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ILC Electron Source Injector Simulations

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ABSTRACT

As part of the global project aimed at proposing an efficient design for the ILC (International Linear Collider), we simulated possible setups for the electron source injector, which will provide insight into how the electron injector for the ILC should be designed in order to efficiently accelerate the electron beams through the bunching system. This study uses three types of software: E-Gun to simulate electron beam emission, Superfish to calculate solenoidal magnetic fields, and GPT (General Particle Tracer) to trace charged particles after emission through magnetic fields and subharmonic bunchers. We performed simulations of the electron source injector using various electron gun bias voltages (140kV – 200kV), emitted beam lengths (500ps – 1ns) and radii (7mm – 10mm), and electromagnetic field strengths of the first subharmonic buncher (5 – 20 MV/m). The results of the simulations show that for the current setup of the ILC, a modest electron gun bias voltage (~140kV) is sufficient to achieve the required bunching of the beam in the injector. Extensive simulations of parameters also involving the second subharmonic buncher should be performed in order to gain more insight into possible efficient designs for the ILC electron source injector.

Introduction

The International Linear Collider (ILC) is a proposed electron-positron collider planned to be built in the near future in hope that the data resulting from it will give insight into the physics of dark matter and dark energy. The global ILC collaboration

aims to improve the accelerator design for high efficiency. We study the design of the electron source injector, which produces, focuses and bunches the beam before it is injected into the damping ring and travels down the accelerator. The design of the injector is crucial for electron beams because it is much more effective to modify the distribution of particles in a beam before it reaches relativistic speeds, which for an electron beam happens almost immediately once in the accelerator. The electron beam is produced in the source injector by a photocathode electron DC gun which initially accelerates the electrons using a cathode voltage bias to the anode. After initial acceleration, charged particle beams are modified by space charge, the effect of the repulsive Coulomb force interactions among the particles within the beam that causes it to grow in cross section and length at a rapid rate [1]. Therefore, the beam is kept focused using a solenoidal field and longitudinally compressed or bunched using subharmonic bunchers (SHB). A SHB bunches the electron beam by applying an electromagnetic field that oscillates in time to modulate the velocities of the particles along the beam length.

The current design of the ILC electron source injector consists of a photocathode electron gun, a solenoidal magnetic field, and two SHB. The photocathode electron gun that will be used for the ILC is based on the design of the gun used for the SLC (Stanford Linear Collider), will have a bias voltage of 140 to 160 kV, and will be optimized to provide a space charge limited current, described by Child's Law:

$$I = K\sqrt{V^3} \quad (1)$$

where I is emitted current, K is the perveance, a physical parameter that depends on the geometry of the photocathode, and V the photocathode bias voltage. Because the desired

electron bunch charge is 3.2 nC at the collision point, the photocathode will emit an electron beam with charge 4.5 - 5nC to account for particle loss before collision. In the current design, the beam will be emitted as a 1 ns pulse, so the photocathode gun must produce a current of 4.5 – 5 A (or 4.5 – 5 nC/ns). The electron beam is focused in the injector using a solenoidal field. To compress or bunch the beam after emission, two SHB are placed just after photocathode gun, operating at frequencies of 216.7 MHz and 433.3 MHz respectively [2]. At SLAC, ILC injector simulations have been conducted using a 120-kV gun and a previous ILC model that consisted of two SHB at 108 MHz and 433.3 MHz respectively [4, 5]. The new setup with the first subharmonic buncher (SHB-I) operating at 216.7 MHz and possibly higher voltage electron guns need to be investigated.

