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NEXT LINEAR COLLIDER: OVERVIEW AND e^-e^- OPTION *

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Next Linear Collider: Overview and e^-e^- Option

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Abstract

A lepton collider capable of generating a luminosity of 5×10^{33} to 1×10^{34} at center-of-mass energies from 0.5 to 1.5 TeV would permit studies of fundamental interactions complementary to those planned at the Large Hadron Collider. Such energies would be more easily achieved for electrons at a linear collider than a conventional storage ring. We describe the Next Linear Collider (NLC), a proposed linear collider which utilizes room-temperature RF systems operating at 11.4 GHz to achieve the desired energies and room-temperature electromagnets and permanent magnets to achive the extremely small beam sizes required to meet the specified luminosity goal. The NLC design has been optimized to permit electron-electron collisions as well as electron-positron collisions. We discuss a few of the detailed technical challenges which are posed by electron-electron collisions in the NLC parameter regime.

1 Introduction

Lepton colliders are widely recognized as an essential tool for understanding fundamental particle interactions. Because of the pointlike, non-composite nature of electrons and positrons, such colliders are ideal for high-precision studies which cannot be undertaken at proton-collider facilities. While present plans in the particle physics community call for establishment of a new energy regime at the Large Hadron Collider (LHC) in 2005, a growing body of work has demonstrated that a lepton collider with a center-of-mass (CM) energy of 0.5 to 1.5 TeV and a luminosity of 5.0×10^{33} to 1.0×10^{34} cm^{-2}sec^{-1} would be an ideal counterpart to the LHC.[1]

The largest and highest-energy lepton collider, the Large Electron-Positron (LEP) collider at CERN, achieves an energy of approximately 200 GeV CM and has a circumference of almost 27 km. The canonical scaling law for circular electron colliders indicates that the collider lifetime cost is minimized if the circumference grows as the square of the CM energy.[2] Using the LEP size as a baseline, then, indicates that the least expensive circular lepton collider capable of achieving 1 TeV CM would be almost 700 km in circumference, a very large machine by any standards. A more reasonable approach to achieving the desired energy is the use of a high-gradient linear accelerator, for which the total size of the collider scales roughly linearly with the desired energy. At this time there are a number of different designs for a linear collider which achieves the energy and luminosity goals listed above. In this paper we describe one of the designs, the Next Linear Collider (NLC), which uses room-temperature RF acceleration at 11.4 GHz.

2 Luminosity in Linear Colliders

The canonical luminosity relationship for colliders is:

$$\mathcal{L} = \frac{f_{\text{rep}}}{4\pi} \frac{n_b N^2}{\sigma_x \sigma_y} H_D, \qquad (1)$$

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where f_{rep} is the natural frequency of the collider, n_b is the number of bunches, N is the bunch population, σ_x and σ_y are the RMS horizontal and vertical beam sizes, respectively, and H_D is the disruption enhancement factor, which represents luminosity gained by virtue of the two beams of charged particles focusing one another at collision. For a linear collider, and in the limit where $\sigma_y \ll \sigma_x$, we may rewrite Eq. 1 as:

$$\mathcal{L} = \frac{2P_b}{4\pi E_{\text{CM}}} \frac{N}{\sigma_x} \frac{H_D}{\sigma_y}, \tag{2}$$

where P_b is the beam power and E_{CM} is the desired center-of-mass energy.[3] The ratio N/σ_x is limited by the detector's ability to tolerate backgrounds due to the photons emitted in the collision (so-called "beamstrahlung" photons), and the number of photons emitted is proportional to N/σ_x. The disruption enhancement, H_D, is a nonlinear function of the beam transverse size, population, and bunch length at the collision; since the focusing effect which drives H_D is also the effect which generates beamstrahlung, H_D is usually constrained by the detector to values between 1 and 2. Thus the free parameters in Eq. 2 are the beam power, the CM energy, and the vertical beam size.

