White Paper for *Frontiers of Plasma Science Panel*

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Indicate the primary area this white paper addresses by placing "P" in right column.
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	"P", "S"
• Plasma Atomic physics and the interface with chemistry and biology	
• Turbulence and transport	
• Interactions of plasmas and waves	P
• Plasma self-organization	
• Statistical mechanics of plasmas	

Indicate type of presentation desired at Town Hall Meeting.

	"X"
Oral	X
Poster	
Either Oral or Poster	
Will not attend	

Title:	Ultra-intense laser-matter interactions with the BELLA-i PW laser facility
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- ***Research frontier* and importance of the scientific challenge.**

The new generation of short-pulse PW lasers (tens of J in tens of fs) [1]are capable of producing unprecedentedly high laser intensities (in excess of 10^{21} W/cm^2) on target. This new technology has ushered in a new regime of ultra-intense laser-matter interactions that has not been previously accessible with traditional long-pulse lasers or with short-pulse lasers below the PW level. Some of the new frontier plasma science that can be studied with ultrahigh intensity include (details on some of these studies can be found in other white papers from LBNL):

- *Laser acceleration of ions*: A number of regimes can be investigated, including Target Normal Sheath Acceleration (TNSA) [2-4], Radiation Pressure Acceleration (RPA)[5-10], Directed Coulomb Explosion (DCE) [11, 12], and Magnetic Vortex Acceleration (MVA) [13]. Particle-in-Cell (PIC) simulations of the PW laser interactions with different targets in the RPA, MVA, and DCE regimes show that 200-300 MeV proton beams can be generated.
- *Electron acceleration in high nonlinear wakes*: Very high laser intensity produces highly nonlinear (blowout or bubble regime) wakes in underdense plasma [14]. Associated physics includes self-trapping and acceleration of electrons [14], nonlinear laser pulse evolution [14], bow waves [15] , and very high harmonic emission [16-19].

- *Flying plasma mirrors*: Dense sheets of plasma can be laser-accelerated to relativistic velocities from which a second laser pulse can be reflected and upshifted to produce coherent x-rays [20]. Flying mirrors can be produced by highly nonlinear wakes in underdense plasma [21] or by laser acceleration of thin foils [22][23, 24].
- *High intensity particle physics*: Nonlinear QED (nonperturbative quantum field theory) effects can be observed in the interaction of an intense laser pulse (< 10^{21} W/cm^2) with a counter-streaming relativistic electron beam (~ 1 GeV or higher). These include the multiphoton Compton effect and multiphoton Breit-Wheeler effect [25].
- *Warm dense matter*: Laser accelerated ions can be used for the isochoric heating of warm dense matter for equation of state and related studies [12]. Simulations indicate that PW lasers can drive targets to temperatures > 10 eV and pressures > 10 Mbar.
- *Laboratory astrophysics*: Many intense laser-plasma interaction phenomena have close analogies with astrophysical phenomena, these include bow waves, collisional shock waves [26], various instabilities, and magnetic reconnection [27].
- *Other applications of laser-accelerated ion beams*: Laser-accelerated ion beams can be used for a wide variety of studies including applications in hadron theory, nuclear physics, active interrogation, material dynamics, radiation hardness testing, etc.

To access this new regime of frontier plasma science, the BELLA-i PW laser facility is under development at LBNL. The goals of the BELLA-i facility are two-fold: (1) To extend the reach of the present BELLA PW laser facility at LBNL by providing short-focal-length beam lines that will enable a wide variety of experimental studies with ultrahigh laser intensity (>10^{21} W/cm^2), and (2) engage the intense laser community by providing user access to the BELLA-i beam lines.

The BELLA-i facility would be open to users from the frontier plasma science community. A scientific advisory committee would be established to evaluate proposals submitted by potential users. The LBNL staff would draw upon the considerable experience available at LBNL on operating user facilities, including the Advance Light Source, the 88-inch cyclotron, and the Molecular Foundry, to ensure efficient and effective operation of the BELLA-i facility. Creation of the BELLA-i facility would allow the US to remain competitive with the considerable investments being made overseas on intense laser facilities, e.g., the three research centers comprising the Extreme Light Infrastructure in Europe (with an investment near one billion euro), which will be used to study a wide range of basic physics and applied science with high-power (1-10 PW), short-pulse lasers.

