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Challenges in Advanced Accelerator Concepts

Towards a PWFA linear collider — opportunities and challenges

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Abstract: I discuss some key opportunities and challenges of a PWFA collider, and outline some objectives which I consider important to be able to assess the machine performance, assuming that numerous technical challenges can be solved. The highlighted topics are purely the choices of this author. Several other articles in this issue are relevant for a collider design, and discuss challenges for different sub-systems of a collider, including the articles on the beam delivery system [1], drive-beam generation [2], and emittance preservation [3]. A more complete overview of agreed challenges and objectives can be found in international research roadmaps [4, 5]. Here, we highlight in particular the option of a PWFA $\gamma\gamma$ collider.

Keywords: Accelerator modelling and simulations (multi-particle dynamics, single-particle dynamics); Wake-field acceleration (laser-driven, electron-driven)

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Contents

1 Linear colliders

A high-energy, high-luminosity electron-positron (e^+e^-) collider [6–8] will provide precision measurements complementing the LHC (and the HL-LHC [9]) results, and be sensitive to beyond-Standard Model physics above the LHC energies. Two linear colliders based on RF technology have been proposed and designed: the International Linear Collider, ILC [6], and the Compact Linear Collider, CLIC [7]. The main linac of the ILC uses superconducting RF cavities operating at an accelerating gradient of 31.5 MV/m. ILC has a footprint (length) of 20–50 km with centre-of-mass energies that can be staged from 250 to 1000 GeV by extending the length. The main linac of CLIC uses normal conducting X-band RF structures operating at an accelerating gradient of 100 MV/m. The proven 100 MV/m gradient of the 12 GHz CLIC accelerating structure is mainly limited by the break-down of the electric field on the cavity wall [10]. The gradient has been achieved after decades of R&D [7, 10] into structure design, break-down physics studies and experimental tests, and is considered to be the state-of-the-art for practical achievable accelerating gradients today. Figure 1a depicts a CLIC 100 MV/m accelerating structure, of about 20 cm length. The CLIC structure has waveguides for the damping of transverse modes, depicted in figure 1b, in order to mitigate transverse instabilities [10] which must be done to preserve the transverse emittances in the main linacs. CLIC has a footprint of 11-50 km, with centre-of-mass energies that can be staged from 380 to 3000 GeV. The designs for the linear colliders have been on-going for several decades in order to develop technology and optimize choices and machine parameters. Despite a rich physics program, the current global funding climate makes the realization of the above colliders challenging, even for the first energy stages. A linear

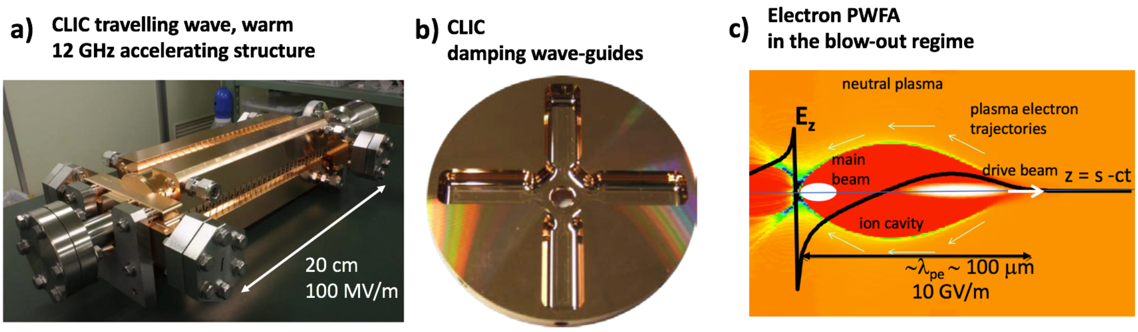

Figure 1. a) Example of a 100 MV/m gradient CLIC traveling wave structure [10]. Reproduced from [7]. CC BY 3.0. b) The wave-guides of the CLIC structure for the damping of transverse modes [10]. Reproduced from [16]. CC BY 3.0. c) A sketch of the PWFA blow-out regime [19] in which gradients of order 10 GV/m have been demonstrated: a driver creates a wave in the plasma, separating electrons from ions, setting up very strong fields that can accelerate a trailing beam. Note the difference in length scale with the CLIC structure. [7]. Reproduced from [4]. CC BY 3.0.

