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Radiative regime of linear colliders, high repetetion rate free electron lasers and associated accelerating structures

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ABSTRACT

A review of various scalings of high energy and high luminosity electron–positron colliders in the highly radiative regime is presented together with the electromagnetic and mechanical limitations of various associated acceleration structures to support operation with high gradients and high repetition rates. The potential for operation of normal conducting linacs in a mode of high repetition rate of 1 kHz or higher, relevant for today's linac-driven free electron lasers, is also discussed.

1. Introduction

The key issues in the operation of a high energy linear electron–positron collider are intimately tied to the achievable acceleration gradient, beam emittance, beam stability and overall power efficiency: they have direct implications on the length (compactness), beam quality (luminosity), average luminosity (physics reach) and wall-plug power (operating cost) of the collider. Here we discuss electromagnetic power sources, acceleration schemes and accelerating structures relevant to such high energy, high luminosity colliders, based upon a deeper look into the collider scaling against various parameters. Though today's linear collider activity focuses on either a 0.5 GeV International Linear Collider (ILC), which is far from the radiative regime, or a 3 TeV Compact Linear Collider (CLIC), which borders on the radiative regime, much of what we discuss here has its motivation in an original study conducted in the Snowmass'96 Workshop [1] a decade and a half ago, but remains valid to this day. Additionally, the topic has renewed impetus today in the context of high repetition rate linear electron accelerators required to drive state-of-the-art free electron lasers (FELs) for various light source scenarios being contemplated recently in the community. In this context a modest acceleration gradient of 20–30 MV/m in a high frequency linear accelerator but operating at a high repetition rate of 1 kHz or higher will be extremely valuable to provide FELs towards valuable pump–probe experiments.

In the context of colliders, there are several important topics that can be considered as part of a review of means of achieving high energy and high luminosity: power sources (such as lasers, THz radiation, klystrons and gyrotrons); structures (such as mm-wave, plasma-based devices, metals, dielectrics, semiconductors and superconductors); dynamics of short bunch wakefields; particle beam dynamics, plasma physics, electrodynamics of microwaves, colliders and new concepts. The frequencies we consider for the electromagnetic power source of the collider range from a few GHz (tens of cm in wavelength) to a hundred THz (a micron in wavelength) with traditional stop-bands at L-band (~1.3 GHz), S-band (~3 GHz), X-band (~11 GHz), W-band (~30 and ~90 GHz) and 1 and 100 THz. High frequency THz sources can be based on either waveguides supporting propagating slow waves or fast waves or on solid-state micro strip lines irradiated by short pulse lasers. Very high frequency sources at 100 THz can be tied to short pulse, high peak power solid-state lasers by themselves or via excitation of a wakefield in a plasma. Accelerating structures in the form of plasma wakefields can also be excited by short pulse of charged particles themselves propagating in plasma.

Collider scalings in the highly radiative environment of collisions at 5 TeV with a luminosity of $10^{35}\ \mathrm{cm}^{-2}\,\mathrm{s}^{-1}$, demand transcending the radiative limitations via various exploratory compensatory schemes (e.g. gamma–gamma collisions, neutralized beams, etc.) Earlier scaling [1] indicated a significant trend towards higher accelerating frequencies in order to achieve high gradients and luminosity. However, when fundamental breakdown physics issues are tied into the design, together with the overall efficiency of acceleration, the linear accelerator frequency becomes restricted [2]. Accelerating structures based on metallic walls such as copper include state-of-the-art damped detuned structures (DDS [3]) and

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waveguide damped structures [4] being explored for the future linear colliders. Extending to very high accelerating gradients naturally leads to a consideration of dielectric structures for laser linac and plasma channel guiding structures for laser wakefield acceleration, as well as plasma wakefield accelerators [5]. Structures at high frequencies and with small dimensions raise obvious concerns regarding wakefields and their harmful effects on beams. These wakefields have both short-range and long-range components, and operate over the length of each individual bunch and along the train of bunches, respectively. The short-range wakefield is essentially decided once the average iris of an accelerating structure has been designed. Collimators also represent impedance to the beam and hence give rise to beam-excited wakefields. Metallic collimators with special grooves, surface coatings and careful shaping can minimize these effects. Recent innovations for the LHC include dispensing with metallic structures and instead utilizing a secondary hollow beam to provide the collimation [6]. These discussions were also grounded to the facts about and experience with the SLC and LHC collimator wakefields. Yet another vital topic is concerned with the power sources that drive these structures at high frequencies. Multi-beam klystrons (MBK) and sheet beam klystrons, two-beam accelerator drivers, gyrotrons and lasers all are potential power sources in this area with efficiency and the ability to provide the requisite power and critical parameters. Recent, albeit preliminary, simulations on MBK operating at high harmonics indicate the potential for significantly enhanced overall efficiency [7] A final discussion is focussed on an appreciation of the progress in laser-plasma and beam-plasma wakefield acceleration of electrons to relativistic energies approaching 1–10 GeV in laboratory settings at various institutions [5,8].

