CONSIDERATIONS FOR A HIGGS FACILITY BASED ON LASER WAKEFIELD ACCELERATION

S. Hillenbrand, KIT, Karlsruhe, Germany and CERN, Geneva, Switzerland
A.-S. Müller, KIT, Karlsruhe, Germany
R.W. Assmann*, D. Schulte, CERN, Geneva, Switzerland

Abstract

Laser Wakefield Accelerators have seen tremendous progress over the last decades. It is hoped that they will allow to significantly reduce the size and cost of a future liner collider. Based on scaling laws, laser-driven plasma accelerators are investigated as drivers for smaller scale facilities capable of producing Z and Higgs bosons.

INTRODUCTION

Over the last decades, Laser Wakefield Accelerators (LWFA) have seen tremendous progress regarding peak energies, beam quality and reproducibility. It is hoped that the high achieved acceleration gradients will allow to significantly reduce the size and cost of a future Linear Collider (LC).

Most current day LWFA operate in the so called Bubble or Blowout regime, which has very beneficial properties for the acceleration of electrons. However, these beneficial properties are completely lost for positrons. For a LC, it is therefore useful to operate in the linear regime, which has almost identical properties for the acceleration of electrons and positrons. For this regime, a set of scaling laws for various accelerator parameters with plasma density has been derived by Schroeder at al., and a LC scenario has been created using computer simulations [1]. Identical scalings and comparable numerical values have been found in [2, 3].

Based on these parameters, we investigate several aspects relevant to a smaller scale LC capable of producing an expected Higgs boson of about 125 GeV/c^2. As many cross sections for electron-positron collisions decrease for increased beam energy and therefore require a higher luminosity for a higher energy collider [4, 5], a Higgs factory could serve as an important test for a multi-TeV facility and deliver interesting physics at the same time.

The scalings regarding beam-beam interaction have been compared to simulation using GUINEA-PIG [6].

REVIEW OF SCALINGS

A re-derivation of scaling laws is beyond the scope of this work, and the reader is referred to [1, 2]. Here, we will only point out a few of the correlations and their implications.

First, the beam power P_b and wall plug power P_{wall} scale with the plasma density n_0 as

$$P_{wall} \propto P_b \propto n_0^{1/2}. \qquad (1)$$

Despite the fact that the maximal accelerating field E_z increases with density as $E_z \propto n_0^{1/2}$, this points at operating at a low plasma density to reduce the power consumption of the accelerator.

However, the number of particles per bunch N increases for a lower plasma density

$$N \propto n_0^{-1/2}. \qquad (2)$$

Whilst this allows for a lower collision frequency for a given luminosity, it can lead to prohibitively large beam beam effects, as will be discussed below. To limit the amount of generated beamstrahlung, one could accelerate less particles than possible for a given plasma density (increasing the repetition rate to keep up the luminosity), or distribute the N particles over m successive oscillations of the plasma wake. However, as shown in [7], this results in a higher power consumption, negating the advantages of operating at a lower plasma density.

Two acceleration method independent key figures of every collider are its energy and luminosity. For an electron-positron collider, the maximal cross section of 200 fb for $e^+e^- \rightarrow ZH$, is at a center of mass energy of about 250 GeV [5]. Assuming same RMS beam size $\sigma^*_{x/y}$ at the interaction point (IP) and same particle number N for both beams, the luminosity $\mathcal{L}$ is given by [4]

$$\mathcal{L} = \frac{fN^2}{4\pi\sigma^*_x\sigma^*_y}, \qquad (3)$$

with f the collision frequency. With the luminosity fixed by experimental requirements and the number of particles given by the chosen plasma density, the collision frequency has to scale as $f \propto N^{-2} \propto n_0$. A desirable luminosity $\mathcal{L} = 1 \cdot 10^{34}\,\mathrm{cm^{-2}s^{-1}}$ would yield 20.000 Higgs in a year ($\approx 1 \cdot 10^7$ s). For comparison, SLC had a luminosity of $\mathcal{L} = 3 \cdot 10^{30}\,\mathrm{cm^{-2}s^{-1}}$ at $E_{CM} \approx 90$ GeV [5].

For a collider, it is important to consider the features of beamstrahlung. They can be expressed in terms of the (average) beamstrahlung parameter [4, 8]

$$\Upsilon \cong \frac{5}{6}\frac{r_e^2}{\alpha}\frac{\gamma}{\sigma_z}\frac{N}{\sigma^*_x + \sigma^*_y}, \qquad (4)$$

with r_e the classical electron radius, α the fine structure constant, σ_z the bunch length and $\sigma^*_{x/y}$ the beam size at the interaction point (IP). In contrast to conventional accelerators, LWFA with their intrinsically short bunches will almost certainly have to operate in the quantum beamstrahlung regime $\Upsilon \gg 1$. For this regime, the number of

