BELLA LASER AND OPERATIONS*

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Abstract

The BELLA laser system is the first high repetition rate petawatt class laser in the world. The laser was acquired from THALES to allow laser plasma acceleration (LPA) experiments that aim at exploring the physics of linear and non-linear interactions of intense lasers with plasmas towards the development of a 10 GeV module. Here we present details of the operation of the BELLA laser and beam line systems, including the control and data acquisition system.

INTRODUCTION

Laser plasma accelerators (LPA) [1] have the potential to drastically cut the cost of doing science with accelerators due to their much reduced size compared to conventional accelerators of the same energy. While it could be decades before a laser plasma accelerator can match or exceed the capabilities of something like the proposed International Linear Collider—a 25 miles (40 kilometers) long machine that would produce electrons and positrons at extremely high energies (0.5 TeV center of mass), straw man designs [2] and more detailed physics studies are underway to explore the possibility of LPA technology towards a linear collider [3,4]. In recent years, LPAs have made significant progress towards producing high quality beams with ever higher energy. In 2004, three independent groups showed the first demonstration of relatively narrow energy spread electron beams at the ~ 100 MeV level from mm-scale devices [5-7]. In 2006 the first production was shown of GeV electron beams from a 3 cm long plasma channel guided LPA at LBNL [8] and in 2011 a novel method for controlling injection via longitudinal tailored density profiles was demonstrated [9]. In the 2006 experiments, the laser peak power was of the order of 40 TW and the operating plasma density was a factor of ~10 lower but extended over a ~10 times longer distance than in the 2004 experiments. Motivated by the success of these experiments, designs were developed at LBNL to achieve 10 GeV electron beams from meter-scale accelerator structures using a PW-class laser system, which led to the formal BELLA (BErkeley Lab Laser Accelerator) project proposal to the Department of Energy, Office of High Energy Physics in 2007. BELLA represents an essential step towards investigating how more powerful accelerators of the future might be more compact. The initial experiments with the BELLA laser system and facility are aimed at demonstrating that high quality 10 GeV electron beams can be generated using a laser powered plasma structure that is about 1 meter long. The research supported by BELLA will also investigate fundamental laser-plasma interaction physics that aims at optimizing the coupling efficiency of laser to electron beam energy, controlling both the energy spread and emittance of the electron beams, and staging multiple LPA modules together. The 10 GeV beams could also be used to study beam driven plasma wakefield acceleration, as well as positron production and subsequent acceleration in plasma based accelerators. Although its main purpose is accelerator research, the development of a compact 10 GeV accelerator has several potential applications. BELLA could be used to build a free-electron laser (FEL) operating in the soft x-ray window that produces few femtosecond radiation pulses that are intrinsically synchronized to laser pulses, to THz radiation pulses or directly to the electron beam. Such a device could be an extraordinarily valuable tool for biologists, chemists, materials scientists, and biomedical researchers, allowing them to observe ultrashort, nanoscale phenomena.

We will next discuss the performance of the BELLA laser. As the key physics in the LPA studies are primarily dependent on laser intensity, the key parameters are laser pulse energy, pulse duration, laser beam profile and their stability. From an operational point-of-view, pointing stability is also essential. We also will introduce the BELLA control system, which is used for both control of all experimental subsystems and data acquisition. Details will be presented elsewhere.

BELLA PROJECT

The project phase of BELLA consisted of the construction and commissioning of a PW-class laser that supports the research aimed at the development of 10 GeV LPA modules. The project was formally launched in October 2007 and funded in 2009. The scope of the BELLA project included the design and construction of the conventional facilities required to house and safely operate the BELLA laser, the acquisition of the BELLA laser system itself, design and construction of ancillary systems to support the laser operations, site and system integration, and performance verification of the BELLA laser system.

The BELLA facility has been fully designed to achieve all key performance parameters of the laser system and future experimental systems. This includes clean-room (class 10,000 and 1,000) areas for the laser and experimental areas, with gowning area, assembly area and tightly controlled environmental conditions to minimize temperature and humidity effects as well as low vibration

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levels; a separate utility room that houses all power supplies and other heat producing equipment; a radiation shielded target area for all high power laser-plasma interaction experiments, including a beam dump to stop and absorb 10 GeV class electron beams; a control room equipped with computer hardware to allow remote operation of the laser system, equipment and personnel safety systems as well as experiments. Legacy infrastructure demolition in the BELLA building and subsequently construction of the new facility took place from October 2010 – March 2011 and March 2011-November 2011, respectively.

