SLC–2000: A LUMINOSITY UPGRADE FOR THE SLC

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Abstract

We discuss a possible upgrade to the Stanford Linear Collider (SLC), whose objective is to increase the SLC luminosity by at least a factor 7, to an average Z production rate of more than 35,000 per week. The centerpiece of the upgrade is the installation of a new superconducting final doublet with a field gradient of 240 T/m, which will be placed at a distance of only 70 cm from the interaction point. In addition, several bending magnets in each final focus will be lengthened and two octupole correctors are added. A complementary upgrade of damping rings and bunch compressors will allow optimum use of the modified final focus and can deliver, or exceed, the targeted luminosity. The proposed upgrade will place the SLC physics program in a very competitive position, and will also enable it to pursue its pioneering role as the first and only linear collider.

Introduction

The goal of the SLC–2000 proposal [1] is to upgrade the Stanford Linear Collider (SLC) in order to produce 3 million polarized Zs in less than four years, and to embark on the rich physics program accessible in future high-luminosity SLC runs [2]. In this document, we outline an upgrade path for the accelerator that will increase the SLC luminosity by roughly a factor of seven and point to related documents for more information.

The average Z production rate during good months of the 1994/95 SLC running cycle was 5000 Zs per week. Assuming 30 week physics runs each year and a 25% reduction of the integrated luminosity due to PEP-II (B factory) operations, then the peak luminosity must be increased from its 1994/95 value by a factor of seven to attain the desired complement of Zs. It should be noted that we have based our luminosity extrapolation on the good performance during the 1994/95 run. If, instead, the luminosity estimate is scaled from the average performance during either 1994-1995 or 1996, where we had numerous operational difficulties, the upgrade would only yield 2 million Zs in four years.

To gain the factor of seven increase in luminosity, we propose to decrease $L^\star$, the free length at the interaction point (IP), by moving the final lens closer to the IP and to decrease the horizontal emittance by 30% at the IP. We considered a number of other approaches such as increasing the bunch charge, the number of bunches per train, or the repetition rate, or decreasing the emittance more substantially, but felt they were all too costly, difficult or uncertain. On the other hand, the optics and aberrations in the final foci are well understood, as demonstrated by studying the operation of the collider at low beam current where the emittance dilutions and pulse-to-pulse orbit variations are small. At a bunch charge of 5×10^9, the measured IP spot sizes are roughly 2.1 μm by 400 nm, in complete agreement with the expected values [3]. Thus, although the proposed upgrade will increase the optical aberrations slightly, we believe that we can accurately calculate these and compensated them with additional octupoles in each final focus.

Unfortunately, at high currents, there are dilutions that are not well understood. For example, with a bunch population of 3.5×10^{10}, the measured vertical IP spot size is typically 50% larger than expected. Fortunately, any emittance dilutions or jitter at high current will get demagnified by the new final lens, and the ratio of actual and expected luminosity will stay constant. Thus, the predicted *relative* luminosity increase due to the change in $L^\star$ is valid at both high and low currents.

The reduction of the horizontal emittance is more difficult to predict because we do not fully understand the emittance dilutions and the luminosity reductions at high current. Fortunately, the horizontal spot size, and thereby emittance, is significantly larger than the vertical and much closer to the expected value giving confidence in our ability to predict a small reduction. In the upgrade, we reduce the horizontal emittance in the damping rings and bunch compressors by a factor of three. Given the known sources of dilution, we would expect this to reduce the IP horizontal emittance by a factor of 50%. Assuming some additional sources, we are conservatively designing for an emittance reduction of only 30%.