- ***Approach to advancing the frontier and new research tools or capabilities that are required.***

The BELLA facility at LBNL incudes the state-of-the-art BELLA PW laser system that provides 40 J, 30 fs laser pulses at a repetition rate of 1 Hz [1]. This is currently the only PW laser in the world operating at this repetition rate and allows experimental studies that produce "science with error bars." Presently the BELLA facility includes a single long-focal-length beam line to provide laser pulses at focus with relatively modest intensities (~ 10^{19} W/cm^2) at relatively large spot sizes (~ 55 microns). This modest intensity and large focal spot is well suited to study laser-plasma acceleration of electrons in the mildly nonlinear wakefield regime in an underdense plasma. The primary objective of the long-focal length BELLA beamline is to demonstrate the laser-plasma acceleration of electrons to the 10 GeV level

using a 10-cm long capillary-discharge-based plasma channel. Experiments on electron acceleration are carried out in a fully shielded cave that houses gas jet or capillary discharge plasma targets, a 10 GeV magnetic spectrometer, high resolution optical spectrometers, and a beam dump, as well as other diagnostics. Recent experiments on the long-focal-length BELLA beamline have demonstrated the production of high quality electrons beams at 4.2 GeV [28].

The BELLA-i facility would include the construction of two new short-focal-length beam lines. Two additional experimental caves would be constructed, which would more than double the amount of shielded space available for experiments. Then new beam lines would consist of a turning box that would direct the BELLA laser pulse to either the long-focal-length beam line or the new BELLA-i beam lines. After the turning box, the laser pulse would pass through a double-plasma-mirror system to produce pulses with exceedingly high contrast > 10^{11} (pre-pulse elimination), which is absolutely necessary to carry out studies on different regimes of ion acceleration from thin foils. After the plasma mirror system, the BELLA-i beam line is split into two separate beam lines directed into two separate experimental caves. Short focal length (~ 1 m) off-axis parabolas would be installed to provide focal spots ~ 4-5 microns and focal intensities 3-5x10^{21} W/cm^2. The first experimental cave would consist of an experimental chamber a variety of diagnostics, such as a betatron x-ray backlighter, for the study of a wide-range of intense laser-matter interactions. The second cave would consist of a second experimental chamber and appropriate diagnostics for the primary purpose of laser acceleration of ions. Included in the second cave would be a superconducting magnetic transport system design to transport and focus the laser-accelerated ion beam to a separate "sample" experimental chamber in which a wide variety of experiments can be carried out using the unique ion beams produced upstream.

- ***Impact of this research on plasma science and related disciplines and potential for societal benefit.***

The BELLA-i beamlines would provide ultrahigh intensity (>10^{21} W/cm^2) PW laser pulses thereby greatly enhancing the physics reach of the BELLA facility at LBNL. The ultrahigh laser intensity would enable a wide variety of experimental studies in frontier plasma science, including ion acceleration in multiple regimes, nonlinear wakefield acceleration of electrons and related phenomena, flying mirrors for coherent x-ray production, fundamental processes in high intensity particle physics (nonlinear QED), isochoric heating of warm dense matter, laboratory astrophysics, and the application of laser-accelerated ion beams to hadron therapy and medicine, nuclear physics, active interrogation, material dynamics, and radiation hardness testing. The BELLA-i beam lines would be developed as a user facility, thereby engaging the frontier plasma science community in a wide variety of studies. The BELLA-i facility would ensure that the US remain competitive in a very exciting and active field of research that is receiving very considerable funding overseas.

