pulser provides up to 10 kA to the load and NIST traceable resistance standards are used to compare with the measured B-dot signal. Typically the calibration data provides a calibration accuracy of $\sim 1\%$.

The VISAR pressure diagnostic uses reflected laser light from the rear surface of a well-characterized metallic sample (for example copper or iron) located on the current path.⁷ The VISAR sample is located 1.39 cm from the load axis. This radial location was chosen to keep the sample pressure below ~ 30 GPa and to minimize radial pressure gradients. The detector is sensitive to motion of the back surface of the sample through a Doppler shift in the reflected light. As the pressure builds up on the front of the sample it is coupled to the back surface of the sample causing rear surface motion. This motion is then measured. The particle velocity of the sample can be correlated to the applied pressure through well characterized material properties. The measurement error of the pressure is 5% today but may be reduced to 1-2% in the near future.

We believe that spectroscopy may be used on the future to directly measure the time- and space-resolved magnetic field in the load. There are a number of issues involving plasma opacity and plasma motion that remain unresolved.

Data

We describe data from Z shot 315. This shot used the direct-drive load design described above. Z delivered a peak current of 19.3 MA, a peak average voltage of 3.5 MV, a peak power of 48.5 TW, and total energy of 2.92 MJ at the main insulator stack (measured with carefully calibrated B-dot and V-dot electrical monitors). This current flowed to the inner load region where it was measured by the local current diagnostics. (See Figure 3.) A small current loss caused the current measured at the insulator stack to be slightly higher than the actual load current. The B-dot data show that the current reaches a peak value of 16.7 ± 0.85 MA in 105 ns. At this current level the peak magnetic field in the 6-mm diameter coaxial load was 1.1 ± 0.05 kT. With a load inductance of 1.38 nH we find that the energy stored in the load is 192 kJ. These data are consistent with the overall energy balance in the vacuum section of Z.

On the same shot the VISAR data show that a peak pressure of 31.4 ± 1.5 GPa was developed at the surface of an iron sample. (See Figure 4.) At

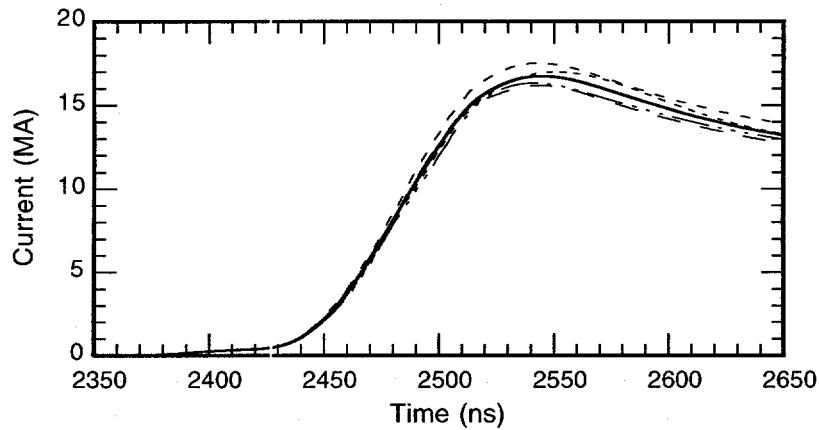


Figure 3 Current waveforms measured with four B-dot current monitors located 4.3 cm from the load. The heavy solid line is the average of the four data waveforms.