Translating the limits specified above into more practical terms, we find that for 1 TeV CM, 10 MW beam power, and approximately 1.5 photons per primary beam particle, we require a bunch population of 1.1×10^{10}, a horizontal RMS size of 250 nm, and a vertical RMS size of approximately 5 nm; this will yield $H_D \approx 1.5$, and luminosities which are comfortably above 1.0×10^{34}. A bunch population of 1.1×10^{10}, in turn, implies that 11,400 bunches must collide per second. Since linear colliders, as the name implies, do not recirculate bunches, the collider must generate, accelerate, and dump 11,400 bunches per second. This can be achieved in several ways. At one extreme, we may consider a pulsed accelerator in which the linac produces RF power in 11,400 pulses per second and every linac pulse accelerates 1 electron bunch; this is wasteful of AC power because of the finite rise/fall time of pulsed RF systems – most of the RF power is expended during the rise or fall of the pulse, and almost none of it is transferred to the beam. At the other extreme, we can consider pulsing the linac very infrequently, perhaps only one time per second, and accelerating 11,400 bunches per linac pulse; this would require an extremely long pulse of high power out of the RF sources, which is difficult to achieve, or alternately a long pulse of low power which is stored in the accelerating structures without losses, which requires superconducting structures. For room-temperature RF accelerators driven by klystrons, the optimum appears to be a linac repetition rate of approximately 100 Hz, and acceleration of 100 bunches per linac cycle.

The challenge of a linear collider such as the one described above, therefore, is to generate 120 trains of 95 bunches of 1.1×10^{10} electrons per second, accelerate the trains to 500 GeV, demagnify the bunches to transverse RMS sizes of 250 nm by 5 nm, and collide them.

3 The Next Linear Collider

Figure 1 shows a schematic of the Next Linear Collider layout. The overall site length is approximately 30 km for the 1 TeV CM design.[4]

3.1 Injector Systems

The NLC electron source is a DC photocathode system similar to the one used by the Stanford Linear Collider (SLC).[5] The source will produce 95 bunches per bunch train, with 2.8 nsec spacing, at the required rate of 120 Hz and with a beam polarization of approximately 80%. Such electron sources typically generate beams with large normalized transverse emittances ($\gamma\epsilon_{x,y} \approx 10^{-4}$ m.rad), and therefore the electron beams are accelerated to 1.98 GeV and injected into a damping ring for emittance reduction to the levels required by the NLC IP ($\gamma\epsilon_x = 3 \times 10^{-6}$ m.rad, $\gamma\epsilon_y = 3 \times 10^{-8}$ m.rad). The damping ring parameters are similar to those of third-generation synchrotron light sources, but in order to maintain the 120 Hz machine rate the damping times are much smaller;

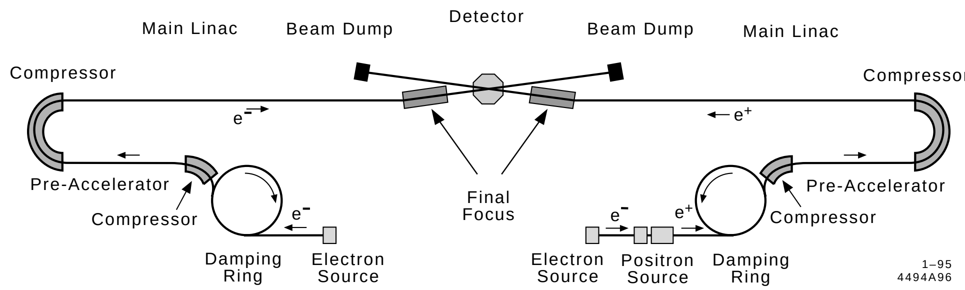

Figure 1: Schematic of the Next Linear Collider.

this is achieved by including a substantial length of wiggler magnet in the damping ring design. The beam extracted from the damping ring has a small transverse emittance but a larger bunch length than the main linac can tolerate ($\sigma_z = 5$ mm), and must be compressed by two stages of bunch compressor to an RMS length of 100 microns. Finally, the injector systems accelerate the beams to 8 GeV for injection into the main linac. Room-temperature RF systems based on the SLAC frequency (2.856 GHz) are used for this.

The positron injector system is nearly identical to the electron injector. The positron system includes a positron target and capture system (for production of positrons via electromagnetic shower), a 6 GeV electron linac and unpolarized electron source (to generate the shower), and a pre-damping ring (to damp the large positron emittances down to the acceptance of the main damping ring).