This paper is organized as follows. In Section 2, we review the classical collider design scaling, taking into account radiative effects at the interaction point (IP). In Section 3, for a 5 TeV design in particular, we expose and demonstrate the failure of this classical design paradigm to provide a credible collider scenario unless we re-consider and re-interpret the radiative constraints at the IP via a shift of paradigm, which we discuss in Section 4; Section 5 gives a brief synopsis and status of the current structures concepts for, and research on colliders up to 5 TeV reach, broken into broad categories of wavelengths, gradients and technologies. Section 6 discusses limits of metallic structures, including a discussion on linacs operating at a repetition rate of 1 kHz or higher. Section 7 addresses THZ, lasers and plasmas as possible sources and structures and Section 8 concludes with an outlook.

2. Classical collider design scalings

A typical collider configuration at the IP is shown in Fig. 1(a). The goal is to ensure the highest probability of collisions (and hence rate of events) without compromising on the severe electromagnetic environment at the IP. The radiative effects at the IP affect the charged particle beam phase space (and hence luminosity and collision kinematics) and generate undesirable backgrounds in the surrounding detector. To achieve high probability of collision, one attempts as high a charge density in the bunch as possible: packing a large number (N) of electrons in a single bunch and squeezing them into a tight focus at the IP (vertical and horizontal spot sizes, respectively, of $\sigma_y{}^*$ and $\sigma_x{}^*=R\sigma_y{}^*$). In addition one tries to collide as frequently as possible (at a rate $f=N_p\,f_{rep}$, with a string of N_p colliding bunches repeated at a rate f_{rep}). The luminosity in this configuration is given by

$$L=\frac{fN^2}{4\pi\sigma_y^{*2}R}H \tag{1}$$

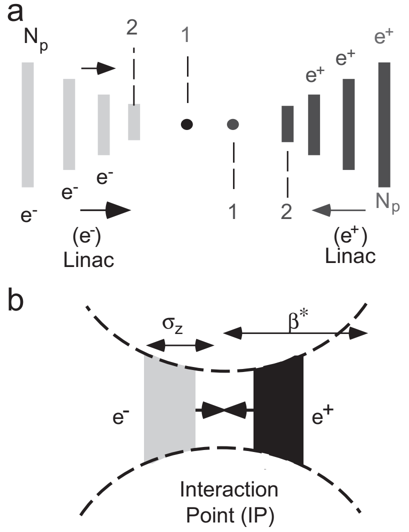

Fig. 1. Schematic of collider configuration at IP.

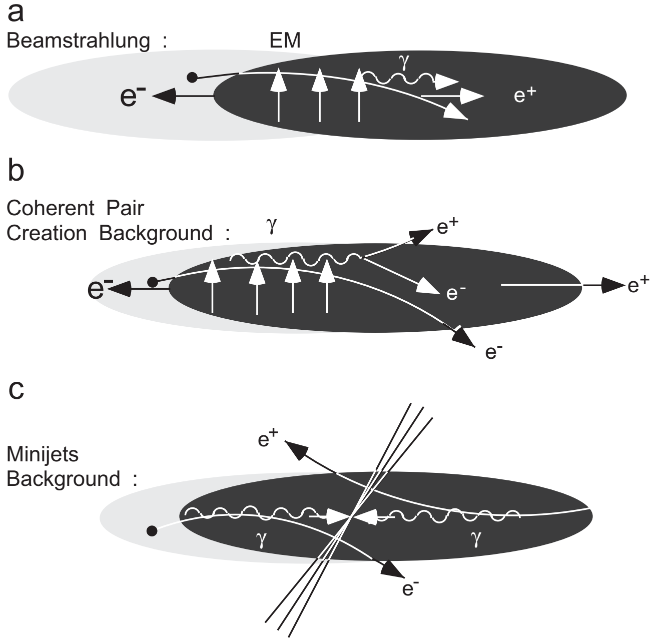

Fig. 2. Schematic illustrating radiative effects.

where H is a luminosity enhancement factor [9] due to the electromagnetic pinching of one beam against another, dependent on the bunch length σ_z and focusing beta function β^* at the IP (Fig. 1(b)). This luminosity comes at the price of a high average power P_b in the colliding beams (two of them) of energy γmc^2, given a certain wallplug-to-beam efficiency η, at a certain cost of the wall-plug power Pw:

$$P_b=2(\gamma mc^2)Nf=\eta P_W \tag{2}$$

A charged particle in one of the colliding beams feels a strong electromagnetic field arising from the macroscopic motion at relativistic speed of the opposing intense beam at collision. The transverse acceleration (or bending) of charged particles in this field leads to emission of energetic photons, known as beamstrahlung photons as depicted in Fig. 2(a) [10].

The first parameter to characterize the radiative effects due to macroscopic beam electromagnetic fields is known as the upsilon