Development of a 20 MeV Dielectric-Loaded Test Accelerator

Steven H. Gold*, Allen K. Kinkead†, Wei Gai¶,
John G. Power,¶ Richard Konecny,¶ Chunguang Jing,¶§
Jidong Long¶, Sami G. Tantawi‡, Christopher D. Nantista‡,
Ralph W. Bruce∆, Arne W. Fliflet*, Marcie Lombardi*,
and David Lewis III°

** Plasma Physics Division, Naval Research Laboratory, Washington, DC 20375, USA*
† LET Corporation, Washington, DC 20007, USA
¶ Argonne National Laboratory, Argonne, IL 60439, USA
§ Euclid Techlabs, LLC, Solon, OH 44139, USA
‡ Stanford Linear Accelerator Center, Menlo Park, CA 94025, USA
∆ RWBruce Associates, Inc., Arnold, MD 21012, USA
° Material Science and Technology Division, Naval Research Laboratory, Washington, DC 20375, USA

Abstract. This paper presents a progress report on a joint project by the Naval Research Laboratory (NRL) and Argonne National Laboratory (ANL), in collaboration with the Stanford Linear Accelerator Center (SLAC), to develop a dielectric-loaded test accelerator in the magnicon facility at NRL. The accelerator will be powered by an experimental 11.424-GHz magnicon amplifier that presently produces 25 MW of output power in a ~250-ns pulse at up to 10 Hz. The accelerator will include a 5-MeV electron injector originally developed at the Tsinghua University in Beijing, China, and can incorporate DLA structures up to 0.5 m in length. The DLA structures are being developed by ANL, and shorter test structures fabricated from a variety of dielectric materials have undergone testing at NRL at gradients up to ~8 MV/m. SLAC has developed components to distribute the power from the two magnicon output arms to the injector and to the DLA accelerating structure with separate control of the power ratio and relative phase. RWBruce Associates, Inc., working with NRL, has investigated means to join short ceramic sections into a continuous accelerator tube by a brazing process using an intense 83-GHz beam. The installation and testing of the first dielectric-loaded test accelerator, including injector, DLA test structure, and spectrometer, should take place within the next year.

Keywords: dielectric-loaded accelerator
PACS: 29.17.+w

INTRODUCTION

Accelerating (or decelerating) particles in a linear rf structure requires matching the phase velocity of the interacting rf mode to the particle velocity, which for high energy leptons is close to *c*. Conventional accelerators make use of periodic metal structures to produce the required synchronism, and the surface electric and magnetic fields in those structures sets limits on the maximum accelerating gradients that can be

Contributed to 12th Advanced Accelerator Concepts Workshop (AAC 2006),
07/10/2006--7/15/2006, Lake Geneva, Wisconsin
Work supported in part by US Department of Energy contract DE-AC02-76SF00515

achieved. Efforts are now in progress to find the maximum fields that can be sustained in such structures without breakdown or surface damage. At the same time, there are parallel efforts to find alternatives to periodic metal structures. One possible alternative is the dielectric-loaded accelerating (DLA) structure [1]. A uniform DLA structure can be used as a slow-wave electron accelerator by choosing a liner material with an appropriate combination of dielectric constant and the inner and outer radii to match the phase velocity of the accelerating mode to *c*. Argonne National Laboratory (ANL) and the Naval Research Laboratory (NRL) are carrying out a joint program [2], in collaboration with the Stanford Linear Accelerator Center (SLAC), to develop and test DLA structures for possible use in future high-gradient accelerators. In this program, ANL develops the structures which are then tested at high gradients at NRL using a high-power X-band magnicon amplifier [3]. Preliminary tests of these structures have been carried out without an electron beam, and various adverse effects observed, including multipactor and breakdown at dielectric joints. Preliminary models have also been developed to explain these effects [4]. This work is described in two accompanying papers [5,6]. The focus of this paper is on the overall program, whose goal is to carry out tests that include an accelerated electron beam and to develop a compact 20-MeV dielectric-loaded accelerator test facility.