3.1.1 Polarization

The NLC electron source will produce electrons which are longitudinally polarized. This is the polarization direction which is typically required at the IP, but longitudinal polarization cannot survive in a storage ring. To prevent depolarization, the spin vector is rotated into the vertical prior to injection into the damping ring: a 60 degree bend rotates the polarization from longitudinal to horizontal, and a pair of solenoids rotate it from horizontal to vertical. The same system in reverse (solenoids followed by 20 degree bend) restores the longitudinal polarization in the damping ring extraction line; this line contains an additional pair of solenoids downstream of the 20 degree bend in order to permit any orientation of polarization vector to be achieved through tuning the relative strengths of the two solenoid families. The solenoids are arranged in pairs such that the xy coupling introduced by the solenoids is optically cancelled while the spin rotation effects add.

While the present NLC design does not envision polarized positrons, the positron damping ring complex is being designed with identical bending angles and optics, and with spaces reserved for the spin-rotation solenoids. Consequently the system can be easily modified for transport of polarized positrons or electrons.

3.2 Main Linacs

The NLC main linacs use an RF system with a frequency 4 times larger than the SLAC frequency (11.424 GHz). This permits greater energy efficiency and greater space efficiency: the 50 GeV SLAC linac is 3 km long and consumes approximately 40 MW while the 500 GeV NLC linac will be 10 km long and consume approximately 100 MW. The disadvantage of the higher frequency is that both the klystrons which provide the RF power, and the disk-loaded structures which provide the acceleration, are more difficult to design and build.

3.2.1 Klystrons

The NLC main linac klystron design produces a peak power of 75 MW over a pulse length of 1.5 microseconds. To achieve 1 TeV CM, a total of 6,500 such klystrons are required. In order to eliminate the complexity, expense, and maintenance liability of the klystron's focusing solenoid, the klystron beam is maintained by a periodic array of permanent magnet rings.

While the specifications above have been met in a periodic permanent magnet (PPM) klystron at 11.424 GHz, recent tests have indicated that pulse lengths of 3.0 microseconds are achievable at the same peak power. This implies that 50% of the klystrons in the present NLC design can be eliminated, and this is the present plan.

3.2.2 RF Structures and Beam Dynamics

The NLC RF structure is 1.8 meters in length and contains 206 cells of $2\pi/3$ mode cavities at 11.424 GHz. In addition to the fundamental (accelerating) mode, which is produced by the incoming RF power, the structures are capable of generating higher-order transverse deflecting modes when excited by a beam passing off-center through the structure. The short-range deflecting effect (in which the head of the bunch generates fields which deflect the tail) is addressed by installing 3 RF structures on a single 6 meter girder and providing the girder with precision remotely controlled translation stages. The structures are then aligned to the beam during operation using RF-BPMs which are integral to the structures. The long-range deflecting effect (in which subsequent bunches are deflected due to fields induced by early bunches) is addressed through a combination of detuning the cells to slightly different dipole frequencies in order to quickly decohere the wakefields, and lightly damping the cells such that higher order modes damp out before the modes can recohere.

3.3 Beam Delivery

Because linear colliders do not recirculate, every bunch which is transported to the IP is accompanied by a halo of particles at large amplitudes in position, angle, and energy offset. In addition, the pulsed nature of the acceleration presents a risk that on a given machine cycle a large number of klystrons will not operate and a bunch train will exit the linac with a large energy error. The post-linac collimation system removes the beam halo and protects the detector and other beamline systems from off-energy beams. Downstream of the collimation system the beam passes through an achromatic 10 mrad arc; the arc provides separation between the detector and muons generated in the collimation system, and also provides a crossing angle at the IP, which is necessary to avoid parasitic collisions in the long bunch trains. Finally the beam is demagnified by a factor of 50 in x and a factor of 300 in y; since the beam has a substantial energy spread and pulse-to-pulse energy jitter, the demagnification system must have a large bandwidth, which is provided by a combination of conventional chromatic correction and sextupoles at IP images to improve off-energy performance. Since the product of the crossing-angle and the bunch length is comparable to the horizontal beam size, the projected horizontal beam size at the IP will be enlarged; to prevent this, a "crab cavity" RF system is used to rotate the bunches such that they collide head-on in the detector. Finally, since the beams are only a few nm in RMS vertical size at the collision point, active stabilization of the final quadrupoles is required to prevent ground motion from driving the beams out of collision.

