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DESIGN OF A HIGH-CURRENT INJECTOR AND TRANSPORT OPTICS FOR THE ILC ELECTRON SOURCE*

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Abstract

A train of 1.3-ns micro bunches of longitudinally polarized electrons are generated in a 140-kV DC-gun based injector in the International Linear Collider electron source; a bunching system with extremely high bunching efficiency to compress the micro-bunch down to 20 ps FWHM is designed. Complete optics to transport the electron bunch to the entrance of the 5-GeV damping ring injection line is developed. Start-to-end multi-particle tracking through the beamline is performed including the bunching system, pre-acceleration, vertical chicane, 5-GeV superconducting booster linac, spin rotators and energy compressor. With optimizations of energy compression, 94% of the electrons from the DC-gun are captured within the damping ring 6-D acceptance − $A_x + A_y \le 0.09$ m and $\Delta E \times \Delta z \le (\pm 25\text{MeV}) \times (\pm 3.46\text{cm})$ − at the entrance of the damping ring injection line.

OVERVIEW

The International Linear Collider (ILC) electron injector consists of a DC-gun incorporating a III-V semiconductor photocathode illuminated by a Ti:sapphire drive laser to produce a train of 1.3-ns long longitudinally-polarized electron microbunches. A highly efficient bunching system consisting of two subharmonic pre-bunchers (SHB) and a β-matched L-band Traveling Wave (TW) buncher compress the bunch length to 20 ps FWHM. The electron bunches are then accelerated to 76 MeV in a normal conducting L-band structure. A chicane downstream of this pre-acceleration system is used to clip off the low energy tail of the bunched beam. After traversing an emittance measurement station downstream of the chicane, the electron bunch is accelerated to 5 GeV using a booster linac consisting of standard ILC-type superconducting (SC) cryo-modules. During transport of the beam from the electron booster linac to the damping ring (DR) injection line, the electron spin vector is adjusted vertical and the energy is compressed. The overall optics and geometry of the electron source are shown in Figs. 1 and 2, respectively.

This paper is organized as follows: first, a system description including the bunching system, chicane, booster linac, spin rotators, and energy compressor is presented; then, the multi-particle tracking from the gun to the entrance of the damping ring injection line is performed; and, finally, the results are summarized and the future work is outlined.

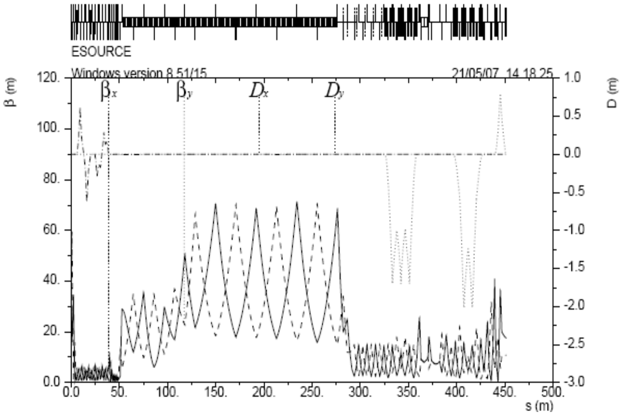

Figure 1: Overall optics of the ILC electron source (76 MeV injector is not shown).

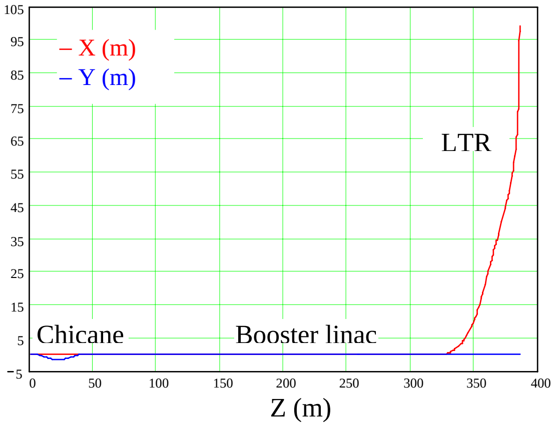

Figure 2: Overall geometry of the ILC electron source (76 MeV injector is not shown).

