Reply to "Comment on 'Beamstrahlung considerations in laser-plasma-accelerator-based linear colliders' "

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(Received 18 July 2013; published 4 October 2013)

We reply to Lebedev and Nagaitsev's foregoing Comment [Phys. Rev. ST Accel. Beams **16**, 108001 (2013)]. We disagree with the conclusion of the Comment that scattering imposes a fundamental limitation on plasma-based accelerator technology. Laser-plasma accelerators are compatible with high-luminosity collider concepts.

DOI: 10.1103/PhysRevSTAB.16.108002 PACS numbers: 52.38.Kd, 41.75.Lx

The foregoing Comment by Lebedev and Nagaitsev [1] offers some detailed criticisms on the "set of parameters for a TeV-scale collider" presented in our previous papers, Refs. [2,3]. Furthermore, they claim that "interactions of accelerating beam with plasma impose fundamental limitations on beam properties and, thus, on attainable luminosity values." We address these criticisms and, in particular, we disagree with the assertion that scattering imposes a fundamental limitation on plasma-based accelerator technology.

The main goal of our paper, Ref. [2], and the earlier work, Ref. [3], is to present scaling laws for some of the important quantities of a collider based on laser-plasma accelerators (LPAs) and to discuss some of the implications of these scaling laws. These scaling laws were derived largely from analytic theory and show the dependency of the various quantities on the plasma density and laser wavelength. These scaling laws were used to discuss, for example, the advantages and disadvantages of operating at low versus high plasma density. They are also of use to provide order-of-magnitude estimates for the required laser parameters. For example, the average laser power needed to drive an LPA stage for collider applications is found to be orders of magnitude beyond the capabilities of present short-pulse laser systems, thus indicating the need to further the development of high-average-power, short-pulse laser technology.

As an illustrative example, we presented a "set of parameters" for an LPA-based collider operating at a specific value of plasma density and for a specific laser wavelength. This set of parameters was based on our scaling laws, along with optimistic assumptions with respect to obtainable efficiencies. For example, we assumed that the amount of charge that could be accelerated was close to the ideal beam-loading limit [4]. Operating near the beam-loading limit is required for high efficiency. We should emphasize that the coefficients used in these scaling laws are only useful to give order-of-magnitude estimates for various quantities. Indeed, the expression used by the authors of Ref. [1] to estimate the beam-loading limit, and then claim that the beam-loading limit "happens to be slightly lower than the value the authors use in their concept," is only an approximation in the linear one-dimensional regime. Many of the criticisms of our set of parameters made in Ref. [1] are beyond the detail that can ascertained by the derived scaling laws. Our papers should not be misconstrued as providing a detailed and *optimized* conceptual design study of an LPA-based collider. Such a design study is clearly beyond the scope of our work.

Furthermore, we should emphasize that our scaling laws were determined by considering only the LPA-based linacs, i.e., determined by the physics of a single LPA stage and extrapolation to higher energies by the coupling of many LPA stages. Other important components of a collider, such as the injector, cooling stages, and the final focus, were not considered. For example, since the final focus is not discussed, the required emittance to achieve the 10 nm scale spot size at the interaction point (IP), resulting in the high luminosity, $2 \times 10^{34}\ \mathrm{s}^{-1}\,\mathrm{cm}^{-2}$, is not discussed.

The issue of beam scattering in the plasma is well known [5,6], and emittance growth due to scattering will occur. This was correctly pointed out in Ref. [1] for the case of an LPA-based collider that uses a *uniform* plasma.

We disagree, however, with the assertion that scattering is a *fundamental* limitation to plasma-based accelerator technology. If the emittance growth is too large (due to scattering or some other mechanism), such that the spot size at the IP cannot be achieved by a conventional final focus system, then novel methods may be considered, such as an adiabatic plasma lens [7]. Technical solutions may also be considered to mitigate scattering. For example, a hollow plasma channel [8,9] could be employed, instead of a parabolic plasma channel, to eliminate Coulomb scattering. A detailed analysis of the mitigation of scattering using hollow plasma channels, as well as scattering in homogeneous plasma, can be found in Ref. [10]. It should be noted that all the plasma density and laser wavelength scalings presented in Ref. [2] are valid for a hollow plasma channel. Because of the rapid acceleration provided by plasma accelerators, beam cooling may also be a potential solution. Furthermore, we note that collisional emittance growth in homogeneous plasma is greatly reduced for the acceleration of heavier particles, such as relativistic beams of muons or protons.

In Ref. [1], the authors of the Comment state "our attempts to correct the above problems by adjusting the parameters while keeping the same overall performance (i.e., beamstrahlung, luminosity, and power consumption) were unsuccessful." We wish to point out that it is straightforward to generate a set of parameters that satisfy the stated collider performance goals by using the scaling laws and other concepts discussed in our papers. It is well known that shaped bunches may be used, in principle, to eliminate energy spread, while achieving high gradients and high efficiency [4]. Table I of Ref. [2] assumed 6% overall efficiency (including wall-to-laser, laser-to-plasma, and plasma-to-beam efficiencies). As discussed in Ref. [2], improved plasma-to-beam efficiency can be obtained using a current distribution in a multibunch train format. For example, if ~40% plasma-to-beam efficiency is desired, then, using the same laser-plasma parameters of Table I, a two-bunch train, each with 2×10^9 particles and rms length 2 μm, focused to 7 nm spot size at the IP, would have ~40% plasma-to-beam efficiency and achieve the same collider performance as shown in Table I of Ref. [2] (i.e., the same luminosity, wall-plug power, and beamstrahlung photons per electron).

The essence of our paper, Ref. [2], is a discussion of LPA scaling laws (dependency on plasma density and laser wavelength), and, in particular, the effect of beamstrahlung when operating at plasma densities below 10^{16} cm^{-3}. The scaling laws derived and the conclusions of our paper (e.g., the effect of beamstrahlung at low plasma densities) are correct. Again, we emphasize that this work is not a technical design report for a collider. As stated in the conclusion of Ref. [2], "A TeV linear collider is extremely challenging for any accelerator technology. Although LPA technology has made rapid experimental progress in recent years, significant laser technology developments are required, as well as LPA maturity, before a detailed LPA-based collider design (i.e., integrated injector, cooling, LPA-based linac, and final focus) is possible. We anticipate that the LPA-collider design will evolve with better understanding of the laser-plasma physics, based on future experimental results, and as the laser technology advances."

This work was supported by the Director, Office of Science, Office of High Energy Physics, of the U.S. Department of Energy under Contract No. DE-AC02-05CH11231.

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