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Research Article

Conceptual design of a 15-TW pulsed-power accelerator for high-energy-density—physics experiments

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Abstract

We have developed a conceptual design of a 15-TW pulsed-power accelerator based on the linear-transformer-driver (LTD) architecture described by Stygar [W. A. Stygar et al., Phys. Rev. ST Accel. Beams 18, 110401 (2015)]. The driver will allow multiple, high-energy-density experiments per day in a university environment and, at the same time, will enable both fundamental and integrated experiments that are scalable to larger facilities. In this design, many individual energy storage units (bricks), each composed of two capacitors and one switch, directly drive the target load without additional pulse compression. Ten LTD modules in parallel drive the load. Each module consists of 16 LTD cavities connected in series, where each cavity is powered by 22 bricks connected in parallel. This design stores up to 2.75 MJ and delivers up to 15 TW in 100 ns to the constant-impedance, water-insulated radial transmission lines. The transmission lines in turn deliver a peak current as high as 12.5 MA to the physics load. To maximize its experimental value and flexibility, the accelerator is coupled to a modern, multibeam laser facility (four beams with up to 5 kJ in 10 ns and one beam with up to 2.6 kJ in 100 ps or less) that can provide auxiliary heating of the physics load. The lasers also enable advanced diagnostic techniques such as X-ray Thomson scattering and multiframe and three-dimensional radiography. The coupled accelerator-laser facility will be the first of its kind and be capable of conducting unprecedented high-energy-density—physics experiments.

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1. Introduction

Since 1970, low-impedance, pulsed-power accelerators have been based on Marx-generator, water-pulse-forming technology. The world's largest and most-powerful pulsed-power accelerator is the Z accelerator [1,2], refurbished from the original facility in 2007 and located at Sandia National Laboratories (SNL) in Albuquerque, NM. Z stores 20 MJ of electrical energy at a charge voltage of 85 kV and delivers as much as 28 MA in 110 ns to a wide range of loads. Z represents the state-of-the-art for Marx-generator, water-pulse-forming accelerators, delivering greater than 2 MJ of energy to a wide range of targets. The coupling of a high-power laser beam [3] to Z has pioneered new high-energy science by providing advanced diagnostic techniques [3] and innovative fusion concepts [4].

In this article, we describe the conceptual design of a compact, highly efficient pulsed-power accelerator, based on a linear-transformer-driver (LTD) machine architecture [5,6],

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coupled to a multibeam, high-power laser system. One of our key goals was to design a pulsed-power accelerator, smaller than Z, that would demonstrate and validate the LTD architecture proposed by Ref. [6] for accelerators larger than Z while coupling an advanced high-power laser system to the pulsed-power loads. Particular attention has been paid to providing extensive diagnostic access to the load while maintaining machine performance. This new LTD design would take advantage of the very efficient coupling of stored energy to the load to build a pulsed-power accelerator capable of delivering up to 12.5 MA and over 600 kJ to a range of dynamic loads for a variety of high energy-density—physics (HEDP) research.

The LTD pulsed-power facility was designed to be coupled to a laser system capable of delivering four, nominally 5-kJ ultraviolet (UV) beams with state-of-the-art beam conditioning, a pulse-shaping capability to generate 150-ps to 10-ns-long laser pulses, and a single, 2.5-kJ infrared (IR) laser beam with a pulse-width range of 1 ps—100 ps. The four UV beams will enable 3-D radiography to precisely measure the evolution of high-energy-density (HED) plasmas. Other configurations would enable auxiliary heating of a plasma and radiography in the same experiment. These laser intensities will make it possible to generate X rays with energies greater than 10 keV for novel HED physics studies, including advanced high-density radiography, X-ray Thomson scattering, and diffraction experiments.