SYSTEM DESCRIPTIONS

76-MeV Injector with High Bunching Efficiency

A train of 1.3-ns micron bunches are generated in a 140-kV DC gun based injector. A bunching system is proposed to compress the micro-bunch down to ~20 ps FWHM from 1.3 ns. It includes two SHBs and an L-band buncher. With the progress on the ILC design, the first SHB evolves from 108 MHz [1-2] to 216 MHz to meet the DR timing requirement. The second SHB works at 433 MHz. Each SHB needs ~50 kV of high voltage. The micro-bunch is first compressed down to 200-ps FWHM (94° at L-band) by the two SHBs. Further compression down to 20 ps FWHM is achieved by the L-band buncher.

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In the TESLA Technical Design Report, two 5-cell, β=1 Standing Wave (SW) structures are used as bunchers [1]. Further studies show that tapered-β traveling wave buncher has higher bunching efficiency [2] compared with the standing wave buncher. In our design, a 5-cell L-band TW structure with tapered β=0.75, 0.78, 0.82, 0.87, and 0.93, and two 50-cell β=1 TW normal conducting L-band structures are used as the buncher and pre-acceleration system, respectively.

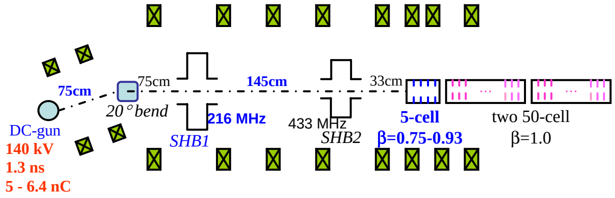

Figure 3: Schematic layout of the ILC 76-MeV electron injector; dimensions are not scaled in the plot.

The schematic layout of the injector with the TW buncher is shown in Fig. 3. The gun is placed at a 20° angle to the injector axis. This arrangement has some technical advantages: allows the laser beam to access the photocathode; permits polarization measurements; protects the gun vacuum; and allows the installation of a second backup gun. The distance from the gun exit to the bend is 75 cm, which is similar to the SLC injector. The distance between the bend and the first SHB (216 MHz) is 75 cm. The beam transported from the gun to the first SHB is focused by three magnetic lenses so that they can be used to adjust the radius and convergence of the beam at the entrance of the solenoid that confines the beam in the SHBs. The edge beam radius can be controlled smaller than 1.5 cm with the lenses. The distance between the two SHBs is 145 cm, and the solenoid field in the region ramps from 50 G to 135 G. The distance between the second SHB and the entrance of the L-band buncher is 33 cm, which allows the installation of diagnostics. The solenoid field ramps from 135 G in the second SHB to 660 G in the buncher to keep the beam small. While the primary bunching is achieved by the L-band buncher, a final, relatively small, increment of bunching takes place in the first several cells in the pre-accelerator, which immediately follows the L-band buncher. The accelerating gradients in the L-band buncher and pre-accelerator are 5.5 MV/m and 8.5 MV/m, respectively, and the beam is accelerated to 76 MeV by the end of the injector. The first ~1.5 m of the L-band sections are immersed in a 660-G solenoid field to focus the beam, and then the field is tapered down to zero as the beam gains energy. Beam modeling using PARMELA is performed starting from the 140-kV DC-gun exit to the 76-MeV injector exit. To account for losses through the injector, a bunch charge of 6.4 nC is assumed at the gun (twice the charge required at the IP). The unnormalized edge emittance at the gun exit is assumed to be 70 µm. Fig. 4 shows the energy and phase spectra at the 76-MeV injector exit. It is shown that at the injector end the energy spread is <100 keV FWHM (<1.5 MeV Full Width) and the bunch length is 9° at L-band or 20 ps FWHM (25° at L-band or 53 ps Full Width). The beam envelope and solenoid field map along the injector are described in detail in Ref. [2].