* Now at DESY, Hamburg, Germany

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emitted beamstrahlung photons per initial particle n_γ and the resulting energy spread of the beam $\delta_B = -\Delta E/E$ can be written as [4]:

$$\delta_B \cong \frac{n_\gamma}{3.3} \cong \frac{\alpha}{18}\left(\frac{5^5\alpha r_e}{2}\right)^{1/3}\frac{1}{\gamma^{1/3}}\left(\frac{N\sqrt{\sigma_z}}{\sigma_x^*}\right)^{2/3}. \quad (5)$$

I.e. $n_\gamma \propto \delta_B \propto \gamma^{-1/3}N^{2/3} \propto \gamma^{-1/3}n_0^{-1/3}$ - the effect is stronger for lower beam energy and higher number of particles (lower plasma density). It is important to point out that this does not only make the evaluation of the experiments more challenging due to the increased uncertainty of the initial energy and increased background, but also reduces the number of particles at highest energy and therefore the effective luminosity. In our simulations, the number of particles with an energy of more than 99 % of the design energy was reduced by 62 % due to beamstrahlung.

In addition, beamstrahlung as most important source can lead to the coherent production of n_b electron-positron pairs, constituting detrimental background in detectors. Furthermore, in an electromagnetic field, n_ν electron-positron pairs can also be created through virtual photons carried by the primary particles. The total number of created pairs per primary electron is given by [8]

$$n_b = \left[\frac{\alpha\sigma_z}{\gamma\lambda_e}\Upsilon\right]^2 \Xi(\Upsilon), \quad n_\nu = \left[\frac{\alpha\sigma_z}{\gamma\lambda_e}\Upsilon\right]\Omega(\Upsilon). \quad (6)$$

with λ_e the Compton wavelength of the electron. Note that the term in square brackets only depends on the number of particles and the transverse beam size at the interaction point (cf. Eq. 4), and therefore scales as N. n_b and n_ν depend on Υ via the functions $\Omega(\Upsilon)$ and $\Xi(\Upsilon)$. For $1 \lesssim \Upsilon \lesssim 10^3$, they are in the order of $10^{-2} \lesssim \Omega(\Upsilon) \lesssim \Xi(\Upsilon) \lesssim 10^{-1}$. Our simulations show an even higher number of generated coherent pairs, $n_b \approx 0.1$ (cf. Table 1).

For $\Upsilon \lesssim 1$, $\Xi(\Upsilon)$ decreases exponentially, with $\Xi(\Upsilon \approx 0.3) \approx 10^{-9}$ - giving a much stronger suppression e.g. for longer bunches common for conventional accelerators.

TECHNOLOGICAL CONSIDERATIONS

The scalings in [1, 3] assume a bunch length $\sigma_z \lesssim 5\,\mu$m and a bunch charge in the order of a few nC. In addition, they assume a wedge shaped longitudinal bunch density tailoring to reduce the acceleration-induced energy spread, as discussed in detail in [9]. For comparison, Fig. 1 illustrates the bunch lengths and particle numbers for exemplary current day and near future conventional accelerators, achieved LWFA beams and the scalings this work is based upon. It is important to point out that the beam quality achieved with conventional accelerators is to date still far superior to the one achieved with LWFA and that, to the best of the authors knowledge, density tailoring for the required bunch lengths has not yet been achieved.

Figure 2 illustrates the laser pulse energy vs. achieved repetition rate for some exemplary high power laser facilities and compares them to the parameters needed to reach a luminosity of $\mathcal{L} = 1 \cdot 10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$.

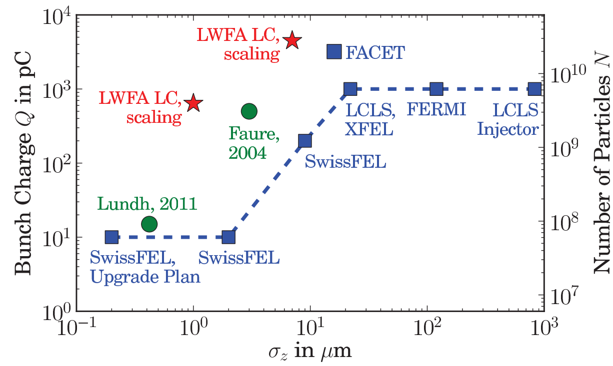

Figure 1: Bunch charge over bunch length. Red stars show the values assumed in the LWFA scalings [1, 3], green circles exemplary achieved LWFA beams [10, 11] and blue squares conventional accelerators. The connected squares are operational and near future FEL at different energies in the order of a few GeV [12, 13, 14, 15], the separate square stands for FACET at an energy of about 23 GeV [16].

