Snowmass21 Letter of Interest: Near-term R&D at BELLA towards a laser-plasma-based collider

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Introduction Laser-plasma accelerators (LPAs) have been proposed as the basis for electron-positron colliders with TeV energy since they offer the possibility of orders of magnitude reduction in the size and an associated reduction in cost. Given the great potential of compact, high gradient, advanced accelerator technologies, such as laser-plasma acceleration, the DOE HEP Office published a report outlining an R&D roadmap toward a collider [1]. The BELLA Center [2] is addressing each of the R&D topics, which include increasing single-stage energy and beam quality, high-efficiency staged acceleration with emittance preservation, and positron acceleration [3].

For efficient staged LPAs [4], there are several technologies that need to be developed. For example, technology must be developed to generate a sufficiently high-quality single stage [5, 6] and to coupling of these single stages, which in turn requires efficient beam transport [7] and coupling of laser energy to subsequent stages. In this Letter of Intent we discuss the technology challenges being addressed by the present R&D program at the BELLA Center.

Optimization of a single LPA stage The long-term goal of the LPA single-stage development at the BELLA Center is to produce a collider-relevant module with about 10 GeV energy gain. The first step is producing the accelerating structure, and the current method is driving a wakefield inside a laser-heated capillary discharge waveguide. Recently, beams up to 8 GeV were demonstrated using this technique [8].

In order to increase the beam energy to 10 GeV, particle-in-cell simulations show that several refinements to the waveguide and the laser system are required. The on-axis density of the waveguide must be reduced to $\simeq 2.2 \times 10^{17}\text{cm}^{-3}$ while maintaining a low matched spot size of $\simeq 65\,\mu$m. It is being investigated whether this can be done with the system currently installed on the BELLA beamline by optimization of the heater laser pulse. We are also investigating the use of alternative waveguide technologies, which are described in Ref. [6]. Increasing the beam energy with the BELLA laser system can also be made possible by spatio-temporal shaping. For example, the near-field profile of current high power laser systems is not ideal for LPAs [9]. Both smoothing of the top-hat near-field spatial profiles, as well as conversion to a Gaussian spatial profile, would be beneficial in increasing the efficiency of laser beam to electron beam energy. Of course, significantly enhanced control and stabilization of high power laser pulses is expected to be realized as kHz systems come online, but there are also significant improvements to be made on current lower repetition rate (1-10 Hz) systems.

In addition to increasing beam energy, the beam quality available from a single stage must be significantly improved to show collider relevance. An important step toward this is demonstrating the production of a

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significantly strong and controlled wakefield over sufficient length without self-trapping of electrons. Due to the requirement of lower density, this may require waveguide development beyond what has been achieved with the inverse bremsstrahlung (collisional) heating technique, motivating work on new guiding techniques [6]. In the first phase, we will implement localized ionization injection to demonstrate high energy beams without the significant low energy components. This is a precursor to significant brightness enhancement that is possible with multi-pulse injectors (e.g., two-color ionization) [10, 11, 5]. Localized injection in a quasi-linear regime using a preformed waveguide allows for a number of important physics studies, including the exploration of dephasing mitigation through plasma density tapering.

Staging Experiments Since collider relevant LPAs relying on a single-stage require short pulse laser systems with >kJ energy operating at >kHz, conceptual collider designs rely on staging, in which depleted laser energy is introduced at each stage with a new pulse [12]. Initial proof-of-principle staging experiments using plasma mirrors have been performed [13]. The next steps are to perform LPA staging at multi-GeV, to increase beam capture (efficiency), and to preserve beam emittance during transport and acceleration. This is the primary mission of the BELLA 2nd Beamline Project, which is currently under construction.

In order to couple the electron beam from one structure to another efficiently, one must be able to generate a low energy spread, low emittance electron beam that can be accurately pointed to the lens that images the beam onto the subsequent stage. However, the requirements of percent level energy spread, >GeV energy, and sub-milliradian pointing fluctuation have not been demonstrated simultaneously. Advanced injection techniques [5] will be required, although it should be noted that collider-relevant parameters will be incredibly challenging, requiring laser stabilization well beyond state of the art, and only possible using active feedback at $\sim$ kHz repetition rates.

With sufficient beam quality, a focusing element can then be used to couple the beam to the second LPA stage. This topic is discussed in Ref. [7]. At BELLA we are considering the use of capillary discharge waveguides, which have been used to successfully focus electron beams in a compact fashion. Ongoing research is required to fully understand and perhaps mitigate the effects of detrimental wakefield generation and beam filamentation in the plasma lens, arising from the high current nature of the electron beams.

A method to couple the second beamline laser pulse to the second stage, is required. Proof-of-principle experiments employed plasma mirrors based on tapes [13]. Liquid crystal plasma mirrors [14] are also being considered since they have the advantage of being thinner, and therefore inducing negligible emittance degradation [15]. Moreover, significantly less debris is expected from liquid crystal films than from tape plasma mirrors. However R&D is required to improve the surface pointing and shape change on each laser shot, and to investigate the possibility of including the heater beam for staging experiments. Increasing repetition rate is also a significant challenge. An alternative solution may be to employ curved plasma channels, as discussed in [6].

With sufficient beam quality from the first stage and optimized matching, particle-in-cell simulations show a small electron bunch size in the second stage and 100% charge transport efficiency [16]. Optimized matching is critical to reduced transverse and longitudinal wake evolution, for example mitigating the effect of charge loss when large laser intensity fluctuations induce significant changes in the wake structure. This will require optimization of both the laser system and the plasma channel [6].

Summary The BELLA Center is addressing each of the components of the DOE HEP R&D laser-plasma accelerator roadmap towards a collider [1]. For a single stage, this means approximately 10 GeV energy gain with unprecedented beam quality. This will require well-matched guiding and controlled injection. Achieving a collider relevant 10 GeV stage is challenging and only possible with a sustained effort. The BELLA PW Laser Facility is well suited to lead this research. In order to reach collider-relevant beam energy with high charge, staging is required. In order to move from proof-of-principle experiments to multi-GeV, highly efficient, emittance-preserving stages, numerous technologies need to be developed in concert. Demonstrating this multi-GeV staging is the goal of the 2nd Beamline Project currently under construction at the BELLA Center.

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