THE BERKELEY LAB LASER ACCELERATOR (BELLA): A 10 GEV LASER PLASMA ACCELERATOR*

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Abstract

An overview is presented of the design of a 10 GeV laser plasma accelerator (LPA) that will be driven by a PW-class laser system and of the BELLA Project, under which the required Ti:sapphire laser system for the acceleration experiments is being installed. The basic design of the 10 GeV stage aims at operation in the quasi-linear regime, where the laser excited wakes are largely sinusoidal and allow acceleration of electrons and positrons. Simulations show that a 10 GeV electron beam can be generated in a meter scale plasma channel guided LPA operating at a density of about 10^{17} cm^{-3} and powered by laser pulses containing 30-40 J of energy in a 50-200 fs duration pulse, focused to a spotsize of 50-100 micron. The lay-out of the facility and laser system will be presented as well as the progress on building the facility.

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. In recent years, LPAs have made significant progress towards producing high quality beams with ever higher energy [2-3]. 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 [4-6]. In 2006 the first production was shown of GeV electron beams from a 3 cm long plasma channel guided LPA at LBNL [7]. 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 project proposal to the Department of Energy, Office of High Energy Physics in 2007. 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 mile (40 km) long machine that would produce electrons and positrons at extremely high energies (0.5 TeV center of mass) — BELLA represents an essential step towards investigating how more powerful accelerators of the future might be more compact. Systems like BELLA hold the promise of making possible a table-top accelerator with particle energies in the tens of GeV range, which would be compact and sufficiently low cost for small universities and hospitals to own.

The project phase of BELLA is comprised of the construction and commissioning of a PW-class laser that will support research aimed at the development of 10 GeV LPA modules. Upon successful completion of BELLA's project phase, the laser system and facility will be used to demonstrate 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 next discuss the basic design considerations for a BELLA 10 GeV accelerator stage, followed by simulation results from particle-in-cell codes that are capable of modeling the detailed laser-plasma interaction and acceleration processes. We then present a brief overview of the Project status.

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10 GEV STAGE DESIGN

Basic Design Considerations

Plasma-based accelerators [1] can sustain electron plasma waves with electric fields on the order of the non-relativistic wavebreaking field $E_0 = cm_e\omega_p/e$, or E_0[V/cm] $\simeq 0.96\ n_0^{1/2}$[cm^{-3}], where $\omega_p = (4\pi n_0 e^2/m_e)^{1/2}$ is the electron plasma frequency, m_e and e are the electron mass and charge, respectively, c is the vacuum speed of light and n_0 is the ambient electron density. For example, $n_0 = 10^{18}$ cm^{-3} gives $E_0 \simeq 100$ GV/m, which is approximately three orders of magnitude greater than that obtained in conventional RF linacs. The wavelength of the accelerating plasma wave (wakefield) is on the order of the plasma wavelength $\lambda_p = 2\pi c/\omega_p$, or $\lambda_p[\mu m] \simeq 3.3 \times 10^{10}(n_0[cm^{-3}])^{-1/2}$, e.g., $\lambda_p \simeq 33$ µm for $n_0 = 10^{18}$ cm^{-3}. This is very short by conventional RF linac standards, which consequently implies that ultra-short ($< \lambda_p/c$) electron bunches can be generated in plasma-based accelerators. An important parameter in the discussion of ultra-intense laser-plasma interactions is the laser strength parameter a_0, defined as the peak amplitude of the normalized vector potential of the laser field, $a = eA/mc^2$. The laser strength parameter is related to the peak intensity I and power P of a linearly polarized, Gaussian laser pulse by $a_0 \simeq 0.85 \times 10^{-9}$ $\lambda[\mu m] I^{1/2}$[W/cm^2], and P[GW] $\simeq 21.5(a_0 r_0/\lambda)^2$, where r_0 is the laser spot size at focus, $\lambda = 2\pi/k$ is the laser wavelength, $\omega = ck$ is the laser frequency, $I = 2P/\pi r_0^2$, and a vector potential of the form $a = a_0 \exp(-r^2/r_0^2) \cos(kz - \omega t)\, e_x$ is assumed.