collider based on RF technology with centre-of-mass energies in the Multi-TeV range seem currently unlikely to be realized due to the large cost and footprint (several 10s of km). A key collider metric is the luminosity per power [7]. Taking into account the effect of beamstrahlung when the intense beams see each other's field [11], the useful luminosity is optimized when beams are flat (vertical size $\ll$ horizontal size). The scaling of the luminosity per power, $\mathscr{L}/P$, can then be expressed as [7] $\mathscr{L}/P \propto \eta/\sqrt{\sigma_z \beta_y \varepsilon_y}$. I.e. to maximize useful luminosity, the vertical emittance ε_y and the vertical focusing function β_y must be minimized, the wall-plug-to-beam efficiency η must be maximized, and bunches of short length σ_z must be collided. In addition, the energy spread must be small (sub-percent) in order to fit in the bandwidth of the beam delivery system. Novel collider concepts should provide similar (or better) power efficiency and similar (or better) beam quality than linear colliders in order to fulfil the luminosity requirements from particle physics (order $10^{34}\,\mathrm{cm}^{-1}\mathrm{s}^{-1}$ [6, 7]) with a reasonable power consumption (about 170 MW for the first stage of CLIC [12]).

2 Plasma wakefield accelerators

In order to overcome gradient limitations of the RF technology, new acceleration mechanisms have been suggested [13] with potential for much higher gradients than RF technology: dielectric acceleration, direct-laser acceleration and plasma-based acceleration. Of those, plasma-based accelerators have proven gradients of 50–100 GV/m [14, 15] and have therefore high promise to greatly reduce the footprint of a Multi-TeV collider. In a plasma-based accelerator, a drive beam propagates through a plasma, creating a strong plasma wake, and in the process losing energy to the plasma, see figure 1c. Part of this energy can be used to accelerate a trailing beam, which, in case of a collider, is the "main beam" to be collided. The driver can be a high-intensity laser beam where the ponderomotive force of the laser pulse drives a plasma wake [16, 17], or a charged particle beam, where the space charge forces drive the wake [18, 19]. As discussed above, power efficiency is of the essence for any Multi-TeV collider. For this reason it may seem, at the time of writing, that the most suited driver for collider applications is a particle beam, since the drive beam can be generated with high efficiency, e.g.

the 55% efficiency of the CLIC drive beam generation [7]. In this text we consider only particle beam-driven plasma wakefield acceleration, and use the abbreviation PWFA for this technology. While proton-driven PWFA as studied at CERN [20] is a promising concept for high-energy, fixed target applications [21], the luminosity targets for a linear collider seems currently out of reach for proton-driven PWFA [21]. We therefore further limit our discussion here to electron beam-driven PWFA.

3 Status of electron beam-driven PWFA

If the drive beam is sufficiently strong, it will expel, or “blow out”, all plasma electrons, forming an ion cavity where strong accelerating fields are formed as plasma electrons oscillate back towards the axis [22]. Figure 1c illustrates the principle of a plasma accelerator in this so called **blow-out regime** [22, 23]. The “accelerating cavity” formed by the plasma is much smaller than that of CLIC, with typical dimensions of order 10–100 µm. The blow-out regime is very well suited for electron acceleration, since a trailing electron beam placed towards the end of the blow-out will experience, in the ideal case, both an accelerating field that is independent of the radial position, as well as a linear focusing force [22, 23]. With proper beam loading [24] the accelerating field can also be made constant along the longitudinal coordinate. Therefore, in the ideal blow-out regime both the emittance and the energy spread can be preserved. The power transfer efficiency between the drive beam and main beam has been shown in simulations to be very high, up to 90%, supported by theoretical considerations [24]. This should be compared to the corresponding drive beam to main beam efficiency for CLIC, which is about 20% [7]. More than 50% power efficiency for collider-parameter PWFA has furthermore been demonstrated in 3D simulations with realistic beam parameters, e.g. [25, 26], as illustrated in figure 2b. Multiple scattering of the electrons in a plasma accelerator has been studied and, depending on the species assumed, could be consistent with collider emittance requirements [27, 28]. Ion motion [29] is another concern for emittance preservation. Recent studies, although not fully conclusive, indicate that the effect of emittance may be reduced to acceptable levels [30, 31]. Recent theoretical and experimental progress on plasma photocathodes indicate that normalized emittances of order 10 nm or less (consistent with collider requirements) may be produced in plasma [32, 33]. In short, theory and simulations indicate that the ingredients for PWFA of electron beams with high-gradient, high-efficiency, and low emittance may be present for carefully selected parameters, and for the case when components and beams are perfectly aligned.