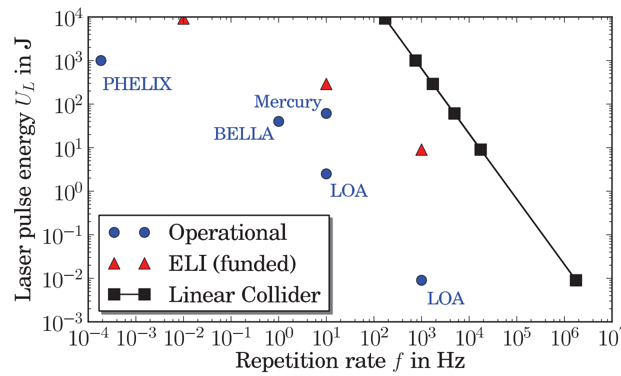

Figure 2: Laser pulse energy vs. repetition rate. The blue circles denote exemplary operational facilities [17, 18, 19, 20], the red triangles long-term goals for the funded ELI project [21]. The connected black squares denote the parameters required by the scalings in [1, 3] for a collider with $\mathcal{L} = 1 \cdot 10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$. A 10 J, 1 kHz demonstrator is envisaged within ICAN for the end of the decade [22]. Note that i) PHELIX and Mercury have pulse length in $\mathcal{O}$(ns), opposed to $\mathcal{O}$(fs) for the other laser systems; and ii) that Mercury was the only laser specifically designed to demonstrate high average power.

SUGGESTED PARAMETER RANGE

Assuming that i) Beamstrahlung does not pose a limit; ii) Laser systems providing the desired pulse energy and repetition rate and iii) Plasma cells of the required length were available for all parameter sets; the scalings would dictate that for a Z / H facility, one would like to operate at plasma densities of about $10^{16}\,\mathrm{cm}^{-3}$. This would minimize the facility footprint and power consumption and remove the need for staging. As reaching these three assumptions (if possible) will require serious R&D, let us consider how we could arrive at an operational facility at an earlier point in time. Ideally, one would like to start with a Z facility with the option to upgrade to a higher energy H facility later. Setting a maximal tolerable amount of beamstrahlung for the Z facility, this sets a lower limit to the plasma density, as $n_\gamma \propto \delta_E \propto \gamma^{-1/3} n_0^{-1/3}$. On the other hand, it is probable that for the closer future the maximal average laser power per stage $P_{avg} \propto n_0^{-1/2}$ will be limited to to a few hundred kW, with a repetition rate of a few kHz. Luminosity considerations for the H facility then limit the usable plasma density to $n_0 \lesssim 1 \cdot 10^{18}\,\mathrm{cm}^{-3}$.

For our exemplary study, we suggest a plasma density $n_0 \approx 5 \cdot 10^{17}\,\mathrm{cm}^{-3}$. This limits the beamstrahlung induced energy spread to 40 % for the Z facility, reducing the challenge of detector development. Operation at 10 kHz could then deliver a Luminosity of $\mathcal{L} \approx 3 \cdot 10^{33}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$. For a H-facility, this results in a total wall plug power consumption for both linac arms of about 12 MW (assuming a wall-plug to beam efficiency of 6 %) and a footprint of about 700 m (assuming a coupling distance between plasma stages of 5 m). A summery of the supposed parameters is given in Table 1.

One might argue that for the energies discussed here, the use of conventional accelerator technology would be beneficial. Still operating in the classical beamstrahlung regime $\Upsilon \ll 1$, conventional accelerators with their longer bunches can deliver significantly better beam quality, at a comparable energy consumption (cf. e.g. [5]). However, as $\Upsilon \propto \gamma$, for a multi-TeV collider it will be very challenging to avoid operation in the quantum beamstrahlung regime. A facility like the one proposed in this work could therefore serve as a vital test for a later larger scale linear collider.

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Table 1: Exemplary parameters for a Z/H-factory, based on the parameters and scalings in [1, 8].

Desired Boson	Z	H
Final energy per beam E_b [GeV]	45	124
Peak Luminosity $\mathcal{L}$ [$\mathrm{cm}^{-2}\mathrm{s}^{-1}$]	$1 \cdot 10^{34}$	
Plasma electron density n_0 in cm^{-3}]	$5.0 \cdot 10^{17}$	
Particles per bunch N	$1.8 \cdot 10^9$	
Laser energy per stage U_L in J	2.9	
Avg laser power per stage P_{avg} in kW	107	
Energy gain per stage W_{stage} in GeV	2.0	
Number of stages N_{stages}	23	62
Collision frequency f in kHz	38	
Beam power P_{beam} in MW	0.5	1.3
Wall-plug power 1 Linac P_{wall} in MW	8	22
RMS beam size at IP $\sigma_{x/y}$ in nm	10	
RMS bunch length σ_z in μm	1	
Beamstrahlung parameter Υ	7.2	20
No. of Beamstrahlung photons n_γ	1.7	1.2
Beamstrahlung energy spread δ_E	0.40	0.33
Coherent Beamstrahlung pairs n_b	$\mathcal{O}$(1e-3)	
Trident Cascade pairs n_ν	$\mathcal{O}$(1e-3)	
Length of single stage L_{stage} in m	0.1	
Total linac length (1 arm) in m		
0 m for coupling	2.1	5.5
5 m for coupling	117	316
25 m for coupling	577	1556

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