THE NRL MAGNICON FACILITY

The heart of the NRL Magnicon Facility is an experimental magnicon amplifier that was developed jointly with Omega-P, Inc. as an alternative to klystrons to power X-band accelerating structures. The magnicon is a high gain, phase-stable frequency-doubling amplifier tube. It operates with a frequency-stable drive signal from a solid-state sweep oscillator that is pulse amplified by a TWT for injection into the magnicon drive cavity. The magnicon output is extracted through two SLAC-style WR-90 waveguide lines, each with a high power TE_{01} output window and SLAC-style directional couplers and loads. It operates over the approximate frequency range 11.424–11.432 GHz, and can produce 25 MW of output power in ~250-ns FWHM pulses at a repetition rate up to 10 Hz. (It can also operate at somewhat lower power in a long-pulse mode to produce 1.1-μs flat-top pulses.) Its output is stable, even in the presence of resonant loads. However, its present performance falls short of the 50 MW output power predicted by design codes [3], and efforts have continued for a number of years to understand the pulse-length dependent limits on the power. In the past year, an effort was made to increase the output power by replacing the electron beam collector, the apparent source of an oscillation that correlated with pulse shortening effects in the magnicon output cavity. However, the new collector did not improve the performance, and the decision was made to return to the old collector and to examine other phenomena that may be at fault. While these investigations are in progress, the magnicon continues to be available for use in DLA structure tests and for other experimental work.

Experiments making use of the magnicon output are currently connected to one of the two output waveguides, with the second terminated in a vacuum load. However, a power combiner has recently been developed by SLAC that will permit the power

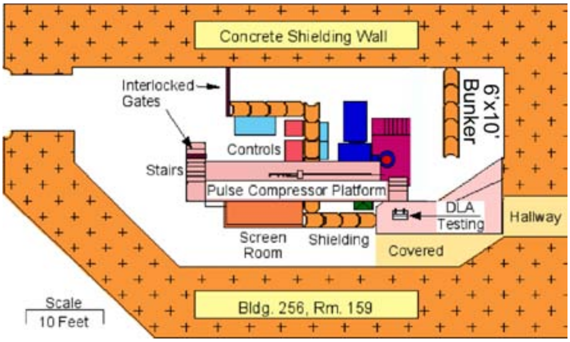

FIGURE 1. Floor plan of NRL magnicon laboratory.

from the two arms to be combined to drive a single load at twice the power, or split in any desired ratio to drive separate loads, such as an electron injector and an accelerating structure. The NRL magnicon facility is illustrated in Fig. 1. Two test stands are located adjacent to the magnicon output. The first, a 5'x25' raised platform for pulse compressor experiments, is 8' high, and passes over the concrete shielding wall. The second, a 10'-high concrete deck area, is currently used for testing DLA structures. A new 6'x10' concrete bunker has been installed behind the shielding wall to house the test accelerator.

THE DIELECTRIC-LOADED TEST ACCELERATOR

Figure 2 shows a schematic diagram of the complete dielectric-loaded test accelerator. A 5-MeV injector will inject ~1 pC electron bunches into a long dielectric structure (up to 50 cm). The injector and structure will be fed by separate output waveguides from a power combiner/phase shifter assembly, in order to operate the injector at constant power while varying the power and relative phase of the accelerating section. The energy gain of the electron bunches will be diagnosed by a conventional magnetic spectrometer. The accelerator will be located in a bunker behind the shielding wall in the magnicon facility. In the remainder of the paper, we describe several separate efforts that are under way in support of this overall goal.

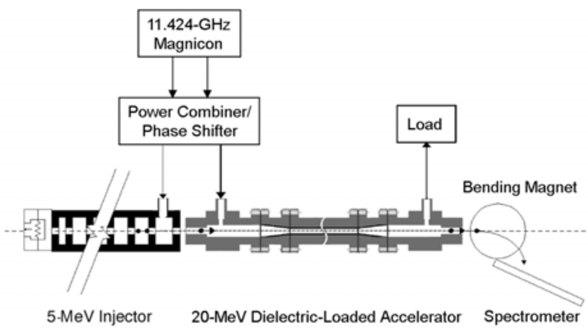

FIGURE 2. Schematic diagram of dielectric-loaded test accelerator.

EXPERIMENTS ON DLA STRUCTURES

A set of experiments have been carried out on a number of traveling-wave DLA structures employing low-loss alumina (Al_2O_3), with or without a TiN surface coating, magnesium calcium titanate ($Mg_xCa_{1-x}TiO_3$), and fused silica. The experimental setup is illustrated in Fig. 3. Measurements have been made at incident powers ranging up to 12 MW and at accelerating gradients up to ~8 MV/m. Thus far, there has been no sign of rf breakdown in the uniform sections of the accelerating structures. However, two key problems have been identified in these experiments: 1) Strong multipactor loading of the dielectric structures, and 2) rf breakdown at the joints between uniform and tapered ceramic sections. Both of these problems are under experimental investigation. This work is described in more detail in Refs [5] and [6].