Experimental progress for electron acceleration in the blow-out regime includes 50 GV/m acceleration gradients [14], meter-scale GV/m acceleration of a beam of electrons with reasonable efficiency [34], and more recently, GV/m acceleration of beams with up to 50% efficiency, and preserved per mille energy level spread, with good stability [35]. In general, two-beam experiments are to a large degree as expected from simulations. Where performance is poorer, compare e.g. figure 2a [34] and figure 2b [25], it has been shown to be largely consistent with non-optimal input parameters in the experiment. In this sense, experimental efforts are “lagging” behind the theoretical and numerical progress for PWFA in the blow-out regime**.** For progress towards colliders, this lag is not necessarily a show stopper, since the blow-out regime now seems sufficiently well understood to progress towards conceptual designs of plasma stages, and eventually collider design. Before a collider could be realized there exists of course a multitude of more technical challenges to be solved first [26], including

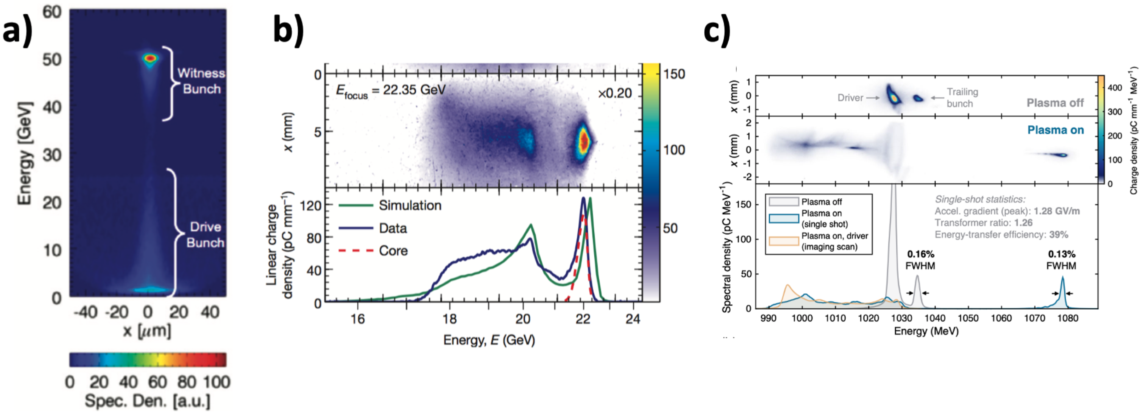

Figure 2. Examples from state-of-the-art for PWFA electron acceleration, simulation and experiment: a) Two-bunch PWFA simulation results [25]; perfectly aligned 25 GeV electron bunches, resulting in energy doubling with high-gradient (about 30 GV/m), high-efficiency (56% from wake to main beam) with low energy spread. Reproduced from [22]. © IOP Publishing Ltd. CC BY 3.0. b) Event from FACET experiments [34]; meter-scale, high-gradient (4 GV/m), high-efficiency (30% from wake to main beam) with few % energy spread. Reproduced with permission from [31]. c) Event from FLASHForward experiments [35]; improved efficiency (39% from wake to main beam), and per mille energy spread. The performance of the experiments is to a large degree as expected from simulations [25, 35]. Reproduced from[32]. CC BY 4.0.

plasma source design, plasma heating, synchronization and timing etc, but in order to correctly address these, including prototyping, it would be useful to establish a set of consistent collider parameters.

4 Status of PWFA collider studies

Several straw-man concepts for a PWFA collider have been put forward in the literature, including [26, 36, 37]. The latest iteration, written up for the US particle physics 2013 Community Summer Study [26], is illustrated in figure 3a. This concept was scrutinized and discussed with experts from the conventional accelerator community (Fermilab, CLIC, ILC), which has led to a number of constructive comments e.g. [38, 39], stimulating further work and some progress towards a PWFA-LC, see for example [39–42] (figures 3b, c, d) and a summary in [43]. However, few resources have been allocated to integrate new results into an overall concept, and there is currently no “host laboratory” for an integrated PWFA collider design study, and no significant progress has been made in quantifying the overall performance of a plasma-based collider since [26].

5 Steps towards a PWFA collider

Since [26, 36, 37] are far from being worked-out designs, no consistent parameter set exists. Even the most critical parameters are uncertain, like the collision repetition rate (is kHz optimal or is MHz desired?), the bunch length (is μm scale desirable, or is 10s of μms preferable?). How tight are the alignment tolerances? Can luminosity targets be reached, even on paper? And so on. Therefore, as of today we cannot perform a comparison between a plasma collider and existing collider projects [6, 7]. Furthermore, we cannot fully define what future test facilities are required, as we are unable to say

