Snowmass 2021 Letter of Interest:
Accelerator phase space-control using high-intensity lasers

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Introduction High power lasers generate the largest electro-magnetic fields that can currently be realised in a controlled lab environment. In combination with a suitable plasma, such lasers may be used as drivers of wakefields for lepton acceleration, one important application being a plasma-based particle collider [1, 2]. From a theoretical perspective, the fields of intensely focused lasers explore the physics of strong field quantum electrodynamics (SFQED). This regime is parameterized by the (beamstrahlung) parameter $\chi = E_\star/E_S$, where $E_\star$ is the the electric field in the rest frame of a charged particle probing the laser, and $E_S = m^2c^3/e\hbar$ is the Sauter-Schwinger QED-critical field [2, 3]. The deep quantum regime, $\chi \gg 1$, is relevant e.g. for the final focus of lepton colliders [4, 5] and requires new theoretical ideas [2]. With this LOI we present arguments for pursuing the following high-field research avenues, all based on laser and electron beam phase space control: (i) radiative momentum transfer of accelerated charges, (ii) the conversion of electrons/photons into new particles, hence the realisation of strong-field particle sources and (iii) the addition of spin-polarisation degrees of freedom. In the latter case, high-intensity lasers and their interactions may provide methods for manipulation of the position-momentum-spin phase-space beams through quantum processes.

Radiative momentum transfer in strong fields For plasma based accelerator applications, at the highest particle energies, the emission of photons in the wakefields may need consideration. Stochastic photon emission processes change the momentum distribution of the leptons, and when combined with structured intense laser light or wakefields may lead to new avenues for quantum beam physics such as radiative cooling of beams. The importance of radiation-"friction", i.e. the energy loss due to photon emission as high-energy particles traverse accelerator field structures has been known since the early days of synchrotron radiation as reviewed e.g. in [6]. However, the exact form of the classical equation of motion in the presence of radiation reaction is still under discussion in the scientific community. In strong field *gradients*, photon emission is expected to be more complex as ponderomotive forces need to be included. As more energetic electron beams interacting with more intense lasers are being considered, the classical description of radiation reaction ceases to be valid. Within a quantum formulation, the derivation of radiation reaction from (SF)QED has seen some progress recently (see [7] and references therein), but a comprehensive and systematic approach is still missing. Such an approach would have to explain a number of quantum phenomena, such as stochastic photon emission [8], the hard cutoff in the emitted photon spectrum [9], as well as the effects of straggling [10], quantum quenching [11], and trapping in travelling [12, 13] and standing [14, 15, 16] EM fields. The trapping dynamics resembles anomalous attractors [17]. These effects can lead to both a contraction/cooling and heating of the beam phase space. Detailed investigations on the opportunities for phase space control of high-energy lepton beams need to be performed.

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Quantum radiation reaction has been the subject of active theoretical and computational research in the past decade (see e.g.[18, 19, 20, 21, 8, 22, 23]). Recently, these efforts have been matched by two experiments at the Central Laser Facility of the Rutherford-Appleton lab to study quantum radiation reaction in interactions of GeV-class electron beams with intense laser pulses at $\chi < 1$ [24, 25]. These experiments had rather low statistics which made a clear-cut analysis difficult. Clearly, additional experimental effort is required here [26].

Going to higher intensities ($\chi \gg 1$) requires stronger beam focusing, but simultaneously this opens new avenues for research and development. The ultimate 4π focusing of the EM waves, usually realized through the use of multiple colliding laser pulses, is predicted to efficiently generate high energy photons when complimented with a high energy electron beam, provide the environment for the study of different types of EM cascades, and allow to study the extreme cases of electron beam and laser pulse energy depletion [27, 28]. However, from a theoretical point of view, in the case of extreme focusing, one needs to go beyond the standard ‘locally constant field approximation’ [29, 30] which basically treats the laser background as slowly varying in space and time. This ceases to be valid at strong focusing, e.g. for SFQED emission processes near the interaction point of a strongly focused collider, [4, 2] where field gradients are large.

Strong-field particle sources Phase space control is particularly important for the efficient conversion of photons and electrons into a desired species of ‘daughter’ particles, hence the realisation of particle sources. The most obvious example is positron generation based on the one- or two-step trident process [31, 32]. With suitable set-ups such as employing a two-color laser even polarized positrons may be generated [33]. Shaped strong field configurations may provide opportunities for strongly focused positron beam production or trapping. This may of particular interest for plasma based acceleration concepts, which have unique requirements for injection and accelerating [34]. Positron-electron pair generation near the final focus may be of interest since the particle beams will be neutral and therefore may undergo self-focusing / filamentary processes. A number of other particles may be generated, reviving the concept of a gamma-gamma collider based on electron-photon conversion via Compton back-scattering. This can be a useful and feasible option even at energies of the order of 1 to 10 GeV as recently reviewed in [35].

Spin dynamics and polarization in strong fields The parameter space accessible through particle collisions may be considerably enhanced by adding spin and polarization degrees of freedom, hence by considering the scattering of spin-polarized particles. For instance, the polarized deep inelastic scattering of polarized leptons on polarized protons revealed intriguing details on the spin-structure of the constituents of the proton [36, 37], and polarized beams have been used in investigations of parity non-conservation effects [38, 39]. Moreover, polarized beams are required for upcoming high-energy lepton-lepton colliders to help suppress background [40]. Plasma accelerators have been put forward as a novel concept for accelerating leptons to high energies. A full understanding of spin dynamics in plasma, including classical spin dynamics and spin scattering interactions, especially during radiation emission, has not been achieved yet. That may be why in most studies of high-intensity laser-plasma interactions the electron polarization is not taken into account [41]. Recent studies have shown that the dynamics of a spin-polarized lepton in extremely strong field *showed model-dependent discrepancies* under certain conditions [42], scrutinizing models of spinning radiating particles. This could be important at the interaction point of polarized lepton colliders, and could possibly be tested with high-power lasers. It thus seems timely to model plasma-based particle acceleration for high energy physics applications including spin dynamics.

Two avenues have been proposed so far, both requiring further study: (1) the injection of pre-polarized beams into the accelerating laser-plasma structures and (2) polarization of the accelerated high-energy beams using strong laser field exploiting SFQED effects. Regarding point (1), research so far has considered the spin precession of polarized electrons injected into a laser wakefield accelerator to determine how the beam depolarizes during acceleration [43]. The authors of [44] proposed to use ionization injection from polarized gas targets.

Regarding point (2) one can employ an analogy with synchrotron radiation, causing electrons to self-polarize via the Sokolov-Ternov effect. In the magnetic nodes of two counter-propagating circular laser pulses, the orbiting electrons can spin-polarize in a direction perpendicular to their plane of motion, in a process that takes only a few femtoseconds [45]. In collisions of electron beams with linearly polarized laser pulses one needs to break the symmetry of the oscillations of the magnetic field in order to establish a distinguished "down" direction. This can be achieved, e.g., by using ultra-short [46, 47] or bi-chromatic laser pulses, whereby both polarized electron and positron beams could be generated [33, 48]. As the methods proposed so far have not yet achieved beams of a quality required for collider applications, further research and development on this topic is necessary.

Summary Experiments involving ultra-high-intensity lasers can therefore support plasma collider development by testing reduced theories that are required to describe interaction point physics for tightly focused beams, demonstrating particle source concepts that may be used in a plasma based collider design and developing new methods for manipulating the position-momentum-spin phase-space beams through quantum processes. In the near term, facilities such as the BELLA Center and ZEUS, both having two beam-line capabilities, should provide an ideal environment for these studies.

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