DEVELOPMENT OF A 5 MeV ELECTRON INJECTOR

While accelerating gradients can be inferred from the drive power injected into the DLA structures, the real test of these structures is to use them as part of a complete accelerator, in which electrons are accelerated and their energy gain directly measured. This requires an rf-driven electron injector that will produce bunches of relativistic electrons for acceleration by the DLA test structures. The Accelerator Laboratory of the Engineering Department, Tsinghua University in Beijing, China, developed a 5 MeV electron injector that is designed to be driven by approximately 5 MW of rf power at 11.424 GHz [2]. The injector uses a LaB_6 cathode, and a 24-cell disk and washer accelerating structure. That injector was delivered to ANL in 2005. Unfortunately, it was slightly mistuned, requiring the development of a method of temperature tuning the operating frequency, and also suffered a broken cathode, which required replacement. As of the date of this Workshop, the replacement cathode has been delivered and the temperature tuning system completed. According to the present schedule, the injector will be ready for delivery to NRL later in 2006. Following

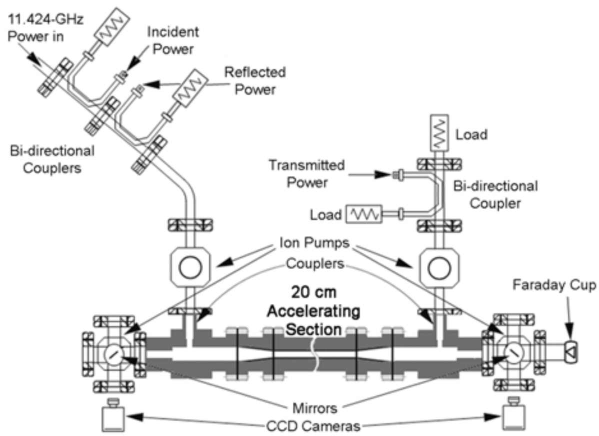

FIGURE 3. Experimental setup for DLA structure tests.

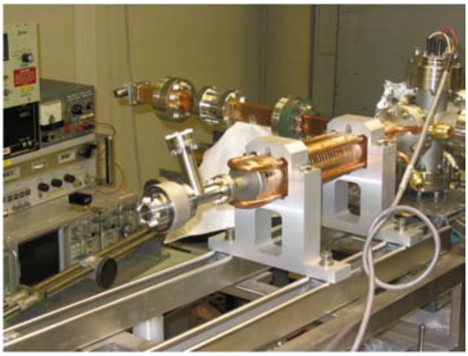

FIGURE 4. Photograph of 5-MeV electron injector at ANL.

delivery, it will be installed on a specially prepared table in the new bunker in the Magnicon Facility. Figure 4 shows a photograph of the injector.

DEVELOPMENT OF AN X-BAND POWER COMBINER

One key requirement for the accelerator is a means to use the combined power from the two magnicon output waveguides to simultaneously drive the electron beam injector and an accelerating structure. The two output waveguides of the magnicon have approximately equal power and a fixed phase relationship. The injector will require a fixed input power, estimated to be ~5 MW, while optimizing the operation of the accelerating structure will require variation of both its drive power and phase. As an important element of our collaboration, SLAC is developing a device that will combine the two magnicon outputs in a 3-dB hybrid coupler. A phase shifter in one of the two input arms to the hybrid will be used to vary the power split, and a second phase shifter in one of the two output arms will allow the relative phase to be controlled.

Figure 5 shows a block diagram of this device. It will use discrete components, including a newly developed inline X-band phase shifter and a magic-H style SLAC hybrid coupler [7]. The hybrid coupler and the first phase shifter, with its mode converters, were recently delivered to NRL, and should be tested at high power later in 2006. These components will allow adjustment of the power between the two output ports of the hybrid. The second phase shifter assembly is expected to be complete by the end of 2006, and will provide control of the relative phase of the two outputs.

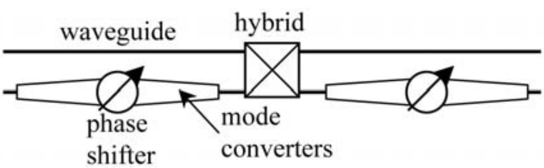

FIGURE 5. Block diagram of magnicon power combiner/phase shifter.

CERAMIC BRAZING

It is currently difficult to obtain single-piece ceramic tubes of the required materials, such as high purity, high density alumina, in the required lengths (50 cm for the current test accelerator, but perhaps >1 m in future accelerator sections), while meeting the necessary dimensional tolerances. The present hot-pressed high purity alumina tubes being evaluated for the DLA are only available in lengths of ~10 cm. Thus, the initial DLA experiments use a simple mechanical assembly of separate ceramic tube sections loaded into a metallic tube. This approach places stringent requirements on the assembly procedures, and can cause difficulties with subsequent handling and with thermal cycling during bakeout, where the large thermal expansion mismatch between the ceramic tube segments and the metallic liner can produce gaps between the tube segments. Such gaps can cause performance degradations through impedance mismatches and can cause localized breakdown.