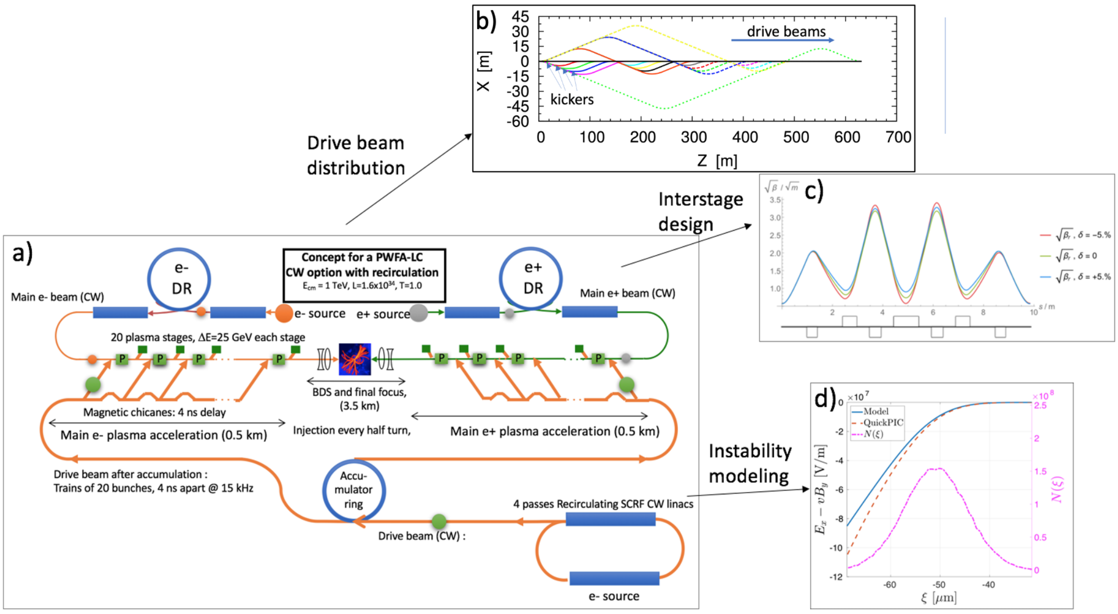

Figure 3. a) A straw-man concept for a PWFA collider, as put together for the US particle physics 2013 Community Summer Study [26]. (Reproduced with permission from [23].) The report did stimulate progress towards a collider in a number of areas, summarized in [43], for example b) drive beam distribution, adapted from [40], c) plasma linac staging [41] (Reproduced from [38]. CC BY 3.0.) and d) simplified models for transverse instabilities [42]. (Reproduced from [39]. © IOP Publishing Ltd, CC BY 3.0.) Recent developments have not been integrated into an overall concept, for reasons explained in the text.

when sufficient performance will have been achieved. Similarly, for costly start-to-end simulations for assessing collider performance [44], reasonable overall parameters should to be identified ahead of simulation runs. I think of this as a sort of knowledge gap between collider studies and experiments/test facilities. The reasons for this gap could be 1) that funding schemes favour experiments, while studies of overall concepts are disfavored, 2) the positron challenge, and 3) limited understanding of tolerances for beam and component misalignment. As a result, the progress towards a PWFA collider has been impeded. Below I give examples of some key topics needed to be addressed in order to arrive at consistent parameter sets for a PWFA collider. These have in common that a lot of progress can be made without new experimental facilities, but rather by theoretical and numerical work.

Transverse instabilities: the beam-plasma hosing instability [45–48], similar to the transverse "beam-breakup instability" found in RF linacs, is seeded by transverse beam- or plasma asymmetries, and is considered a potential impediment for realizing a PWFA collider [38, 39, 49]. Can high-gradient acceleration with high efficiency and good beam quality be achieved for a realistic machine, as opposed to a perfectly aligned machine? This depends on how well the transverse instabilities can be mitigated and how tight the corresponding transverse tolerances are. For normal conducting linear colliders like CLIC [7, 10] and NLC [50], transverse instabilities have a direct impact on main parameters and overall efficiency, as the charge per bunch needs to be limited. As a result, in CLIC the bunch charge is split in multiple bunches per RF pulse [7]. Figure 1b illustrates the damping wave-guides for CLIC, another design choice done to mitigate the transverse instabilities in the accelerating structures. How strong transverse instabilities are, how well they can be mitigated, and the