Table 1 lists IP beam parameters for the SLC-2000 upgrade. The upgrade rests on the following assumptions: First, the luminosity limitations in the present SLC are due to purely geometric effects, *i.e.*, transverse wakefields, magnetic errors, transverse jitter, *etc.*, that dilute the projected horizontal and vertical phase space densities *upstream* of the final triplet. In this case, the limiting dilutions will be demagnified by the new final doublet along with the spot sizes. This assumption is believed to be true because all known chromatic and chromo-geometric sources which can partially negate the chromatic correction have been estimated to be negligible. Second, the chromatic properties of the present SLC final focus agree with predictions, giving confidence that we can predict the chromatic properties of the new design. Experimental data which support this are summarized in [4, 5]. Third, the required 500 μm bunch lengths at the IP can be produced and collided with acceptable backgrounds. It should be noted that the SLC operated with 750 μm bunch lengths at the IP during the first half of the 1994-1995 run. Fourth, the horizontal emittance reduction at the IP can be accomplished. This assumption has been verified recently by operating the present damping ring coupled, decreasing the extracted horizontal emittance by roughly 50% at the expense of the vertical. Further evidence for it arises from the behavior of the vertical emittance which was decreased substantially by operating the damping rings off the coupling resonance, and from studies of emittance growth in the collider arcs [5, 6]. Fifth, the luminosity is not limited by collision related backgrounds, *i.e.*, background sources that arise from the electromagnetic interaction of the two bunches.

Final-Focus Upgrade

The centerpiece of the final-focus upgrade is a pair of new LHC-style superconducting final doublets with a field gradient of 240 T/m. These doublets will replace the present SLC final triplets which have gradients of about 100 T/m. The free length to the IP, $L^\star$, will be reduced from 2.2 m in the present final focus to 70 cm in the upgrade. In addition, three new bending magnets and two octupole correctors will be installed in each final focus, to reduce the effects of synchrotron radiation and higher-order aberrations.

At present the SLC final focus operates with flat beams. IP beta functions are about $\beta_x \approx 7$ mm, $\beta_y \approx 2$–3 mm, and the high-current emittances are $\gamma\epsilon_x \approx 5.6 \times 10^{-5}$ m, and $\gamma\epsilon_y \approx 1.0 \times 10^{-5}$ m. Under good running conditions, the spot size can be 2.1 μm×0.7 μm at high current (bunch charges larger than 3.5×10^{10}). The upgrade is designed to reduce the spot size to 1.15 μm×0.25 μm for horizontal and vertical beta functions of 2.1 mm and 500 μm, respectively. This corresponds to a luminosity of 500 Zs per hour, which increases to more than 1000 Zs per hour, if the horizontal emittance is reduced to $\gamma\epsilon_x \approx 4.0 \times 10^{-5}$ m, and the rms bunch length shortened to 0.5 mm.

The present IP spot size is limited by three different effects [3, 7]: linear optics, nonlinear aberrations—primarily due to the interleaved sextupoles—and synchrotron radiation in the bending magnets. The latter increases both the horizontal spot size, due to the induced emittance growth, and the vertical spot size by virtue of the large triplet chromaticity. To reduce these limitations, we have considered the following improvements to the final focus: First, the three last bending magnets will be replaced by 50% longer magnets. Sufficient space for the new dipoles is available. Second, two octupole magnets, on remotely controlled movers, will be added to each final focus. These will correct the dominant nonlinear aberrations, and improve the energy bandpass of the system. It will also be advantageous to mount the four main sextupoles in each final focus on remote movers, and to install additional 1-μm resolution BPMs, as used in the Final Focus Test Beam. The last two items are relatively minor modifications, which will facilitate operation. Third, as stated, the heart of the final-focus upgrade is the installation of a new superconducting final doublet. In order to fit into the detector at the reduced $L^\star$ of 70 cm, the maximum outer radius of the new doublet cryostat is about 20 cm. To provide sufficient beam stay-clear, the inner radius is chosen as 2.54 cm. These dimensions closely resemble those of the superconducting quadrupoles fabricated for the LHC [8] and proposed for the TESLA final focus [9], which have an effective pole-tip field of 6 T. To achieve such a high pole-tip field, and to make use of LHC technology, the cryogenics system must be upgraded to 1.8-K operation. For comparison, the present SLC triplet, which operates at a temperature of 4 K, has an effective pole-tip field of only 2.2 T at a similar radius. The quadrupole design for TESLA [9] would meet all the SLC–2000 requirements.