Our conceptual design is for a pulsed-power accelerator that has a single stage of pulse compression and has a matched electrical impedance throughout, as described by Stygar et al. [6], thereby minimizing electrical reflections and maximizing overall electrical coupling efficiency to the load. Depending on the load details, coupling efficiencies as large as 25% (load kinetic energy/stored energy) can be realized. We have fixed the $\sqrt{LC}$ time constant of the prime-power store to be ~100 ns to eliminate the need for further pulse compression (with its attendant losses in efficiency). The LTD design enables longer electrical pulses by pulse shaping the current via independent triggering of the bricks. The goal is to maximize the flexibility of the driver for HEDP research.

The architecture of our accelerator is based on the generic LTD architecture described by Stygar et al. [6]. Our design assumes the use of an LTD brick based on two, 80-nF capacitors and a single, low-inductance gas switch connected electrically in series (see Fig. 1). Multiple bricks are assembled in parallel in a cavity. The cavities are arranged in series into a single module. Multiple modules, feeding through coaxial water lines, comprise the entire accelerator and drive a single load via a tri-plate magnetically insulated transmission line.

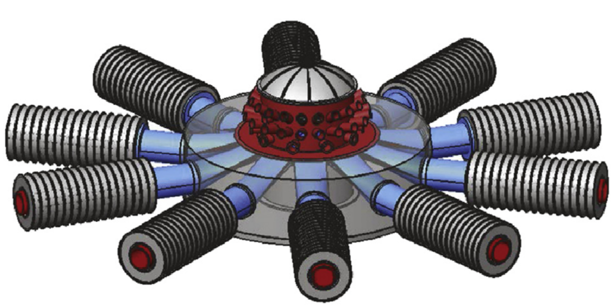

Fig. 1. Schematic of an LTD brick showing two double-ended capacitors and a single 200-kV low-inductance gas switch.

Detailed circuit simulations using *Screamer* [7,8] model the performance of the accelerator with different loads. These simulations model all of the elements of the accelerator from the bricks (switch losses), the cavities (core losses), the modules, the water transmission lines (water losses), the magnetically insulated transmission lines (electron losses), and the post-hole convolute (vacuum-electron-flow losses) to the load. Detailed descriptions of the designs and the assumptions used in the simulations are provided in Secs. 2 and 3.

This pulsed-power accelerator could serve as the first large-scale demonstration of LTD architecture. Such a facility will facilitate a wide range of HEDP experiments that will incorporate modern pulsed-power with state-of-the-art laser capabilities. Given the research enabled by coupling the Z facility with the Z-Beamlet [3] (the successful prototype of a National Ignition Facility beamline) at Sandia, it is likely that any future pulsed-power facility of scale will incorporate multiple, high-power lasers. The facility described in this paper could therefore serve as a "prototype" for any future facility of scale [6].

2. Conceptual design for a 15-TW pulsed-power accelerator

2.1. Overview

This conceptual electrical design has performance parameters that are roughly 1/4 scale in energy and power from SNL's original Z machine (3 MV, 20 MA, 100 ns, 0.12 Ω, 60 TW) [9—12]. This new design operates at ~2 × lower peak current than the original Z and it addresses the following key design goals:

- LTD architecture and pulse shaping: The driver design is based on an LTD prime-power architecture [6]. The choice of the LTD as the prime-power source is motivated by the fundamental efficiency and pulse-shaping flexibility of LTD designs [13], the maturity of SNL's LTD engineering, the reduced maintenance of LTD components, the lack of water shock, and the technological impact to the National Pulsed-Power Program. Such a facility would also motivate and help develop the needed "supply chain" for critical components for any future, large-scale pulsed-power facility.
- The ability to efficiently drive a wide array of HEDP experiments that are scalable to present (Z) and future, high-energy pulsed-power facilities: Currents must be large enough to stably implode scaled liners to relevant velocities (~10^7 cm/s). Scalable HEDP experiments that exploit the X-ray energy and power produced by wire arrays or gas puffs are also a desired capability. The ability to