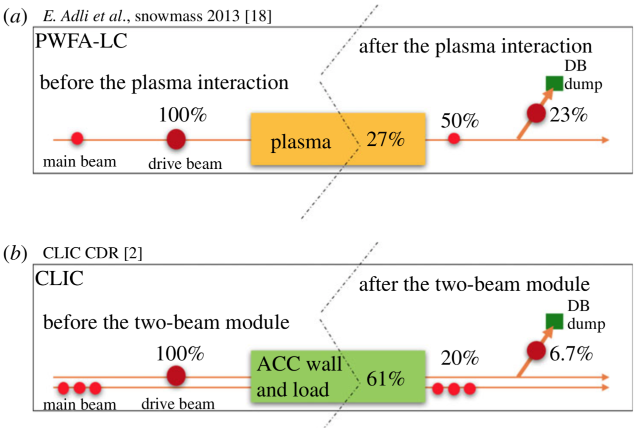

Figure 4. Drive-beam to main-beam efficiency, as simulated for a PWFA collider [26] (Reproduced with permission from [23].) (a) and as calculated for the CLIC design [7] (Reproduced from [4]. CC BY 3.0.) (b). The numbers indicate the fraction of the energy of the bunches before and after acceleration. For the PWFA collider 50% of the drive beam energy is transferred to the main beam, 27% is dumped in the plasma and 23% remains in the drive beam, sent to a beam dump. The corresponding CLIC drive-beam to main-beam efficiency is 20%. An important distinction between the two estimates is that the RF to beam efficiency of CLIC is constrained by transverse wakefields, while for the PWFA collider [26] transverse instabilities were not yet considered for the overall parameter choices, and must be taken into account in future designs.

corresponding efficiency and tolerances are considered by the accelerator community to be paramount for answering whether a plasma collider is practically realizable [38, 39, 49]. While increasingly more precise models of the transverse instabilities have been developed [45–47], there have been little published experimental results on PWFA instabilities and mitigation methods, possibly due to the fact that the beam quality in earlier experiments was not sufficient for instabilities to grow [51–53]. Figure 4, from [43], illustrates well a root of the debate on instability versus efficiency in PWFA: in simulations, PWFA has significantly better drive beam to main beam power efficiency (50%) than that of CLIC (20%), giving promise of high luminosity per power. If this 50% could be achieved in a PWFA collider, while keeping the luminosity requirement, that would be a significant advantage. Whether the high power efficiency in plasmas can be maintained when transverse instabilities are taken into account therefore needs to be investigated in detail before arriving at a conceptual design.

Bunch length/aspect ratio versus luminosity: luminosity scaling laws for e^+e^- colliders [11] indicate that one gains by using very short bunches. Since bunches of μm length scales are readily produced and accelerated in plasma-based accelerators [19], it might be possible to gain a significant luminosity factor with plasma accelerators, with respect to RF, due to shorter bunches. Preliminary studies on the luminosity scalings for short e^+e^- bunches [76], shown in figure 5, confirm that using short beams is a promising direction for further investigation in order to achieve high luminosities. The luminosities in figure 5 have been simulated assuming that the β^* can be achieved. However, in order to profit from the luminosity enhancement, novel beam delivery systems would need to be designed in order to provide the required β^* [1]. Another question is whether flat beams, with high horizontal to vertical size ratios [6, 7], are well suited for PWFA, especially in the case of positron acceleration where the beam loading and beam quality may be different in each plane [54]. Studies for an improved beam delivery system (BDS) seems therefore to be a natural part of a PWFA collider design study.

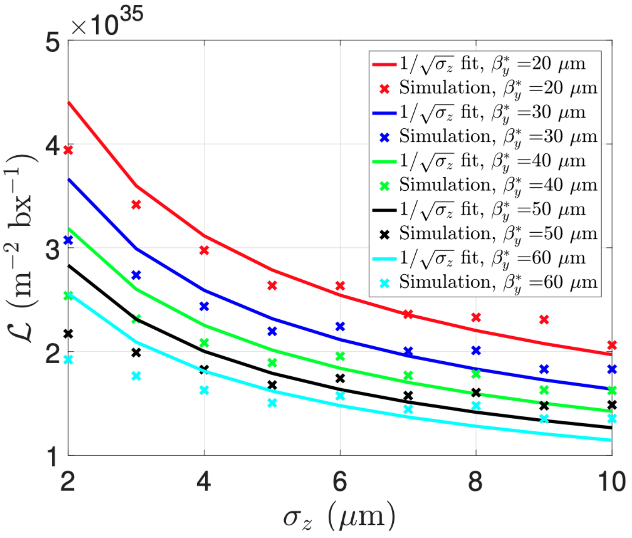

Figure 5. Total luminosity L per bunch crossing versus rms beam length σ_z, for several vertical beta functions β_y^*, along with corresponding theoretical $1/\sqrt{\sigma_z}$ luminosity fits. Reproduced with permission from [73].

The positron challenge: positrons cannot be accelerated inside the plasma blow-out, shown in figure 1c, since they will experience a defocusing force. High-gradient PWFA acceleration of positrons has been demonstrated [55–57], however, both theory and experimental results indicate that the positron beam quality strongly deteriorates in the process, regardless of the method used [55–58]. There are currently several newer ideas for regimes for efficient acceleration of positrons with good beam quality and/or good efficiency and high gradients [54, 59]. See [54] for more references to recent PWFA positron work. However, none of the regimes show so far as good overall performance as the blow-out regime for electrons. This challenge is, in my opinion, a distinct obstacle on the way towards a collider since even if significant resources were available, it is not clear how to work towards a consistent parameter set for an e^+e^- collider. While the development of performant positron schemes should continue with high priority in order to arrive at e^+e^- collider design, it may be worth considering an option without positron acceleration, the PWFA $\gamma\gamma$ collider.