In this work, we study a variety of electron gun and initial beam parameters, and buncher operating conditions that can be incorporated into the ILC electron source injector design described above. The injector design can only be optimized under the physical limitations of equipment available for the ILC by finding efficient combinations of the many parameters. Optimum bunching of an electron beam occurs for beams whose time length fits into the quarter period of the SHB. Therefore, the length of the beam when it reaches the first buncher should fit into the quarter period of the first buncher and the first buncher should compress the beam down to length that should just fit into the quarter period of second subharmonic buncher (SHB-II). We calculate this desired bunch length in the following way where $\nu_1=216.7$ MHz and $\nu_2=433.3$ MHz are the frequencies of the two SHB, T_1 and T_2 their periods, and l_{len_1} and l_{len_2} the desired bunch lengths respectively.

$$T_i = \frac{1}{\nu_i} \quad (2)$$

$$tlen_i = \frac{1}{4} T_i = \frac{1}{4\nu_i} \quad (3)$$

Consequently, $tlen_1=1.15$ ns and $tlen_2=577$ ps. As a result, efficient bunching occurs for an electron beam that is 1.15 ns long when it reaches SHB-I and 577 ps when it reaches SHB-II. For the case of the ILC accelerator which has a driving frequency of 1.3 GHz, the efficient bunch length is 200 ps. This efficient bunch length for the accelerator means that the electron beam should be compressed by SHB-II down to 200 ps just before it is injected into the damping ring on its way to the accelerator.

After acquiring and analyzing the data of the electron beam in the various injector setups, we can draw conclusions about how the electron injector setup can be designed for the ILC for operational and cost efficiency.

Materials and Methods

The simulations of the ILC electron source were performed using three types of software: E-Gun [5], Superfish, and General Particle Tracer (GPT). E-Gun was used to simulate the electron beam as it is emitted by the electron gun, Superfish to calculate the magnetic fields resulting from different arrangements of electromagnets, and GPT to trace the particles in the beam after it is emitted from the electron gun. We performed simulations of the electron source injector using a range of electron gun bias voltages (140kV – 200kV), emitted beam lengths (500ps – 1ns) and radii (7mm – 10mm), and electromagnetic field strengths of the first subharmonic buncher (5 – 20 MV/m).

E-Gun

In E-Gun, a photocathode gun, as shown in Fig. 1, was specified by its bias

voltage V , the radius of the electron emitting area r_k and the perveance K , a physical quantity that depends on the geometry of the photocathode.

The three variables of interest defined in E-Gun were r_k , V , and the initial time pulse length of the electron beam Δt . The radius of the electron emitting area and the bias voltage can be input directly into the program, but the beam peak current is defined by the perveance (K). The reason for this is clear from the relationship between these parameters. Using eqn. 6 and the definition of current ($I \equiv \frac{dq}{dt}$):

$$I = K\sqrt{V^3} = \frac{Q}{\Delta t} \quad (7)$$

Rearranging eqn 7 gives:

$$\Delta t\sqrt{V^3} = \frac{Q}{K} \quad (8)$$

where Q is the current of the electron beam emitted by the gun over the time Δt . Taking into account that $Q=5nC$, eqn. 8 becomes:

$$\Delta t\sqrt{V^3} = \frac{5nC}{K} \quad (9)$$

where eqn. 9 now expresses the two variables of interest, Δt and V , as a function of the perveance K . Therefore, for a desired given input V , K was chosen to correspond to the desired Δt to be tested.

After calculating the emitted current using Child's Law and tracing the particles to the end of the gun, E-Gun presents information broken down to the individual rays making up the beam, each representing a macro particle of electrons. The number of rays used must be input. Because of space charge, the electron beam cannot be represented as a single body, but instead as several particles that act upon each other as the beam moves.