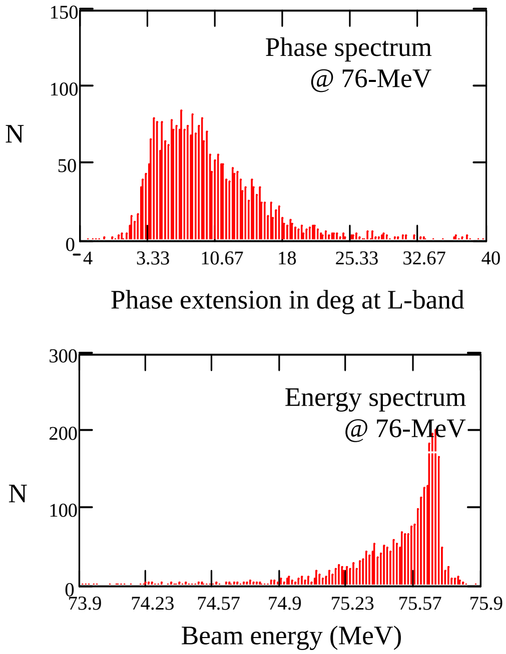

Figure 4: Phase (top) and energy spectra (bottom) at 76 MeV injector exit.

Vertical Chicane and Emittance Measurement Station

In the ILC electron source baseline design, horizontal doglegs are used to combine two normal conducting pre-acceleration systems and to clip off the electrons in the low energy tail before injecting into the SC electron booster linac. In September 2006, after the Vancouver Global Design Effort meeting, the backup normal conducting pre-acceleration system was removed to save the cost. But the energy collimation is still required. To make future services, repair and replacement particularly for cryomodules straightforward, a vertical chicane including several 90° FODO cells inserted with bends is proposed. An energy collimator is installed near the maximum dispersion in the chicane. The tracking shows that the electrons in the lower end of the energy tail are efficiently collimated. A section to match Twiss parameters at the injector exit with the chicane is considered. The injector beam emittance is measured at a station downstream of the vertical chicane using conventional wire scanners. Two matching sections to match the chicane with the emittance station and the emittance station with the SC booster linac are needed.

Optics of the 5-GeV Superconducting Linac

Twenty-one standard ILC-type SC cryomodules are used to accelerate the electron beam to 5 GeV. Typical

FODO cells are used to focus the beam through the cryomodules. The booster linac has two sections. The energy in the first section ranges in between 76 MeV and 1.717 GeV. One quadrupole sits inbetween two cryomodules for beam focusing, and the field strength of quadrupoles, $(\partial B/\partial x)\times L$, is in the range of 0.10-0.40 T. In the second section, the electron beam is accelerated to 5 GeV. Its quadrupole spacing doubles that in the first section, and $(\partial B/\partial x)\times L$ is in the range of 0.40-0.93 T.