6 $\gamma\gamma$ colliders

A possible way to bypass the positron problem entirely could be to pursue a Multi-TeV photon collider, or "$\gamma\gamma$ collider" [60, 61] instead of an e^+e^- collider. We include here a few sections as a reminder of the $\gamma\gamma$ option for a PWFA collider, first discussed in [36]. In a $\gamma\gamma$ collider, the colliding beams consist of hard photons, produced by Inverse Compton Scattering [62] of laser light shone onto high energy electron beams. The resulting photon beams can reach almost the same energy and intensity as the electron beams. The principle is illustrated in figure 6a. This type of collider has been studied since the early 1980s [63] but never implemented. With the advancement of PWFA, this concept could now be taken to the TeV scale, for example a $\gamma\gamma$ collider where two electron beams of energy $E = 5$ TeV are used to generate the photon beams. Examples for this "10 TeV $\gamma\gamma$ collider" are given below. No positron generation or acceleration is required for such a machine.

Example of $\gamma\gamma$ collider luminosity spectrum and physics: the luminosity spectrum for a $\gamma\gamma$ collider can be calculated by propagating the generated photons to the interaction point (IP). This has been done in figure 6b for a 10 TeV $\gamma\gamma$ collider, assuming a laser with the optimal wavelength (20 µm, see below) and pulse energy. In this calculation, no active separation of electrons and photons at the IP is done, therefore e^-e^- , γe^- and $\gamma\gamma$ collisions are taking place. Unpolarized beams were used for the calculations. The spectrum, including all species, is used for the physics studies mentioned below [64]. For studies where the electrons would be an undesired background, the electrons could be bent away from the IP through a sufficiently high distance between the photon generation and the IP, combined with a sufficiently high bending field (order of Tesla-meter [63]). While the luminosity spectrum is not monochromatic as for e^+e^- colliders, a $\gamma\gamma$ collider has the advantage that the cross sections for charged particle production may be significantly higher than those in e^+e^- collisions. A $\gamma\gamma$ collider therefore provides a possibility to test many aspects of the Standard Model and beyond.

Several studies of the physics potential of a $\gamma\gamma$ collider as a complement to an e^+e^- collider have been performed in earlier work including for the 500 GeV Tesla/ILC collider [60, 61], and for $\gamma\gamma$ collider Higgs factories [65, 66]. The physics potential for a 10 TeV $\gamma\gamma$ collider has recently been studied by the CLIC energy upgrade working group [64]. In the working group, the $\gamma\gamma$-performance [67] has been quantified by assuming a phenomenological MSSM SUSY model with 11 parameters. Using the luminosity spectrum of figure 6b, WHIZARD [68] (a standard tool for linear collider physics studies) was used to calculate the cross section for SUSY pair production for charged particles in a $\gamma\gamma$ collider. The results [69], in figure 6c, show that the performance of a $\gamma\gamma$ collider may be superior to an e^+e^- collider for some channels, while neutral particles are not accessible to a $\gamma\gamma$ collider at the tree level. In general, a 10 TeV $\gamma\gamma$ collider would in many cases extend the direct mass reach of the HL-LHC significantly. While many more channels must be studied to map the full physics potential, these preliminary studies indicate the interesting aspects of a Multi-TeV $\gamma\gamma$ collider.

Laser system: the laser wavelength that gives the highest $\gamma\gamma$-collision energy, and also the highest collider power efficiency can, using Inverse Compton Scattering theory, be calculated as $\lambda_L[\mu\text{m}] \approx 4E[\text{TeV}]$ [60]. For a 10 TeV $\gamma\gamma$ collider ($E = 5$ TeV electron beams), this corresponds to $\lambda_L = 20\,\mu\text{m}$. Long wavelength lasers are therefore needed to reach the highest collider energies. A mature technology providing wavelengths around 10 µm at high pulse energies is the CO_2 laser [71, 72]. Using lasers with 10 µm wavelength, as opposed to the ideal laser wavelength, would for the 10 TeV collider lead to order of 10% reduction in centre-of-mass energy, as well as power efficiency. Depending on collider parameters, laser pulses of order 100 ps length and 100 J of energy (peak power of about 1 TW) could be required. These parameters also seem to be comparable to what is reported for current CO_2 laser technology [71, 72]. On the other hand, a significant amount of technology development would be needed to devise a CO_2-laser system well adapted for a $\gamma\gamma$ collider, including for reaching collider requirements on repetition rate and average power. Another idea, proposed in [73], is to use a dedicated Free Electron Laser for the collider, allowing to optimize the wavelength for the electron beam energy. Such an option would also need significant R&D. To sum up, several study paths are possible for achieving the required laser parameters, though they all need significant design effort, and a substantial investment in laser technology, in order to arrive at an appropriate system for a Multi-TeV $\gamma\gamma$ collider.