Therefore, the greater the number of rays used to represent the beam, the more realistic the problem and the more accurate the results. However, with a greater number of rays to account for, the required computation time increases. For each ray, the program presents the ray position, kinetic energy, current, and divergence angle for the beam at the end of the gun. The software gives the ray positions in the two dimensional r-z plane, where z is the direction of the current, orthogonal to the surface of the photocathode, and r the radial distance from the z-axis. Presenting position in 2-D is sufficient because the photocathode is cylindrically symmetric and consequently the emitted electron beam is also cylindrically symmetric. Another output value of interest from the program is the emittance of the beam at the end of the gun. The information about the rays at the end of the gun from E-Gun was then used to define the initial conditions of the particles in GPT. The position and kinetic energy coordinates for each ray must be transformed and input into GPT as phase space Cartesian coordinates $(x, y, z, \gamma\beta_x, \gamma\beta_y, \gamma\beta_z)$, where the product $\gamma\beta$ of the Lorentz factor γ and the relativistic β is known as the particle normalized momentum. Because the electron beam is cylindrically symmetric, an array of random azimuthal angles φ could be used to transform the r coordinates of the rays in E-Gun to (x,y) coordinates for use in GPT. The r and z -components of the particle normalized momentum $\gamma\beta_r$ and $\gamma\beta_z$ respectively for each ray was calculated from the kinetic energy T and divergence angle θ provided by E-Gun. Then the coordinates $\gamma\beta_x$ and $\gamma\beta_y$ were transformed from $\gamma\beta_r$ and φ using the following procedure:

$$\gamma = 1 + \frac{T}{m_e c^2} \quad (11)$$

$$\beta = \sqrt{1 - \frac{1}{\gamma^2}} \quad (12)$$

$$\gamma\beta_z = \gamma\beta \cos \theta \quad (13)$$

$$\gamma\beta_r = \gamma\beta \sin \theta \quad (14)$$

$$\gamma\beta_x = \gamma\beta_r \cos \varphi \quad (15)$$

$$\gamma\beta_y = \gamma\beta_r \sin \varphi \quad (16)$$

where m_e is the electron rest mass and c the speed of light. The last array of data needed for the initial conditions of the rays in GPT is the number of electrons that each ray represents N . The number of electrons N_j for a ray j is:

$$N_j = \frac{\Delta I_j}{I} \quad (17)$$

where ΔI_j is the amount of current of ray j and I is the total current of the electron beam.

Superfish

Different arrangements of solenoids, reflectors, Helmholtz coils were input into Superfish to calculate the resulting magnetic fields. We set the current in the coils of the electromagnets, the dimensions of the components, and the permittivity and permeability of the reflector material. Since the components are cylindrically symmetric about the beam, the program displays them in the r-z plane. The two data arrays taken from Superfish and imported into GPT describe the z-component of the magnetic field as a function of position along the accelerator $B_z(z)$. The arrangement of components in Superfish that we chose to use was one that resulted in the most symmetric, constant function for $B_z(z)$.

GPT

The electric fields due to the subharmonic bunchers were defined in GPT and were of the form:

$$E_z(r, z) = E_z(z)\cos(\omega t + \phi) \quad (18)$$

where $E_z(z)$ is the function representing the z component of the electric field as it varies in space within the bunching cavity, ω the angular frequency of the SHB, t the time variable, and ϕ the phase shift. The electric field in space $E_z(z)$, takes the shape of a Gaussian function with its peak at the location of the SHB, $z=1.5\text{m}$:

$$E_z(z) = E_0 e^{-\pi(z-1.5)^2} \quad (19)$$

where E_0 is a constant in place for the amplitude. GPT then simulates the electron beam imported from E-Gun in time by tracing the individual rays subject to space charge, external and self-induced magnetic and electric fields. The program then presents the beam trajectory in the r - z plane. One example of a beam trajectory at all times is shown in Fig. 2. From the trajectory, the program calculates the beam emittance, length, radius, and particle loss in time. A particle was considered lost if its r or z coordinate had a difference of more than three standard deviations from the average coordinates of the beam.

Data Analysis

The initial time pulse length of the electron beam Δt , the radius of the electron emitting area r_k and bias voltage V of the photocathode, the solenoidal field, and the phase shift ϕ and amplitude E_0 of the RF cavities were all varied in order to determine the behavior of the electron beam for different electron injector setups.

Using our data of resulting electron bunch length as a function of SHB-I electromagnetic field strength, we calculate the electromagnetic field strength of SHB-I needed to compress the bunch down to 577ps. This calculation was performed for beams of radius $r_k = 10mm$ at the photocathode.

