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BEAM DYNAMICS CHALLENGES FOR HIGH-ENERGY LINEAR COLLIDERS

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Abstract

CLIC can in principle be extended to higher energies than the currently foreseen 3 TeV final stage. Cost and site lengths will increase. Improved accelerating structures, potentially using new materials or plasma-based colliders might nevertheless be a very cost-effective path to much higher collision energies, even within a relatively compact linear collider facility.
At these higher energies (~10 TeV or above), a linear collider would also face a power consumption or luminosity challenge. This note discussed the beam dynamics challenges, e.g. tolerances, stability, emittances, bunch structure, charge and size, that need to be faced in parallel with the gradient challenge.

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The highest energy lepton collider proposed during the Update of the European Strategy for Particle Physics[1] was CLIC, an electron-positron linear collider with an upper centre-of-mass energy of 3 TeV[2]. In addition, R&D has been proposed for two other lepton collider options that could potentially reach higher energies. One is based on the use of plasma acceleration and one on the use of muon beams.

CLIC can in principle be extended to higher energies, but the site length and cost are of concern; they would increase roughly linearly with energy. One might hope to address these issues by the use of improved materials for the accelerating structures or by the use of plasma acceleration in the main linacs - the gradients in plasma cells can be much higher than in the normal-conducting copper structures of CLIC. One can thus hope to have a significantly cheaper and shorter machine. Whether these promises of a cost reduction can be realised is largely a technology question, which can only be answered by an experimental programme. In parallel with experimental work, an integrated design study would be needed to inform parameter choices for a plasma linac, identify which energy can be reached, and compare the performance to existing main linacs designs.

At higher energies, CLIC would also face a power consumption or luminosity challenge. For the investigation of particles in the s-channel a scaling of the luminosity as $\mathcal{L} \propto s$ is required. A natural scaling for a linear collider is to maintain the beam current and increase the power consumption linearly with energy. The normalised beam emittances and the focusing beta function would remain constant. This keeps the quality of the luminosity spectrum and the hourglass effect constant. The luminosity per current then scales linearly with the energy, i.e. it remains proportional to the beam power. In practice maintaining the emittances and beta functions becomes increasingly difficult with energy, due mainly (for the latter) to radiation effects in the focusing lattice. With this scaling one can estimate that CLIC at 14 TeV would require 130 MW of beam power to provide a luminosity of 2.8×10^{35} cm^2/s; the power consumption for the drive beam would then increase to about 1.5 GW.

A plasma-based collider will have to face two important fields of beam dynamics challenges. The first is to maintain beam stability in the plasma and to preserve its quality all along the main linac. The second is to produce short, small-emittance beams and to focus them in the interaction point to produce higher beam brilliance in order to achieve high luminosity with limited beam current.

The acceleration of electrons in the plasma poses important challenges. Beam break-up is a key concern since transverse wakefield-like effects are large. Strong focusing by the plasma and ion motion might suppress the instability. However, this strong focusing introduces very tight tolerances on the driver in the plasma, be it an electron or laser pulse, as pointed out in [3]. Both a position and an angle jitter of the driver will move the focusing centre of the plasma and hence induce a jitter in the main beam. For plasma parameters proposed in the past angular tolerance of nanoradian have been found [3]. The driver would thus have to have a stability similar to the required main beam stability.

A hollow plasma would remove this effect because it does not provide focusing but in exchange it would create new challenges. The lack of stabilising focusing and ion motion will increase the challenge of beam break-up, likely by orders of magnitude. Also the walls of the hollow channel would play an important role in the beam dynamics, similar to the copper irises of normal conducting accelerating structures. One can expect the tolerance of the location of these walls to be extremely tight.

Positron acceleration is a key to a plasma collider and deserves full attention. Parameter proposals using the same bunch charge for electrons and positrons miss this key point. Studies of the collider optimisation for unequal bunch charges is a key to realistic designs.

If positrons cannot be accelerated with sufficient efficiency one can consider the use of plasma technology in a gamma-gamma collider. In this case the two electron beams would each collide with a laser beam just before the interaction point in which the high-energy backscattered photons would collide. The resulting luminosity spectrum is relatively broad and the fraction close to the highest energy is less than the luminosity achieved in electron-positron beams. It would therefore be important to reduce the collision beam sizes below the values of electron-positron colliders, which is possible from the physics point of view since beamstrahlung limitations do not play a substantial role in this scenario.

Different means can be considered for improving the luminosity to beam power ratio.

- A reduction of the vertical emittance would be beneficial both for conventional and plasma-based colliders. However, the current CLIC vertical emittance target is already very challenging and requires cutting edge technologies to align and stabilise the beamline.

- One can profit from the tendency of the plasma-based colliders to use short bunches. This would allow one in principle to reduce the vertical beta function. However, this requires an important and dedicated effort since linear colliders, in particular CLIC, attempted to reduce the vertical beta function but found limits mainly from synchrotron radiation.

- A shorter bunch also suppresses beamstrahlung at very high energies. This in principle allows one to reduce the horizontal beam size. However, again this is a challenging task because a reduction of the horizontal beta function makes it more difficult to achieve a small vertical beta function.

- A reduction of the horizontal emittance requires an important R&D effort, since the CLIC parameters use the smallest horizontal emittance that a very advanced damping ring design could obtain.

Conclusion

Improved accelerating structures, potentially using new materials or plasma-based colliders might be a cost-effective path to high collision energies in lepton colliders. However, the plasma-based approach faces important beam dynamics challenges in the main linac. In particular, very tight tolerances for the drive beam, be it electrons or laser, exists. To develop a concept of how to achieve such tolerances is thus instrumental to make a plasma-based collider an option.

In addition, plasma-based colliders have to substantially improve the low-emittance beam source and the final focusing relative to today's linear colliders. The naturally shorter bunches in such a facility allow one in principle to reduce the collision beam sizes and increase the luminosity. This requires the development of novel focusing systems and beam sources, which would be an important step to make the technology attractive for higher energies, and motivates a strong R&D programme. These efforts would also help to make a gamma-gamma collider a more attractive option.

References

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