We consider two broad regimes of operation: quasi-linear and strongly nonlinear. In both regimes, scalings [1] indicate that, assuming a guided laser at fixed intensity, the electron energy gain is limited by dephasing and is proportional to n^{-1} at a length proportional to $n^{-3/2}$, where n is the plasma density. The energy gain in the quasi-linear regime is given by ΔW_d[GeV] $\approx$ I[W/cm^2]/n[cm^{-3}], where it is assumed that the accelerator length is matched to the dephasing length $L_d \simeq (\omega^2/\omega_p^2)\ \lambda_p = (n_c/n)\ \lambda_p$ for $a_0 = 1$. Here $n_c = 1.74\text{x}10^{21}$ cm^{-3} is the critical plasma density for a laser operating at 0.8 µm. This regime offers advantages including symmetric acceleration of electrons and positrons and shaping of the fields, while the nonlinear regime offers higher gradients and uniform focusing fields. In the strongly non-linear regime, $a_0 >> 1$, the laser is sufficiently intense to completely expel all plasma electrons from its path and create a bubble-like accelerating structure [8,9]. Inside the bubble, large accelerating gradients are generated with linear transverse focusing forces for electrons. Positrons, however, can only be accelerated and focused over a very narrow region. Furthermore, continuous injection of plasma electrons from the surrounding plasma can occur along the entire length of the accelerator structure, which would result in the generation of electron beams with significant low energy background. Although the BELLA laser system will be able to access both the quasi-linear and strongly non-linear regime, in this paper we will concentrate on the design of a 10 GeV stage in the quasi-linear regime.

There are several important basic design considerations for operation in the quasi-linear regime where the wake is approximately sinusoidal. Linear theory describes the wake and energy gain as being proportional to intensity. The normalized vector potential of the drive laser beam, a_0, should be of order unity and the laser pulse length is of the order of half the plasma period. This ensures that the wake remains roughly sinusoidal, that the laser pulse couples resonantly to the plasma wave and that the dephasing distance (over which the electron outruns the accelerating wave) and the pump depletion distance (over which the laser depletes its energy by one e-folding) are about equal. The laser power must be near or below the threshold for relativistic self-focusing, as otherwise the laser self-focuses resulting in an intensity increase that can enter the non-linear regime. For a_0=1, this requires a laser spot not larger than the plasma wavelength λ_p ($k_p w_0 < 2\pi$). On the other hand, guiding of modes with $k_p w_0 < \pi$ significantly reduces laser group velocity and hence energy gain due to the relatively short dephasing distance. These limits on spot size set the power range for the laser.

The basic design of the 10 GeV LPA accelerating module is based on the assumption of an externally injected beam. Production of the initial electron beam could be accomplished in a preceding LPA of mm-scale (e.g. gas jet based) or cm-scale (capillary discharge based) by relying on the highly non-linear or bubble regime, or using techniques such as down ramp [10,11] or colliding pulse injection [12,13]. In this two-stage design, an injection structure would be integrated with the main, meter-scale, accelerator structure that is designed to operate without self-trapping [14]. This so-called dark current free structure provides the best prospect for generating low energy spread high quality beams by avoiding continuous injection along the entire length of the plasma structure.

As a numerical example of a basic LPA design that can achieve ΔW_d = 10 GeV in the quasi-linear regime [1]we apply the basic scaling laws and constraints discussed above. We find that a ~40 J laser operating at 0.8 µm wavelength, with a pulse duration of ~260 fs focused to a spot size of ~60 µm and a 0.8 m long plasma at ~$1.73\text{x}10^{17}$ cm^{-3} density are required, where we assumed $k_p w_0 = 5.9$ and $P/P_c = 0.9$. These simple scaling laws do not include important effects such as laser self-focusing and other non-linear process, and do not model the details of laser beam evolution, nor the effect of the accelerated beam on the plasma wake (i.e., beam loading). More accurate modeling using two dimensional (2D) and three dimensional (3D) simulations have been performed. Due to the fact that 3D simulations of a meter-scale LPA are computationally very challenging, a limited number of them have been done to date. Fortunately, simulations show that, in the linear regime, 2D simulations reproduce the wake with sufficient accuracy, as well as focusing and other properties of 3D simulations. In addition, a breakthrough in simulating these meter-scale LPAs in full 3D has been achieved through the use of a Lorentz boosted frame [15-17]. These simulations have been discussed in Ref. [18]. An example of input parameters and results are shown in Table 1. The key parameters (a_0, k_pL, k_pw_0) were optimized while keeping the constraints, discussed above, in mind. The density was set simply by the requirement on the energy gain of the LPA. For comparison, linear dephasing and pump depletion distances are provided. As can be seen, mildly non-linear effects result in stages that are slightly shorter than predicted from linear theory.