Results and Discussion

The arrangement of the solenoids used to contain the beam and the corresponding magnetic field is shown in Fig. 3 and 4, respectively. The required electromagnetic field strengths for SHB-I needed in order to result in a 577 ps bunch length for the different sets of parameters are shown in Table 1.

Our results show that the beam will not grow longitudinally due to space charge beyond the quarter wave length of SHB I for all investigated initial pulse lengths and gun bias voltage cases. Moreover, a gun bias voltages of 140 kV is sufficient; thereby reducing the cost and risk associated with the gun. On the other hand, by using very high power electron gun (200 kV) and high electromagnetic field for SHB-I (15 MV/m), the need for SHB-II can be eliminated as SHB-I would be sufficient to compress the beam bunch length to 200 ps as demonstrated in one case of our simulations in which the electron gun and SHB-I compressed a 890 ps beam at the electron gun into a 222 ps long one.

Future work would involve including SHB-II in the simulations, further optimization of solenoidal fields, changing the z-location of SHB-I, and investigation of the possibility of using only one SHB in the injector. The electron source injector is crucial to the quality of the beam as it travels down the accelerator and collides at the

detector. An optimized electron injector design is of particular interest to the ILC as it is the source of all beams (including the positron beam) used throughout the injector.

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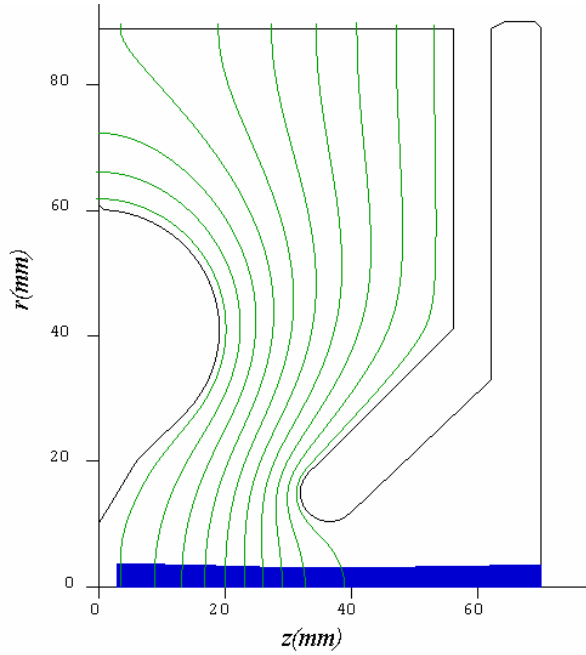


Figure 1. Electron gun in the r-z plane that was used to simulate emission of electron beam.

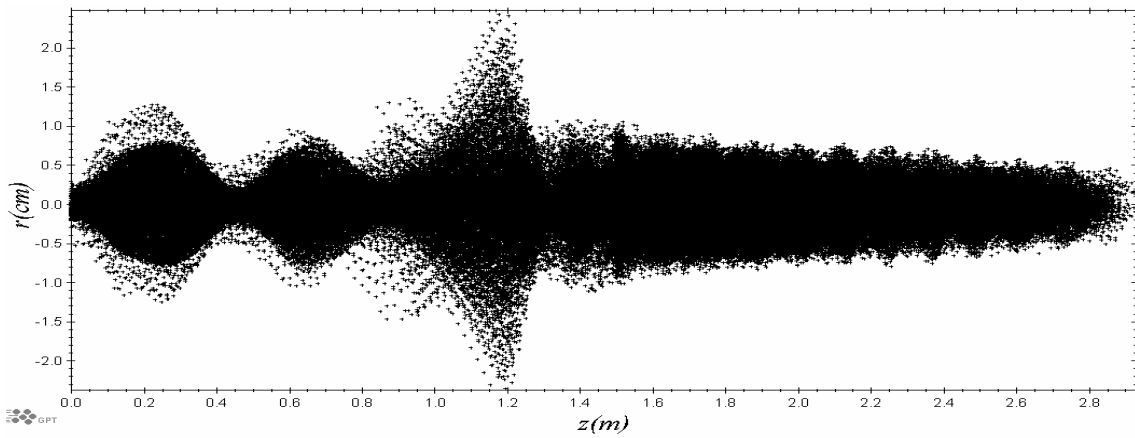


Figure 2. Example trajectory from GPT of electron beam taken at all times in the r-z plane.