The BELLA laser was constructed by a commercial vendor (THALES) [10] and first built at the THALES factory from November 2009 through January 2012. Following factory acceptance testing in February 2012, the laser was shipped to Berkeley in April 2012 and installed at LBNL from April 2012 through July 2012. More than 80 crates arrived in April 2012 carrying well over 40 metric ton in equipment. The laser was first operated in July 2012 at which time a new world record was set: > 1 PW peak power at a repetition rate of 1 Hz [11].

Final acceptance testing took place in September 2012.

BELLA LASER PERFORMANCE

The overall layout of the BELLA facility is shown in Fig. 1. The laser system occupies a large optical table located in the BELLA laser bay. The power supplies for the laser are located in a separate utility room, which is located right above the laser bay. Following a sequence of amplifiers that increases the energy of initially stretched pulses from nanoJoules to tens of Joule, a grating based optical compressor generates sub-40 fs pulses with peak power up to 1.3 PW at 1 Hz. The beam transport system delivers and focuses (with an off-axis parabola) the high power laser pulses to a target region where the plasma source is located. An achromatic high power laser diagnostic telescope images the target region onto a dedicated suite of diagnostics system to analyze the laser beam properties at all power levels. The first optic in the telescope has a hole in the middle to allow the electron beam to pass through towards a monitoring phosphor screen, an integrating current transformer, the magnetic spectrometer system and the electron beam dump. The entire system is controlled remotely via a LabVIEW based control system. Details on the laser system, laser beam transport, laser diagnostics and control system are discussed next. Details on the magnetic spectrometer design and operation will be published elsewhere.

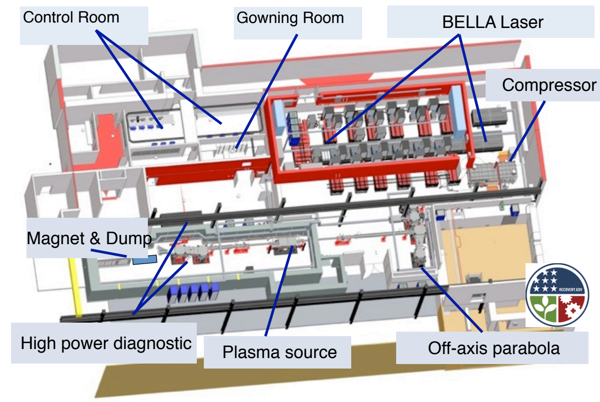

Figure 1: Layout of the BELLA facility. The laser beam is generated in the BELLA laser room. The Compressor is a grating based system for laser pulse compression. An off-axis parabola focuses the beam on the plasma source, which is located in a radiation shielded experimental area. The high power diagnostic is used to image the focused laser beam onto a broad suite of diagnostics. The magnet and beam dump are used to characterize the electron beams and safely stop them. The experiments are run remotely from a control room.

BELLA Laser System

The BELLA laser system is based on Ti:sapphire as gain medium. Pulses from a 75 MHz oscillator are first stretched, amplified in a regenerative amplifier, compressed and contrast improved in a cross-polarized wave (XPW) system. A booster amplifier and pre-amplifier followed by a first high-energy amplifier (AMP1) increase the energy to the 1.2-1.5 J level. A second high-energy amplifier (AMP2) brings the energy to about 20 J and a final amplifier (AMP3) increases this energy to as much as 65 J. The regenerative and booster amplifiers operate at 1 kHz, the preamplifier and AMP1 operate at up to 10 Hz, and AMP2 and AMP3 are operating at 1 Hz. The 1 Hz repetition rate is determined by the repetition rate of the twelve large aperture frequency doubled Nd:YAG pump lasers (GAIAs) that provide 15 J pulse energy each: four of them pump AMP2 and eight pump AMP3. The ultimate laser pulse energy in the main Ti:sapphire laser line can be adjusted with fine control from about 25 mJ to more than 40 J on target. The commissioned laser system is shown in Fig. 2.