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Figures

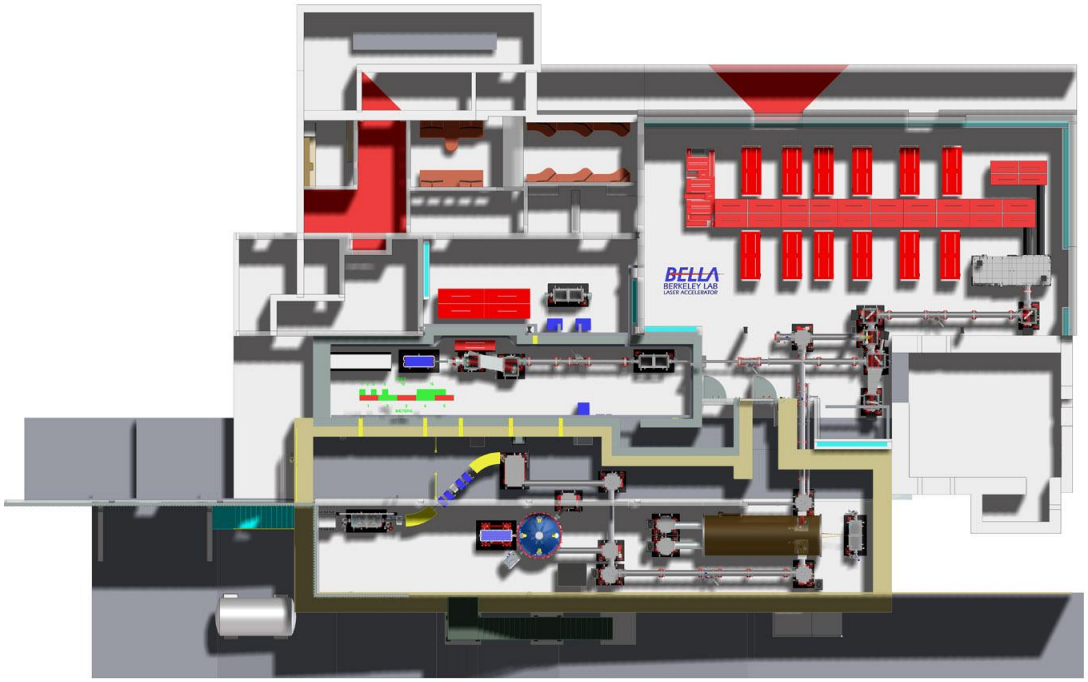

Fig. 1: Floor plan of the existing BELLA PW laser, the long-focal-length BELLA beam line, and the proposed short-focal-length BELLA-i beam lines and associated equipment.

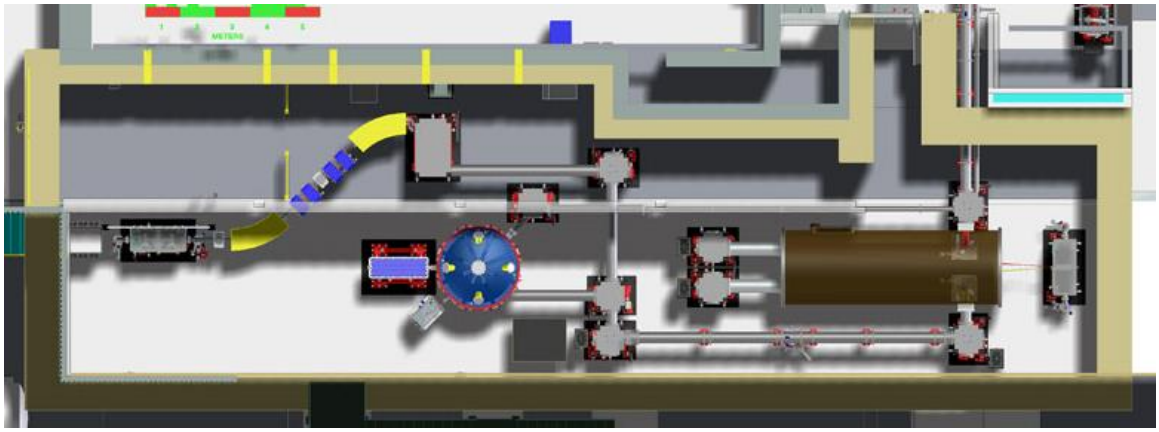

Fig. 2: Floor plan of the proposed short-focal-length BELLA-i beam lines and associated equipment. The PW BELLA laser (along with a probe laser) enters at the upper right. This is followed by a double plasma mirror system for contrast enhancement and beam lines to transport and focus the laser to two experimental chambers. The second chamber includes a superconducting magnet to transport laser-accelerated ions for use in additional experiments