Table 1. Example of a Design of a Quasilinear 10 GeV BELLA Stage

Laser & Plasma Parameters	BELLA 10 GeV
Laser energy [J]	40
a_0	1.4
λ_p [μm]	107.5
k_pL_{laser}	1
L_{laser} [fs]	57
w_0 [μm]	91.4
P [TW]	554
k_pw_0	5.3
P/P_c	1.7
Linear dephasing length [m]	0.97
Pump depletion length [m]	1.98
Stage length in simulation [m]	0.6
Energy gain in simulation [GeV]	10

Techniques to increase the efficiency from laser energy to particle beam energy, and to improve the phase space properties are being developed. Use of density tapering along the propagation length can enhance energy gain and reduce energy spread by allowing phase control in the structure [19]. The difference between laser group velocity in the plasma and electron beam velocity ordinarily results in slippage or dephasing between the electron beam and wake, limiting energy gain and reducing bunch quality because the bunch is subject to fields that vary over propagation. An increasing density gradient causes the plasma wavelength to shorten, and this can be balanced to offset group velocity dephasing, and can be further adjusted to control phase in the wake. Tapered stage designs have been simulated [18] and indicate that beam energy can be enhanced significantly (3x for a linear taper and ~5x for an optimized taper) and that 10% or greater efficiency with percent energy spread is achievable.

Methods for controlling and minimizing emittance are also being studied for the BELLA 10 GeV stage design. Externally injected bunches loaded into the LPA stage with a radius that is matched to the focusing forces in the stage were shown to be accelerated without significant growth in emittance or bunch size using PIC code simulations, and particle tracking simulations in prescribed fields using the code GPT [20]. These simulations were carried out for parameters based on an analytic design of the 10 GeV stage and used Gaussian transverse laser modes. Although simplest in its implementation, one significant drawback of using Gaussian transverse laser modes, combined with the requirement that, ultimately, the stage must preserve collider-relevant emittances, is the fact that small emittance-matched bunch radii ($k_p\sigma_r < 0.1$) are required. This impacts beam loading performance and stage efficiency. High order transverse modes to shape the accelerating/focusing structure are being explored in order to allow the use of large transverse spots by mixing a zeroth and first order Laguerre-Gaussian mode. Initial simulations show that use of higher order laser modes can decrease focusing forces several fold, allowing use of larger spots and increasing energy transfer efficiency from laser to accelerated beam while maintaining emittance matching [21].

Simulations of meter-scale laser-plasma accelerators have been done by relying on the use of a Lorentz boosted computational frame implemented in WARP3D [15-16]. Figure 1 shows the density wake excited in the Lorentz boosted frame moving at $\gamma = 10$ by an intense laser pulse and the externally injected electron beam accelerated by the wake. A 40 J laser pulse with a pulse duration of 57 fs ($k_pL = 1$), was focused to a Gaussian transverse spot size $w_0 = 89$ μm at the plasma channel entrance. The plasma channel had an on-axis density $n_0 = 10^{17}$ cm^{-3}, a length of 0.65 m with a parabolic channel (factor=0.6) and a longitudinal taper of the form $n(x)=n_0(1.32\ x+1)$. Electrons were externally injected with an initial energy of 100 MeV and reached ~10 GeV at the exit of the structure.

In conclusion, both theoretical modeling and simulations support that 10 GeV electron beams can be produced with a >30 J laser using a pulse length of 50-120 fs and a spot size ranging from 40-100 micron. The acquisition, installation and commissioning of the laser and facility to support the research forms the main scope of the BELLA Project.

