An Inverse Free Electron Laser Driven Linear Collider Electron-Positron B-Factory

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Abstract

We discuss an electron-positron linear collider B-Factory using Inverse Free Electron Lasers (IFEL) to accelerate the beams. The requirements on luminosity, larger than 10^{33} cm^{-2} s^{-1}, and energy spread of a B Factory introduce stringent conditions on the accelerator and the interaction region. We study the longitudinal dynamics through the IFEL, the efficiency of the acceleration process, and the ratio of particles which become accelerated, and fall within the resonance. The device is found to perform well in the presence of large variations in the laser field intensity over the beam. We also discuss the laser system powering the IFEL, and some of the system tolerances.

Introduction

The set of beam requirements demanded by a linear collider B-Factory, summarized in Table 1 is very difficult to satisfy, and represents a challenge for a novel acceleration technique such as the IFEL. The set of parameters needed at the interaction point (IP) for such a B-Factory were identified in a previous paper [1] on which this work is based. Such an accelerator must meet stringent requirements for the beamstrahlung fractional energy spread, the final energy spread of the accelerator, and the luminosity.

Because the particles are delivered from the injector at a random phase with respect to the optical wave, care must be taken to match these initial particles to the acceleration buckets. This matching is crucial to achieving a final energy spread which has a maximal overlap with the Upsilon(4S) resonance, having a full width of 24 MeV. We examine the efficiency of this matching and present simulation results.

An advantage of the IFEL over conventional accelerators is the efficiency in utilizing the incoming electromagnetic energy. This is the result of having the radiation confined to a region close to the bunch. The efficiency of energy extraction, or beam loading, is influenced by the choice of parameters, such as the beam current. An upper limit on this beam loading must be chosen based on the effect on the acceleration process as a result of modifying the peak electric field. We note that in the IFEL, beam loading does not directly lead to an energy spread, such as in a conventional linac.

By altering the waveguide dimensions, it is possible to modify the slippage of the bunch relative to the radiation pulse. The zero slip regime offers the possibility of adjusting the tapering to compensate for the loss in power of the radiation. Also, because this approach lends itself more readily to using multiple acceleration sections, the power density required of the drive laser is decreased.

The average power and repetition frequency requirement on the drive laser make a free electron laser the most likely candidate for this task [1]. Driven by a superconducting linac, such an FEL, assuming 40 percent energy extraction, can insure good wallplug efficiency for the entire system.

Table 1. Beam and Collider Parameters

Beam Energy (GeV)	5
Luminosity (cm^{-2}s^{-1})	10^{33}
Average Beamstrahlung. $\Delta E/E$	2×10^{-3}
No. Particles/Bunch	1.14×10^{10}
Pulse Repetition Rate (sec^{-1})	10^4
σ_t (μm)	0.249
β^* at I.P. (mm)	0.31
σ_z (mm)	0.31
Disruption Parameter	16
Pinch Enhancement	6
Invariant Emittance (m-rad)	2×10^{-6}

IFEL Designs

We envision an IFEL which begins with an untapered prebunching section, then a set of acceleration modules, and finally a section which reduces the energy spread. We choose a constant period wiggler, which is not the optimum case but the easiest to examine. The resonant phase ψ_r, describing the particle which does not undergo synchrotron oscillations, is set to $\pi/4$, as a compromise between high acceleration rate and sensitivity to parameters. Several studies have been made of the waveguide used to contain the radiation which suggest that low loss propagation is feasible [4,5,6]. With a suitable choice in waveguide parameters, the amount of slippage between the particles and the radiation can be altered. Case A of Table 2 has no slippage control and consists of a single

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module, while Case B is an example of zero slip [7] and has 18 modules. The application of the zero slip condition leads to a severely restricted waveguide aperture, (2 mm). While an actual device using these parameters may have problems with beam propagation, this example will demonstrate what is possible using the zero slip approach.

We note that before reaching the IP, it is necessary to wash out the bunching existing on the optical scale with a dispersive section, so as not to exacerbate the beam-beam effects.

Table 2: IFEL Characteristics

Parameter	Case A	Case B
Laser Wavelength (μm)	10	10
Injection Energy (MeV)	500	500
Dimensions of Waveguide (cm)	0.8 x 0.8	0.2 x 0.4
Peak Laser Electric Field (V/m)	1.04 x10^{10}	1.84 x10^{10}
Laser Power Density (W/cm^2)	1.45 x10^{13}	4.49 x10^{13}
Laser Pulse Energy (Joules)	104	4.9
Bunch Train Rep. Rate (Hz)	10^4	10^4
Optical Pulses per Train	1	18
Average Laser Power (Watts)	1.04 x10^6	8.8 x10^5
Max. Wiggler B-Field (Gauss)	5 x10^4	2.3 x10^3
Wiggler Period (cm)	26.5	160
Total Length of Wiggler (m)	146	282
Acceleration Gradient (MV/m)	31	16

Initial Matching

In the interest of utilizing the maximum number of 500 MeV initial particles, it is necessary to precondition the beam, increasing the overlap with the acceleration buckets. In addition, the parameters of Table 2 have buckets which are deeper than the allowable energy spread. To avoid problems with this, the beam conditioner can also be used to match the initial distribution to the longitudinal phase space.