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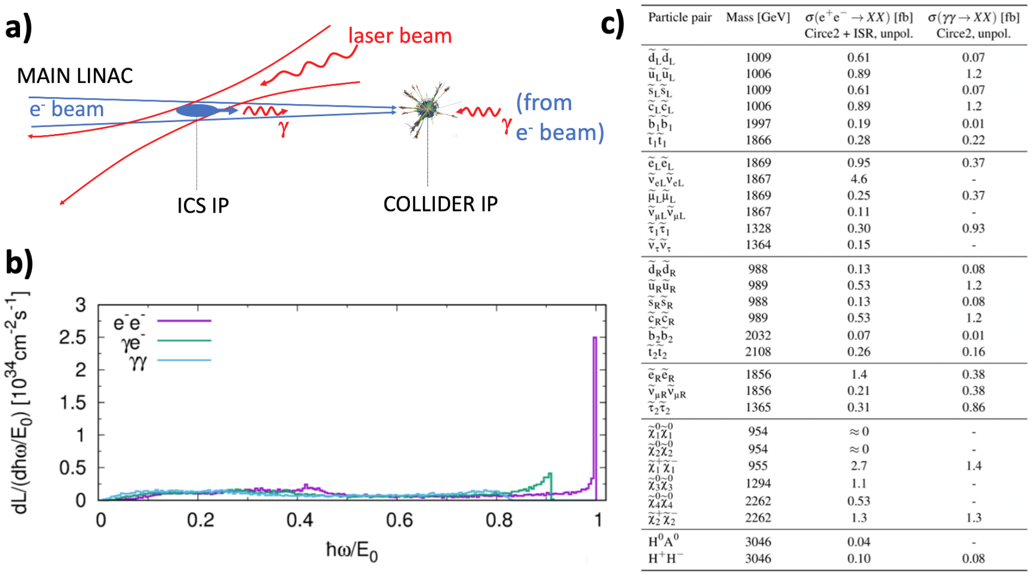

Particle pair	Mass [GeV]	$\sigma(e^+e^- \to XX)$ [fb] Circe2 + ISR, unpol.	$\sigma(\gamma\gamma \to XX)$ [fb] Circe2, unpol.
$\tilde{d}_L\tilde{d}_L$	1009	0.61	0.07
$\tilde{u}_L\tilde{u}_L$	1006	0.89	1.2
$\tilde{s}_L\tilde{s}_L$	1009	0.61	0.07
$\tilde{c}_L\tilde{c}_L$	1006	0.89	1.2
$\tilde{b}_1\tilde{b}_1$	1997	0.19	0.01
$\tilde{t}_1\tilde{t}_1$	1866	0.28	0.22
$\tilde{e}_L\tilde{e}_L$	1869	0.95	0.37
$\tilde{\nu}_{eL}\tilde{\nu}_{eL}$	1867	4.6	-
$\tilde{\mu}_L\tilde{\mu}_L$	1869	0.25	0.37
$\tilde{\nu}_{\mu L}\tilde{\nu}_{\mu L}$	1867	0.11	-
$\tilde{\tau}_1\tilde{\tau}_1$	1328	0.30	0.93
$\tilde{\nu}_\tau\tilde{\nu}_\tau$	1364	0.15	-
$\tilde{d}_R\tilde{d}_R$	988	0.13	0.08
$\tilde{u}_R\tilde{u}_R$	989	0.53	1.2
$\tilde{s}_R\tilde{s}_R$	988	0.13	0.08
$\tilde{c}_R\tilde{c}_R$	989	0.53	1.2
$\tilde{b}_2\tilde{b}_2$	2032	0.07	0.01
$\tilde{t}_2\tilde{t}_2$	2108	0.26	0.16
$\tilde{e}_R\tilde{e}_R$	1856	1.4	0.38
$\tilde{\nu}_{\mu R}\tilde{\nu}_{\mu R}$	1856	0.21	0.38
$\tilde{\tau}_2\tilde{\tau}_2$	1365	0.31	0.86
$\tilde{\chi}_1^0\tilde{\chi}_1^0$	954	≈ 0	-
$\tilde{\chi}_2^0\tilde{\chi}_2^0$	954	≈ 0	-
$\tilde{\chi}_1^+\tilde{\chi}_1^-$	955	2.7	1.4
$\tilde{\chi}_3^0\tilde{\chi}_3^0$	1294	1.1	-
$\tilde{\chi}_4^0\tilde{\chi}_4^0$	2262	0.53	-
$\tilde{\chi}_2^+\tilde{\chi}_2^-$	2262	1.3	1.3
H^0A^0	3046	0.04	-
H^+H^-	3046	0.10	0.08