3.4 Extraction Line

The quality of the beams emerging from the collision is quite poor compared to the incoming beams due to the aforementioned phenomenon of disruption: the angular divergences are increased, the beam develops a long low-energy tail, a large number of electron-positron pairs are generated, and up to 10% of the beam power is converted to a cone of beamstrahlung photons. The extraction line transports this ill-conditioned beam to the high-power dump; the beamstrahlung photons are transported to the same dump for simplicity. The extraction line also contains diagnostics for monitoring the collided beams in order to reconstruct features of the collision such as the luminosity spectrum.

4 Test Facilities

In order to verify the subsystem designs of the NLC, a number of dedicated test facilities have been constructed. These are:

- The Accelerator Test Facility (ATF) at KEK, a prototype linear collider damping ring.[6]
- The Accelerator Structure Test Facility (ASSET), a facility in the SLAC linac for measuring long-range structure wakefields.[7]
- The Next Linear Collider Test Accelerator (NLCTA), a 300 MeV linac of 1.8 meter 11.4 GHz RF structures for verifying the acceleration properties and control of a long-pulse highly-loaded accelerator at the NLC frequency.[8]
- The Final Focus Test Beam (FFTB), a prototype linear collider final focus which demagnifies the 46.6 GeV SLAC beam by the same factor as required in the NLC.[9]

5 Electron-Electron Option

The option of colliding in electron-electron mode has been carefully included in the NLC design. Converting the nominal positron system to electrons requires the following changes:

- Installation of a polarized electron gun in the vicinity of the positron production target (space reserved in present model)
- Addition of a bypass line from the positron booster linac to the main positron damping ring, skipping the pre-damping ring (included in present design)
- Addition of spin rotators upstream and downstream of the positron main damping ring (space reserved in present model)
- Reversal of many magnet polarities (operational issue, not design issue).

The only beam-dynamics issues of any consequence which are specific to electron-electron operation are interactions with the detector solenoid and collision effects.

5.1 Interaction with Solenoid

The NLC beams enter the detector with a ± 10 mrad angle with respect to the solenoidal axis. For electron and positron beams, the solenoid deflects the two beams in opposite vertical directions by $30 - 100$ micrometers. This is corrected by steering the beams back into collision via moving the final quadrupole in vertical position. In the case of electron-electron collisions, both beams are deflected in the same vertical direction, so no steering is needed to preserve collisions. Unfortunately, the like-signed beams will now collide with a vertical crossing angle of 66 microradians (1 TeV CM) to 220 microradians (350 GeV CM). This is a large enough crossing angle to require a vertical crab-cavity for luminosity preservation. All optical effects of the solenoid are identical to those which impact the electron-positron collisions, and they may be easily corrected.

5.2 Collision Effects

Unlike electron-positron collisions, in which the counterpropagating beams focus one another with the result of enhanced luminosity, counterpropagating like-signed beams defocus one another. The result in a luminosity disenhancement. Using the results of Thompson and Chen,[10] H_D is typically 0.45 for electron-electron collisions using the nominal NLC parameters at 500 GeV and 1 TeV CM, while for electron-positron collisions H_D is close to 1.5. Thus the luminosity for electron-electron will typically be 1/3 that of electron-positron for comparable beam parameters.

In addition to the decreased luminosity, the electron-electron beams leave the collision with an angular divergence which is approximately 3 times as large as it would be for comparable electron-positron parameters.[11] Such a large outgoing divergence would complicate extraction of the beam and transport to the dump.

A final effect of the like-signed collision is increased sensitivity to vertical offsets.[11] The same mutual-focusing effect which enhances the electron-positron luminosity reduces the sensitivity to transverse beam offsets: the beams attract each other ("pinch effect") and the sensitivity to offsets is reduced by approximately a factor of 2 relative to neutral-beam collisions. For like-signed beams, there is instead a slight "anti-pinch:" the luminosity is slightly more sensitive to offsets than it would be for neutral beams. This implies that the vertical jitter tolerances for electron-electron collisions will be tighter than the tolerances for electron-positron collisions by a factor of 2, and that a collision feedback which can detect and correct offsets within a bunch train may be required.

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