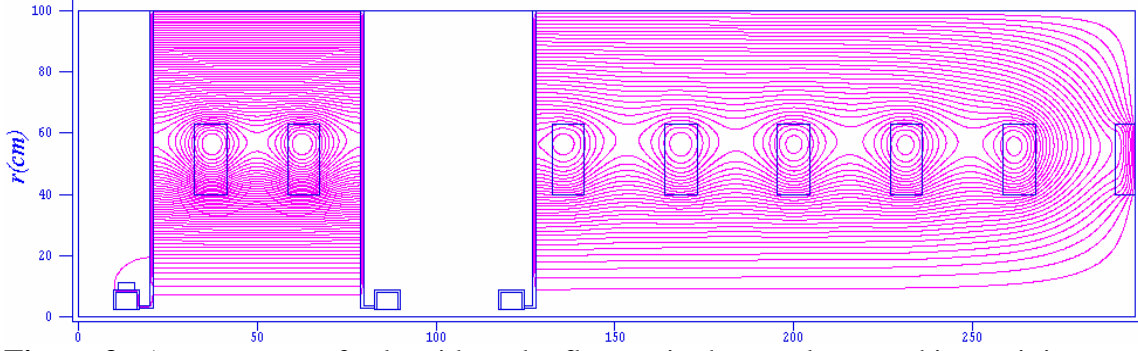


Figure 3. Arrangement of solenoids and reflectors in the r-z plane used in our injector setup to produce the magnetic field to focus the beam.

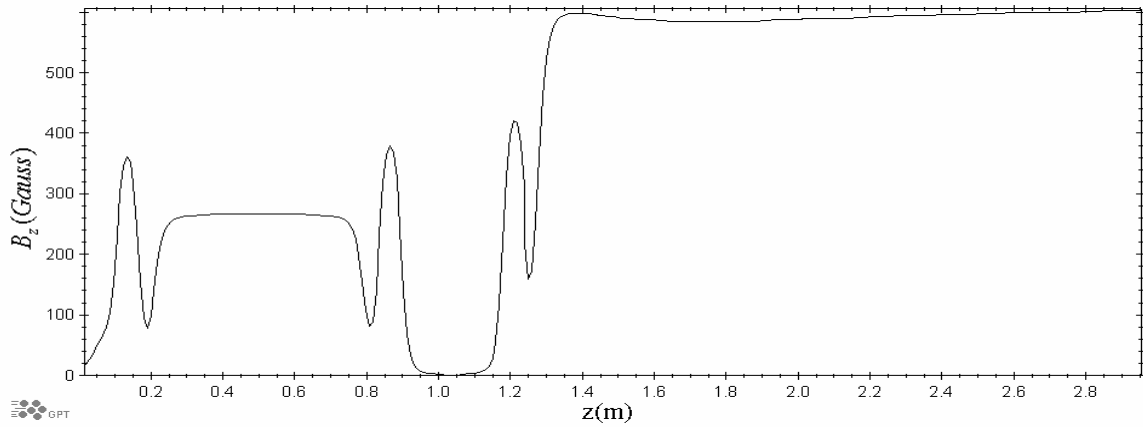


Figure 4. The magnetic field due to the arrangement of solenoids and reflectors shown in Fig. 3.

		Electron Gun Bias Voltage, $V(kV)$			
		140	160	180	200
Initial time pulse length, $\Delta t(ps)$	500	7.58	6.92	8.03	11.12
	630	7.46	8.19	8.36	12.06
	760	7.66	6.48	7.59	7.81
	890	7.20	9.28	7.03	8.69
	1020	5.64	6.04	6.83	8.17

Table 1. SHB-I field strength $E_z(MV/m)$ needed to compress bunch to 577 ps.