parameter	present	FF	FF+DR+BC
$\gamma\epsilon_x$ (m)	5.6×10^{-5}	5.6×10^{-5}	4.0×10^{-5}
$\gamma\epsilon_y$ (m)	1.0×10^{-5}	1.1×10^{-5}	1.1×10^{-5}
$\theta_x^\star$	300 μrad	550 μrad	550 μrad
$\theta_y^\star$	200 μrad	500 μrad	500 μrad
$\beta_x^\star$	7 mm	2.09 mm	1.47 mm
$\beta_y^\star$	2.75 mm	0.5 mm	0.5 mm
δ_{rms}	0.10%	0.12%	0.2 %
σ_z	1 mm	0.8 mm	0.5 mm
N	3.5×10^{10}	3.5×10^{10}	3.5×10^{10}
$\sigma_x^\star$	2.1 μm	1.15 μm	810 nm
$\sigma_y^\star$	600 nm	250 nm	250 nm
L_0	100 Zs/hr	450 Zs/hr	640 Zs/hr
L	150 Zs/hr	524 Zs/hr	1073 Zs/hr
θ_x	0.59 mrad	1.00 mrad	1.29 mrad
θ_y	456 μrad	524 μrad	661 μrad
$< \frac{dE}{E} >$	0.039%	0.18%	0.61%
σ_E	52 MeV	166 MeV	482 MeV

Table 1: Estimated IP beam parameters and predicted peak luminosity for the present final focus, for only the final-focus upgrade, and for the complete SLC-2000 upgrade involving final focus, damping ring and bunch compressor. The symbol L_0 (L) denotes the luminosity without (with) pinch and hourglass effect. The last four parameters refer to the spent beam and were obtained using the code GUINEA-PIG [10].

A reduced $L^\star$ alone already alleviates all three effects limiting the IP spot size: It allows higher IP beam divergence, providing a larger acceptance, and thus facilitates a squeeze of $\beta_x^\star$, $\beta_y^\star$. Next, it reduces the chromaticity of the system, thus reducing the effect of synchrotron radiation on the vertical spot. The beta function at the exit of the last quadrupole is about $\beta_{Q1} \approx L^{\star 2}/\beta_y^\star$. If the quadrupole strength is changed in proportion to the divergence, *i.e.*, $K_{Q1} \sim \theta_y^\star$, the chromaticity $\xi \approx \int \beta_y(s) K_{Q1} ds$ scales as $\xi \sim L^{\star 2}/\beta_y^{\star 3/2}$. Hence, a reduction of $L^\star$ roughly implies a reduction of $\beta_y^\star$ by about the same factor. In addition, a reduced $L^\star$ leads to reduced nonlinear aberrations since the strength of the sextupoles, which generate the aberrations, scales in proportion to the chromaticity.

We have also studied a more ambitious option for SLC–2000, namely to substitute the present final focus by an FFTB-like system with noninterleaved sextupoles. The performance of such a system would be superb. However, it is thought to be more (too) expensive, and we do not further discuss it here.

IP beam parameters for the present and the upgraded final-focus systems have been summarized in Table 1. The table shows that the luminosity improves by about a factor of 3.5, when only the final focus is upgraded, and that it further increases, by a total factor of 7, if damping rings and bunch compressors are also modified. It should be emphasized that the actual average luminosity delivered in the 1994/95 SLC run was about 60 Zs per hour, and thus short by a factor of 2–3 compared with the ideal estimate of Table 1. The origin of this discrepancy is not fully understood. Regardless, since the aberrations and dilutions will be demagnified by the new doublet, the ratio of expected and actual luminosity is believed to stay the same for the upgrade, so that we expect exactly the predicted factors of 3.5 or 7 improvement in luminosity.