RWBruce Associates, Inc., working with NRL, has been exploring the use of reactive oxide glass brazes and localized millimeter-wave beam heating to produce mechanical strong joints that have uniform dielectric properties and negligible geometric discontinuities. Their first approach used rotating fixturing, susceptors to improve the millimeter-wave coupling to the ceramic materials, and radiation shielding to ensure uniform heating of the joint region through a thermal cycle ranging from 800°C to 1500°C, in order to bond the material, diffuse the braze material into the joint, and recrystallize the joint region [2]. More recently, a new approach has been employed using an elliptical cavity to produce symmetric illumination of a workpiece located at one of its two foci (see Fig. 6). This approach eliminates the necessity of rotating the workpiece, which was found to interfere with the maintenance of precise alignment. In both approaches, the millimeter-wave beam system permits use of simple fixtures for maintaining alignment and applying pressure to joints, and the use of inexpensive instrumentation for process control and monitoring. The final result is a crystalline joint with dielectric, thermal and mechanical properties very similar to the material being joined. The dielectric properties have been confirmed by network analyzer measurements at ANL. Based on this work, it appears that straightforward solutions exist to the problem of making long dielectric accelerating structures.

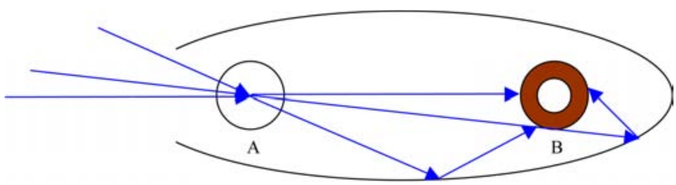

FIGURE 6. Schematic view of elliptical cavity for brazing ceramic tubes together. The quasioptical beam from the gyrotron is brought to a focus at A

SUMMARY

The goal of this project is develop a test bed to study structure-based advanced accelerator concepts in X-band, and in particular, dielectric-loaded accelerated structures. The heart of the facility is an 11.424-GHz magnicon amplifier that can produce 25 MW of output power, split evenly over two waveguide feeds, in ~250-ns FWHM pulses. To date, tests have been carried out of structures at high fields using the power from a single output arm of the magnicon. In order to move from high gradient tests of accelerating structures to actual acceleration tests, an electron injector was acquired from the Tsinghua University in Beijing, China. It is designed to produce ~1 pC bunches of 5-MeV electrons for injection into the accelerating structure. It will soon be installed in a new concrete bunker in the NRL magnicon facility. SLAC has developed a power combiner to permit the two magnicon output arms to be combined and then split to power the injector and the accelerating structure, and it should be installed and tested later in 2006. A project related to the DLA structure development has been under way by RWBruce Associates, Inc., in collaboration with NRL. The goal of the project is to develop a means to braze ceramic tubes into a continuous structure, without discontinuities in the joint region that can lead to mismatches, field enhancement, and rf breakdown. This project has demonstrated the ability to achieve mechanical joints with good mechanical and rf properties between high-purity alumina sections that are difficult to join by conventional means. All of these related efforts are intended to lead to a working dielectric-loaded test accelerator within approximately one year.

ACKNOWLEDGMENT

This work was supported by the Office of High Energy Physics, U.S. Department of Energy and by the U.S. Office of Naval Research.

REFERENCES

1. E. Chojnacki et al., *J. Appl. Phys.* **69**, 6257 (1991).
2. S. H. Gold et al., in *Advanced Accelerator Concepts*, edited by V. Yakimenko, AIP Conference Proceedings **737**, (New York: AIP, 2004), pp. 281–287.
3. O. A. Nezhevenko et al., "Performance of X-Band Pulsed Magnicon Amplifier," in *Proc. 2003 Particle Accelerator Conf.*, edited by J. Chew et al. (IEEE, Piscataway, NJ, 2003), pp. 1128–1130.
4. J. G. Power et al., *Phys. Rev. Lett.* **92**, 164801 (23 April 2004).
5. J. G. Power et al., paper in this proceedings.
6. C. Jing et al., paper in this proceedings.
7. C. D. Nantista et al., "Planar Waveguide Hybrids for Very High Power RF," in *Proc. 1999 Particle Accelerator Conference*, edited by A. Luccio and W. MacKay (IEEE, Piscataway, NJ, 1999), **2**, pp. 1432–1434; also SLAC-PUB-8142.