Figure 6. a) Principle of a "$\gamma\gamma$ collider" (a high-energy photon collider): laser beams are shone on high-energy electron beams just ahead of the interaction point, generating photon beams with up to 80% of the electron beam energy through Inverse Compton Scattering. b) The luminosity spectrum for a E_0 = 10 TeV $\gamma\gamma$ collider, assuming a laser with the optimal wavelength and energy. The incoming electron and laser beams are assumed unpolarized. The electrons are not separated from the photons, giving luminosity for e^-e^- , γe^- and $\gamma\gamma$ collisions. c) Calculated cross sections for a SUSY model [67] for a 10 TeV $\gamma\gamma$ collider (right) compared to a 10 TeV e^+e^- collider (left). For production of charged particles (quarks, sleptons and charginos) the $\gamma\gamma$ collider compares well. The luminosity spectrum for the e^+e^- is scaled from the 3 TeV CLIC studies. Reproduced from [67]. CC BY 4.0. The table is adapted from [70].

7 Selected areas with recent progress

Before concluding, I highlight a few more PWFA research areas where progress relevant for collider design studies has recently been made. These highlights are, again, choices of the author, and more comprehensive summaries of progress may be found in [4, 5].

Repetition rate: the choice of bunch structure and repetition rate will affect many other aspects of the collider design. To understand the constraints of a high-repetition-rate PWFA accelerator is therefore important for a conceptual design. Therefore, studies of high-average-power PWFA, at kHz and MHz repetition rates [74], and plasma evolution studies [74, 75], are of high importance as they could indicate constraints on the collider repetition rate.

Plasma lenses: experimental results show that both active [77, 78] and passive [79] plasmas lenses are gradually becoming more mature, with potential for multi-kT/m axial symmetric, linear strong focusing fields. This progress may open up new paths towards improved BDS design [1], cf. the above discussion.

Longitudinal correction: tolerances and stability requirements for PWFA colliders is estimated to be very stringent, due to the high frequency and small length scales of PWFA "cavities" [39]. In [80] it is shown that the phase and current profile of the main bunch can be manipulated to reduce energy errors, while [81] shows that the use of multiple stages enables self correction mechanisms in plasma accelerators, significantly increasing their tolerance to timing jitter and other beam imperfections. This result may have major positive implications to the realization of plasma colliders with their high beam quality and stability requirements.

8 Connection to linear collider projects

The European Strategy for particle physics prioritizes a Higgs factory as the next machine [82]. The option of a PWFA Multi-TeV $\gamma\gamma$ collider would well complement the results of a Higgs factory (a linear or circular e^+e^- collider with a few 100 GeV energy [83]) if the latter is built first. For example an e^+e^- Higgs factory would provide model independent measurements of the Higgs [84]. If the Higgs factory were linear, a Multi-TeV PWFA collider could reuse the tunnel and much of the infrastructure [12]. E.g., in the 2×3.5 km linacs of a 380 GeV CLIC [85], beams of 5 TeV could be produced in the same tunnel by plasma acceleration, assuming about 1 GV/m average gradient (a conservative assumption for plasma accelerators). Thus, it will be fruitful, and maybe required, to study a PWFA collider in close collaboration with the RF-based linear collider design studies, since a PWFA collider could materialize either as an inexpensive Multi-TeV upgrade path following an eventual first stage e^+e^- linear Higgs factory, or a novel track to Multi-TeV collisions. Even in the latter case, RF-based linear collider studies have advanced the state-of-the-art of accelerator stability and alignment, and these results would be directly useful for the development of an advanced linear collider based on novel accelerator technology as well.

9 Summary

A required step in order to verify the promises of reduced footprint, high efficiency and high luminosity collisions, at Multi-TeV centre of mass energies, should be to develop a PWFA collider conceptual design. This will allow to do a performance comparison with existing collider projects based on RF technology. Examples of subsystems that need to be designed for a PWFA collider are a suitable drive beam generation scheme [40], and an BDS adapted for the PWFA bunches [1]. I highlighted in addition a couple of topics that require further research before a design can be finalized: the attainable energy efficiency of the plasma accelerators process of a collider should be clarified. Possible advantages of short bunches should be investigated. In addition, sufficient performance for positron acceleration in simulations should be reached. As an alternative to solving the positron acceleration challenge, parameters as well as a more detailed physics case for a Multi-TeV $\gamma\gamma$ collider, could be studied. Nevertheless, there has been much recent progress on collider relevant topics, and the path towards a collider should be pushed further forward with help of the recently published roadmap [4], which indeed puts a pre-conceptual design as the highest priority.

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