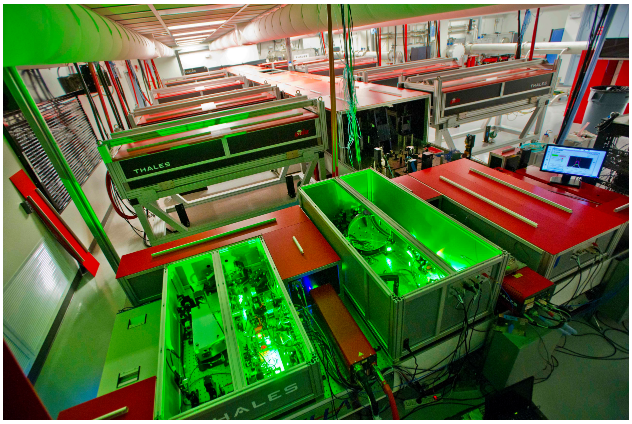

Figure 2: Picture of the BELLA laser system installed at LBNL. The green glow is from scattered light at 532 nm produced by the pump lasers in the front end of the laser. The high energy pump lasers (GAIA) are seen in the center part of the picture.

A plot of energy output vs. time is shown in Fig. 3. The best r.m.s. stability that has been obtained so far is of the order of 0.3%. The stability is affected by both vibrations causing beam motion and the stability of the pump laser systems.

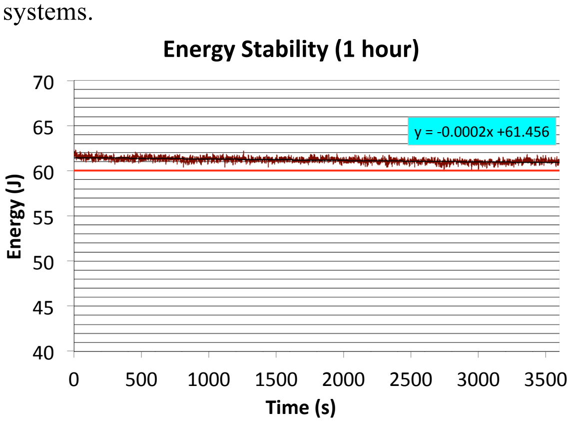

Figure 3: Example of BELLA laser energy stability vs. time.

Following amplification the wavefront of the beam can be adjusted and optimized using a commercial deformable mirror with 52 pistons. The deformable mirror (DM) has allowed focusing of the laser beam at full power onto the targets with a Strehl ratio in excess of 0.9. An example of the achieved mode profile at 32 J is shown in Fig. 5. Note that the mode was measured using an optic with hole in the middle (see below).

Following the DM, an all-reflective telescope magnifies the laser beam to ensure that the fluence is low enough to avoid damage on gratings of a four grating vacuum compressor. Pulse duration can be tuned by control of the separation of the gratings and pulse shape can be tuned using grating angles. To date, pulses as short as 35 fs have been produced at energies in excess of 42 J, i.e., providing >1 PW peak optical power in each pulse at a repetition rate of 1 Hz. The flexibility in pulse duration and energy tuning enable access to a broad range of pulse duration and peak power levels to carry out a large variety of studies of LPAs.

Laser Beam Transport System and Diagnostics

Following compression, the beam is sent to the target area using four routing mirrors, one of which is the final focusing off-axis paraboloid with a focal length of nominally 13.5 m. Each one of the routing mirrors is equipped with a beam pointing monitoring system and motorized controls to ensure correct pointing of the beam throughout the entire laser transport system. Leakage through one of the mirrors in the compressor is sent to a dedicated diagnostic bench where experiment relevant laser performance parameters are monitored. These include laser near- and far-field profiles, laser pulse shapes using a Frequency Resolved Optical Gating system (FROG/GRENOUILLE), laser pulse energy, laser pulse duration and beam wavefront using a Shack-Hartmann sensor. The wavefront sensor enables control of the DM to ensure high Strehl ratio beams at focus in the target chamber. An example of a GRENOUILLE trace and retrieved laser pulse shape are shown in Fig. 4. The shortest pulse duration obtained at the target location to date is about 35 fs (FWHM).