Optics of the Linac-to-Ring System

The electron Linac-to-Ring (LTR) system, which extracts the electrons from the booster linac system and injects them into the DR injection line, has two main functions: one is to rotate the electron spin vector to the vertical plane; and the other is to manipulate the energy compression to meet the DR longitudinal acceptance. The longitudinal polarization of the electrons is generated at the gun and preserved prior to the DR. In the DR, only electron spin directions parallel or anti-parallel to the magnet field – that is, transverse to the plane of the DR – will preserve their polarization. The LTR system consists of bending magnets and solenoid that change the spin of the electrons first from the longitudinal to the horizontal plane and then from horizontal to vertical, parallel to the magnetic field of the DR (the magnetic field in the DR is in the vertical plane). The spin precession with respect to the momentum vector caused by a bending angle, θ_{bend}, is given by $\theta_{spin\_bend} = \frac{E(GeV)}{0.44065}\cdot\theta_{bend}$, where E is the electron energy. Rotation of the spin vector in the horizontal plane by $n\cdot 90°$ (n is an odd integer) from the longitudinal direction requires a total bending angle of $\theta_{bend} = n\cdot 7.929^{\circ}$ at 5 GeV. When an electron passes through a solenoid, its component of spin perpendicular to the solenoid field is rotated around the solenoid field axis. The spin rotation angle caused by a solenoid is given by: $\theta_{spin\_sole} \approx \frac{B_z\cdot L_{sole}}{B\rho}$, where B_z is the longitudinal solenoid magnetic field, L_{sole} is the solenoid length, $B\rho$ is the magnetic rigidity. For a 90° of spin rotation from the horizontal to the vertical plane at 5 GeV, a solenoid magnetic field integral of $B_z\times L_{sole}$ = 26.23 T.m is needed. Two 4.15-m-long superconducting solenoid with B_z=3.16 T are used.

The bunch decompression or energy compression can be realized by properly manipulating the linac RF phase with a suitable transfer function, $R_{56} = \int\frac{D_x}{\rho}ds$ (D_x is the dispersion, and ρ is the bending radius), generated in bends. The first LTR arc having four FODO cells inserted with 8 bends is designed for the energy compression and the spin rotation [2]. A bending angle of $7\times 7.929°$= 55.5° is chosen in the design. The nominal R_{56} is 86 cm but adjustable within the range of ±30cm. After the bunch decompression, an RF voltage of 180 MV provided by a 12-m-long superconducting linac is implemented to rotate the electrons in the longitudinal phase space to match the DR longitudinal acceptance. The rest of the LTR system includes a section to have an additional 34.5° horizontal-bending arc and a matching section to be same as the one in the ILC e+ source.

TRACKING WITH OPTIMIZATION OF ENERGY COMPRESSION

Multi-particle tracking from the gun to the entrance of the DR injection line has been performed. PARMELA is first used to track electrons from the gun to the 76-MeV normal conducting pre-accelerator. The ELEGANT code [3] is then used to track the beam through the rest of electron beamline including the vertical chicane, the SC booster linac, and finally the LTR system. Electron 6-D coordinates at the pre-accelerator exit from the PARMELA simulation are used as the input data in the ELEGANT code tracking. To accommodate more electrons within the DR 6-D acceptance – $A_x + A_y \le 0.09$ m and $\Delta E\times\Delta z \le (\pm 25\text{MeV})\times(\pm 3.46\text{cm})$ [4], the energy compression is optimized in the LTR before injecting into the DR injection line. For that purpose, the booster linac upstream of the LTR runs the booster linac RF phase off-crest to create a suitable correlated energy spread. Tracking shows that 94% of the electrons from the gun can survive the transport through the complete beamline based on the physical apertures of the beam pipes [2] and all of the transmitted electrons are captured within the DR 6-D acceptance.

SUMMARY AND FUTURE WORK

The bunching system and transport optics for the 140-kV DC-gun based ILC polarized electron source are developed; start-to-end particles tracking shows that 94% of electrons from the gun are captured within the DR 6-D acceptance at the entrance of the DR injection line. Looking toward the Engineering Design Report, more detail work is needed including: (1) bunching system optimizations to integrate with the engineering design; (2) beamline optics and physical aperture optimizations to integrate with the engineering design; (3) component tolerances definition; and (4) defining tuning requirements.

REFERENCES

[1] A. Curtoni, *et al.*, “Study of the TESLA preaccelerator for the polarized electron beam”, TESLA 2001-22, 2001.

[2] F. Zhou, *et al.*, “Start-to-end transport design and multi-particle tracking for the ILC electron source”, SLAC-pub-12240, Jan 2007.

[3] M. Borland, Technical Report No. LS-287, Argonne national lab, 2000.

[4] A. Wolski, private communication, Nov. 2006.