The small oscillations near the resonant particle are described by ellipses characterized by,

$$\delta\gamma = \delta\psi\sqrt{\frac{\lambda}{2\pi}\frac{f_b}{2}\frac{\gamma_o{}^2 a_w a_s}{1+a_w{}^2/2}\cos(\psi_r)} \qquad (1)$$

where γ is the Lorentz factor, f_b is the Bessel function factor, $a_s = eE_0\lambda/2\pi mc^2$ (E_0 is the peak radiation field), $a_w = eB\lambda_w/2\pi mc^2$ (B is the peak magnetic field), and ψ_r is the resonant phase. In order to stay away from the nonlinear parts of the phase space, which may cause filamentation, we wish to match the initial distribution to these ellipses. If an untapered wiggler section is used as a buncher, only a fraction of the particles will be matched, the rest being close to the separatrix or untrapped.

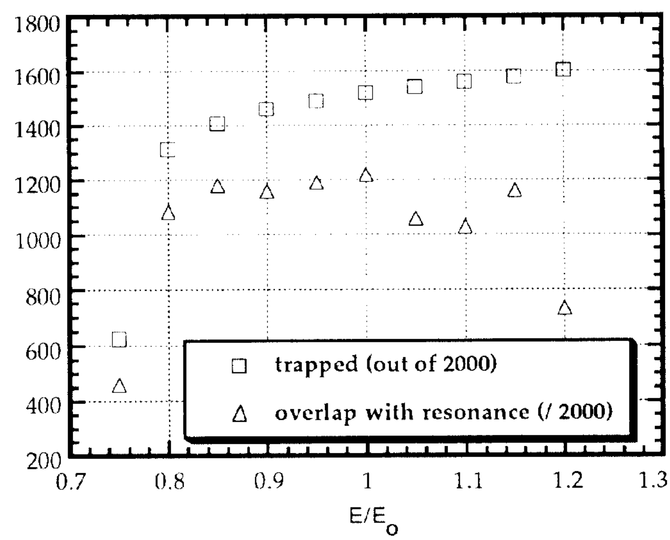
This matching will be undermined by any variation in parameters such as a difference in the radiation field over the extent of the beam. A slight variation in E_0 will modify ψ_r and cause synchrotron oscillations for the microbunch. In a more severe case, the nonlinear effects will filament the distribution.

Numerical Results

We present simulation results motivated by the concerns raised in the last section. To this end, the high radiation intensity and large γ allow us to neglect the optical properties of the beam (guiding, index of refraction, etc.) The system can be modeled through a straightforward application of the wiggle period averaged equations of motion for the particles, found in reference [2]. An extra term containing λ_c, the cutoff frequency of the waveguide, can be added to the usual equation for the phase evolution:

$$\frac{d\psi}{dz} = \frac{2\pi}{\lambda}\left(\frac{\lambda}{\lambda_w} - \frac{1}{2}\left(\frac{\lambda}{\lambda_c}\right)^2 - \frac{1+a_w{}^2/2}{2\gamma^2}\right) \qquad (2)$$

In this model, we have not considered the effect of betatron motion, and also assume that the particles do not see the variation of the fields off axis.



Plot 1: The overlap with the resonance when different sections of the beam see a variation in the laser field E.

For Case A, the combination of slippage and beam loading assures that the radiation in the vicinity of the beam's leading edge will diminish in intensity. The situation which is simplest to compute is one where each slice of the beam is exposed to a constant intensity throughout the acceleration. For Case B, the interest in keeping the radiation pulse as short as possible again brings unwanted intensity variations. Plot 1 is the result of a series of runs in which the peak electric field was varied. The parameters relevant to Case B were used for this, but the results are also valid for Case A because here the final energy spread is always slightly smaller. The particles were initially injected in a 1.5 MeV band and with random phases. The prebunching and final energy spread reduction were optimized for the reference electric field, and then kept constant. The final energy spread reduction section consists of a dispersive section and a 9 m untapered section utilizing a 1.84 x10^9 V/m peak electric field. The effect is to rotate the distribution in the longitudinal phase space so that $\delta\gamma$ comes to a minimum. The benefit of this energy spread reduction technique is strongly limited by conservation of phase space area and nonlinear dynamics.

These results reveal that the performance degrades gracefully even when the electric field is lowered by as much as 20%. The difference between the number of trapped particles and the number which overlap with the resonance indicates the amount of wasted energy. In summary, effectively 60 per cent of the particles from the injector end up effectively in the resonance. A similar analysis for the trapped particles, which take energy away from the radiation, reveals that 80 per cent of them overlap with the resonance.

The above simulation work did not implicitly treat energy balance. This may seem not to be the correct treatment for Case B, where E_0 is diminished by 5 per cent near the end of each accelerating section. We have carried out additional simulation work to verify that this effect is not very detrimental, but in a more realistic accelerator design the rate of tapering would be adjusted to compensate for this.

Conclusions

The previous section suggests that the amount of energy extraction from the radiation can safely be made higher - perhaps to the 15 or 20 percent level. Such a change would lead to a favorable impact on the amount of power required of the drive laser. In reference [1], a drive laser design using an FEL is presented, making use of a 23 kA and 9 kA drive beams for Case A and Case B respectively. A twofold increase in efficiency, assuming that any relevant instability issues are studied (such as side bands), would result in lowering these beam requirements to more reasonable levels.

There is ample opportunity to optimize the parameters of this accelerator. For example, the wiggler can have a tapered period, to bring about a reduction in the maximum required magnetic field near the end of the device.

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