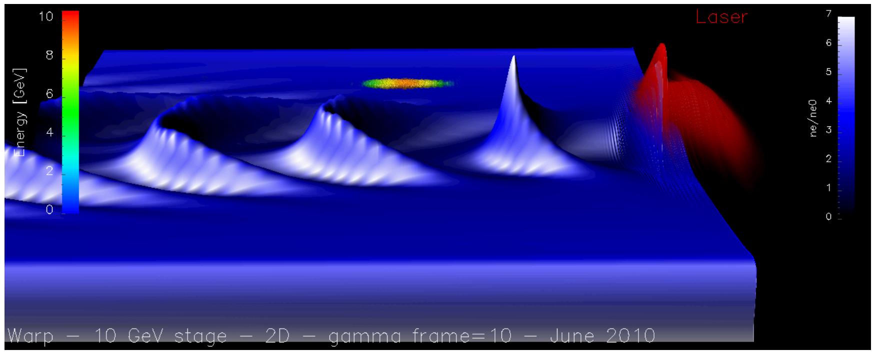

Figure 1: Simulation of a 10 GeV LPA stage from the code WARP3D, using a Lorentz boosted frame. The image shows an externally injected electron bunch (rainbow color) riding a density wake (light blue) excited by an intense laser pulse (red), propagating in a 0.65 m long plasma channel. The laser pulse (~40 J in ~57 fs), focused to ~90 μm spot size at the entrance of the channel, has reached the end of the plasma channel. The electron bunch energy has reached ~10 GeV.

BELLA PROJECT

The scope of the BELLA project includes the design and construction of the conventional facilities required to house and safely operate the BELLA laser (see Fig. 2), 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. As shown in Fig. 2, the primary elements of the facility include a laser bay which houses the laser system in a temperature and humidity controlled clean room environment (Class 10,000 and local Class 1,000 areas); a power supply and utility room located on top of the roof; a shielded experimental cave; and a control room. The BELLA laser is under construction by a commercial vendor (THALES) [22] and will be installed and commissioned at LBNL. The laser system will be capable of delivering >40 Joules of infrared laser energy (at a wavelength ~ 0.8 μm) per pulse in <30 fs (i.e., providing >1.3 PW peak optical power in each pulse) for experiments at a repetition rate of 1 Hz. Based on the design studies for the 10 GeV stage, laser pulses with pulse durations ranging from the minimum pulse duration of 30 fs to several 100 fs long pulses will be provided to the experiment by an adjustable final pulse compressor system. At the present time, the front-end of the laser system (>1.7 J at 10 Hz) as well as eight of the twelve pump laser systems (each producing >14 J at 532 nm, at 1 Hz) have been constructed and are operational at the THALES facility. Final commissioning of the laser system will be done at Berkeley during 2012.

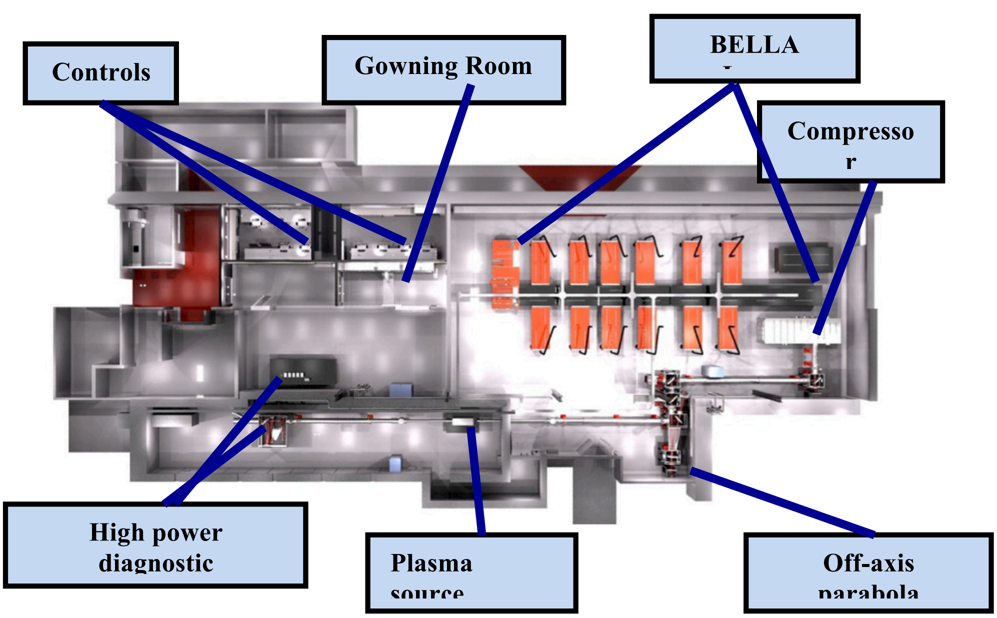

Figure 2: Lay-out of the BELLA Facility, which is under construction at LBNL.

To control the transverse mode profile of the laser beam, a deformable mirror and techniques to produce higher order modes will be implemented.