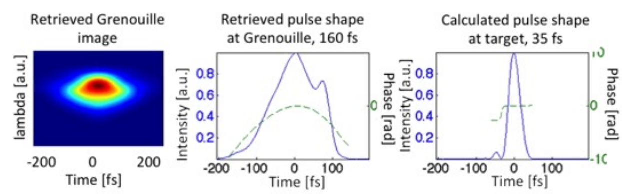

Figure 4: Example of a GRENOUILLE trace and a retrieved laser pulse shape obtained at ~ 40 J on target.

An example of the typical laser mode at medium energy is shown in Fig. 5. Similar or better quality modal shapes have been obtained at all energy levels. The Strehl ratio is typically in the range of 0.85-0.95.

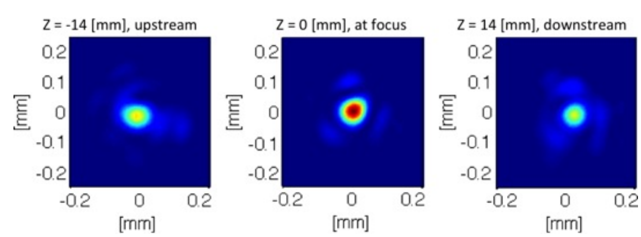

Figure 5: Example of the laser mode at ~32 J on target. The laser beam was imaged onto a 12 bit CCD camera using the high power diagnostic, including a wedge with hole. The hole contributes to the Airy pattern like fringes of the image and the actual focal quality of the beam is better as verified in separate measurements using a wedge without hole. The typical Strehl ratio of the beam at focus is higher than 0.85 and beams with 0.95 Strehl ratio have been obtained following extensive optimization with the deformable mirror.

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Significant attention has also been paid in the design and implementation of both the laser system and the beam line components. Due to the long focal length of the focusing system, tight tolerances on pointing stability are essential for experiments involving special capillary discharges. The floor of the BELLA facility was vibration tested and met tight specifications. Mirror mounts and supports were designed, constructed and tested/optimized to minimize vibrations. As a result, beam pointing stability at the focus (i.e., target chamber location) is measured to be better than 1.2 micro-rad. A beam monitoring system has been implemented to ensure also that on a day-to-day basis, the laser beam path is properly aligned.

CONTROL SYSTEM

The BELLA control system was developed in-house and incorporates requirements that had been developed during the BELLA project phase and are based on past and present experience with the development of laser plasma accelerators. The GEECS platform (Generalized Equipment and Experiment Control System) monitors and controls equipment distributed across a network, performs experiments by scanning input variables, and collects and stores various types of data synchronously from devices. Examples of devices include cameras, motors, and pressure gauges. GEECS is based upon LabView graphical object oriented programming (GOOP), allowing for a modular and scalable framework. Data is published for subscription of an arbitrary number of variables over TCP. A secondary framework allows easy development of graphical user interfaces for a combined control of any available devices on the control system without the need of programming knowledge. This allows for rapid integration of GEECS into a wide variety of systems. A database interface provides for device and process configuration while allowing the user to save large quantities of data to local or network drives.

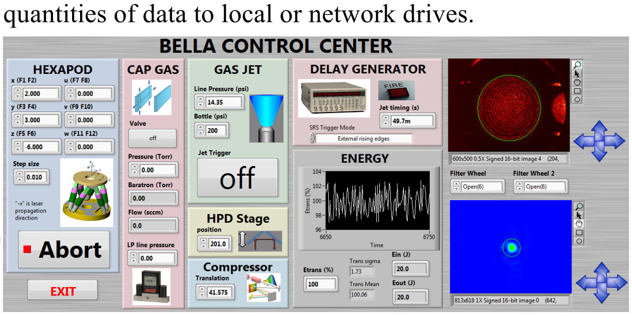

Figure 6: Graphical User Interfaces (GUI) such as this, containing data of different types, can be built in minutes with minimal programming knowledge using the GEECS framework.

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