Table 1 also shows average energy loss and energy spread of the spent beam, which both increase by a factor 10–20 to values of the order of one percent for the upgrade. The number of beamstrahlung photons and the average photon energy are increased by a similar factor. The parameters for disruption and beamstrahlung are very close to, if not larger than, those expected for the Next Linear Collider (NLC).

Ref. [11] describes the optics of the upgraded SLC final-focus system. The peak of the vertical beta function in the final doublet is reduced by about a factor of 5 from its present value, while the maximum of the horizontal beta function is about a factor 3 larger. The dispersion function is the same as in the current system. The total momentum bandwidth of the final-focus upgrade is larger than $\pm 0.3\%$ (defined by a doubling of the beta function), which is sufficient for an expected beam-energy spread of about 0.2%. The effects of synchrotron radiation and nonlinearities are still small for these beta functions, and there is, hence, a potential for further decreasing the IP spot size, until the hourglass effect, the physical aperture in the final doublet, or the beam stay-clear for the spent beam will finally set a limit. Another fundamental limit on the spot size is due to the Oide effect (synchrotron radiation in the final doublet) which, for emittances of $\gamma\epsilon_x \approx 4 \times 10^{-5}$ m and $\gamma\epsilon_y \approx 1 \times 10^{-5}$ m, imposes a minimum horizontal and vertical spot sizes of 700 nm and about 100 nm, respectively. Thus, this limit will not be important for SLC-2000.

The 10-σ beam envelopes of the incoming beam in the final doublet are comparable to, or better than, the present situation, and the beam stay-clear in the doublet is more than sufficient. The stay-clear of the spent beam in the high-dispersion points of the CCS is of some concern, because the energy loss and energy spread are largely increased due to enhanced beamstrahlung [12].

For SLC–2000 the background from synchrotron radiation in the final doublet looks considerably improved, thanks to the shorter $L^\star$ [12]. As regards synchrotron-radiation generated upstream of the final doublet, there is no significant difference between SLC–2000 and the present design [11]. Furthermore, masks can be installed to intercept most of this radiation.

Damping Rings, Bunch Compressor, Linac

In addition to the final focus upgrade, the SLC–2000 scenario requires a smaller horizontal emittance. This is produced by modifying the present damping rings to use combined function bending magnets as described in [13, 14]. Here, a single 70 cm combined function magnet replaces two 30 cm bending magnets and a defocusing quadrupole located between the bending magnets. This decreases the horizontal dispersion in the magnet and increases the horizontal damping partition to 1.7 with a net effect of decreasing the horizontal emittance by a factor of three to $\gamma\epsilon_x = 0.9 \times 10^{-5}$ m.

To further improve the collider performance, we also plan to modify the bunch compressors which immediately follow the damping rings. Presently the bunches are compressed in transport lines which are corrected chromatically through second order. Unfortunately, these have proven difficult to tune and operate and are a possible source of beam halo which could cause backgrounds in the detector. In the upgrade, we will add a short magnetic chicane after injection into the SLAC linac. The bunch compression is then performed using the chicane and the old compressor beam lines simply transport the beams from the rings to the linac.

Finally, the upgrade requires shorter bunch lengths at the IP. These are obtained by decreasing the bunch lengths in the linac from roughly 1.1 mm to 0.9 mm and inducing a correlated energy deviation along the bunches which causes them to be further compressed in the arcs that transport the beams from the linac to the IP. To achieve sufficient compression, the energy spread must be increased from 0.1% to 0.2∼0.3%.

Conclusion

The SLC–2000 upgrade encompasses a new final lens, a smaller horizontal emittance, produced by a modified damping ring, and shorter bunches at the IP. Based on the performance during good months of the 1994/95 run, the upgrade should produce 3 million Zs in 4 years. Of course, the upgrade scenario presented is still preliminary and a number of additional calculations and experiments are needed before the design can be completed with full confidence. Finally, the upgrade is expected to cost roughly 20 M$.

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