The laser system will have an elaborate continuous monitoring and diagnostic system, built-in by the vendor, providing vital information on the pulse energies, spectral properties and pointing of the main laser beam at various stages of the laser chain, as well as information on the pump laser beams (homogeneity, amplitude, pointing, and timing). A pilot laser beam inserted immediately before the final amplifier will also be part of the system, and will be used for aiming the main laser beam for experiments.

As part of the BELLA Project phase, there are three subsystems that will control and/or characterize the laser beam after it leaves the laser system. These subsystems are the 'Compressor to Final Focus Diagnostic' system, the 'Final Focusing and Beam Transport' system, and the 'Final Focus Diagnostic (Low Power)'. The purpose of the 'Compressor to Final Focus Diagnostic' system situated after the compressor is to measure the key properties of the laser beam prior to sending the pulses onto the final focusing optics. This diagnostic system is being built by THALES and has the capability of monitoring crucial laser parameters of every shot that is sent to the target area, at a 1 Hz repetition rate. The purpose of the 'Final Focus and Beam Transport' system is to focus the beam to a spot size of order 50-100 μm with an achromatic, all-reflective off-axis paraboloidal mirror (OAP). The 'Final Focus Diagnostic (Low Power)' system will be used to verify the laser focal spot quality and its position at a plane where, following completion of the BELLA Project, the plasma based targets will be located during experiments with the BELLA laser.

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 levels; a separate utility room that will house 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 ands experiments. Facility construction at LBNL is currently underway with beneficial occupancy expected by September 2011.

In parallel with the facility construction, work is going on for the design and construction of a 'Final Focus Diagnostic (High Power),' a meter-scale plasma structure, and electron beam diagnostics. The 'Final Focus Diagnostic (High Power)' system will be capable of measuring the beam properties of the laser at all power levels up to full power, at the entrance and exit (1 meter downstream) locations of the plasma target. The entrance of the plasma target will be the vacuum focus location of the BELLA laser beam. The diagnostic includes an all-reflective, achromatic beam attenuation and imaging system, as well as a diagnostic suite similar to the post-compressor diagnostic system. Details on the meter-scale structure and electron diagnostic will be discussed in later publications.

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REFERENCES

[1] E. Esarey, C. B. Schroeder, and W. P. Leemans, Rev. Mod. Phys. 81, 1229-1285 (2009).
[2] W. P. Leemans and E. Esarey, Physics Today 62, 44-49 (2009).
[3] C. B. Schroeder, E. Esarey, C. Geddes, C. Benedetti, and W. P. Leemans, Phys. Rev. ST-Accel. Beams, 13, 101301 (2010).
[4] C. G. R. Geddes et al., Nature 431, 538 (2004).
[5] S. P. D. Mangles et al., Nature 431, 535 (2004).
[6] J. Faure et al., Nature 431, 541 (2004).
[7] W. P. Leemans et al., Nature Physics 2, 696 (2006).
[8] A. Pukhov, J. Meyer-ter-Vehn, Appl. Phys. B 74, 355 (2002).
[9] W. Lu et al., Phys. Rev. ST-Accel. Beams 10, 061301 (2007).
[10] S. Bulanov, N. Naumova, F. Pegoraro, and J. Sakai, Phys. Rev. E 58, R5257 (1998).
[11] C. G. R. Geddes et al., Phys. Rev. Lett. 100, 215004 (2008).
[12] E. Esarey et al., Phys. Rev. Lett. 79, 2682 (1997).
[13] J. Faure et al., Nature 444, 737 (2006).
[14] A. J. W. Reitsma et al., Phys. Rev. ST-Accel. Beams 5, 051302 (2002).
[15] J. L. Vay, Phys. Rev. Lett. 98, 130405 (2007).
[16] J. L. Vay, et al., J. Phys. Conf. Series 180, 12006 (2009).
[17] S. F. Martins et al., Nature Physics 6, 311 (2010).
[18] W. Leemans et al., Proc. 2010 Advanced Accel. Concepts Workshop, AIP Conf. Proc. 1299, p. 3-11 (2010).
[19] W. Rittershofer et al., Phys. Plasmas 17, 063104 (2010).
[20] http://www.pulsar.nl/gpt
[21] E. Cormier-Michel et al., Phys. Rev. ST-Accel. Beams, 14, 031303 (2011).
[22] http://thales.nuxit.net/