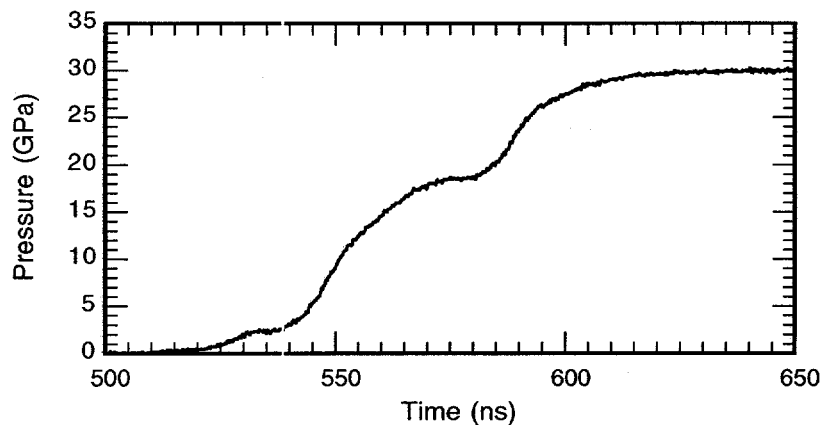


Figure 4 The pressure waveform measured with the VISAR diagnostic. The peak pressure measured by is 31.4 GPa. The structure in the data is due to the material properties of iron.

this pressure the surface magnetic field acting on the VISAR sample was 280.9 ± 7 T. The current at a radius of 1.39 cm, consistent with this pressure and magnetic field, was 19.45 ± 0.5 MA. The VISAR data was of sufficiently high quality that detailed iron material properties were obtained. The time units in Figure 4 are relative.

We found that the current measured by the VISAR sample was slightly higher than that measured by the current monitors. We do not fully understand

the discrepancy yet but possibilities include the conductor skin depth at these higher current densities or plasma shielding of the B-dot probes. Refinements in MHD calculations using the best equations-of-state and material resistivities may reduce this apparent difference.

Conclusions

The development of 100-ns, 20-MA pulsed power drivers enables a large class of high magnetic field experiments. These experiments, at fields greater than 1 kT, permit the study of basic material properties at pressures and densities heretofore unavailable. The capabilities of this new class of pulsed power driver have not been explored in any level of detail. We expect new experiments using Z and future drivers at higher magnetic fields will yield a wealth of new data and will result in changes in our fundamental understanding of materials at high pressure and density.

Acknowledgement

This work was supported by the United States Department of Energy under Contract DE-AC04-94AL85000.

References

- ¹R. B. Spielman, T. W. Hussey, D. L. Hanson, and S. F. Lopez, *Megagauss Fields and Pulsed Power Systems*, edited by V. M. Titov and G. A. Shvetsov (NOVA Science Publishers, NY 1990), p. 43.
- ²R. B. Spielman, T. H. Martin, D. H. McDaniel, M. Savage, and H. Woodall, *Megagauss Magnetic Fields and Applications*, edited by M. Cowan and R. B. Spielman (NOVA Science Publishers, NY 1995), pp. 437-444.
- ³D. D. Bloomquist, R. W. Stinnett, D. H. McDaniel, J. R. Lee, A. W. Sharpe, J. A. Halbleib, L. G. Schlitt, P. W. Spence, and P. Corcoran, *Proc. of the Sixth IEEE Pulsed Power Conf.*, Arlington, VA edited by P. J. Turchi and B. H. Bernstein (IEEE, New York, 1987), p. 310.
- ⁴R. B. Spielman, W. A. Stygar, J. F. Seamen, F. Long, H. Ives, R. Garcia, T. Wagoner, K. W. Struve, M. Mostrom, I. Smith, P. Spence, and P. Corcoran, *Proc. of the Eleventh IEEE Pulsed Power Conf.*, Baltimore, MD 1997, p. 709.
- ⁵W. A. Stygar, R. B. Spielman, H. Ives, W. B. S. Moore, J. F. Seamen, A. W. Sharpe, T. C. Wagoner, T. L. Gilliland, R. S. Broyles, J. A. Mills, T. A. Dinwoodie, J. S. Slopek, K. W. Struve, and P. G. Reynolds, *Proc. of the Eleventh IEEE Pulsed Power Conf.*, Baltimore, MD 1997, p. 1258.
- ⁶L. M. Barker and R. E. Hollenbach, *J. Appl. Phys.* **45**, 4872 (1974).
- ⁷J. R. Asay, C. A. Hall, K. J. Fleming, W. A. Trott, K. G. Holland, M. A. Bernard, B. Clark, R. B. Spielman and W. A. Stygar, "Z-Pinch Drivers for Shock Physics Research", these proceedings.

Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy under contract DE-AC04-94AL85000.