1 JLC-X/NLC Overview

1.1 Introduction

The JLC-X/NLC is a linear collider designed to provide luminosity at center-of-mass (c.m.) energies between 90 GeV and 1.3 TeV. It is based on normal conducting X-band rf technology. This technology was chosen for four reasons. First, at the higher rf frequency, the X-band technology is a reasonable extrapolation from the well understood S-band technology and it permits much higher accelerator gradients. Although the gradients achieved so far have not proved to be as high as initially thought, they are still much higher than possible at lower rf frequencies. Second, although the higher rf frequency demands tighter tolerances than S-band or lower frequencies, these tolerances have either been achieved in test facilities or are a small extrapolation (a factor of 2-3) from what has been attained. Third, the normal conducting design allows the linear collider subsystem designs to be based on other operating accelerators or accelerator subsystems. This is very important because, while the rf systems can be demonstrated in relatively inexpensive test facilities, it would be difficult and expensive to verify the other subsystems which are essential for the luminosity performance of the collider. Finally, all technologies which have presently been considered for reaching the multi-TeV region will have challenges similar to those that have been addressed in the X-band design but more difficult. Thus, the normal-conducting design provides an essential link to still higher collision energies.

The JLC and NLC have been presented in detail in the 1997 JLC Design Study (JDS) [?] and the 1996 Zeroth-Order Design Report (ZDR) [?]. During the last five years, the two designs have converged on a common parameter set while the linear collider R&D programs have led to substantial improvements over the original proposals. In addition, over the last five years, the physics program for a linear collider has evolved significantly, and as a consequence, the JLC-X/NLC has been modified to provide greater flexibility and higher luminosity. Further details on the design can be found in the 2000 International Study Group Report [?] and the 2001 Report on the Next Linear Collider [?].

The X-band linear collider is based on extensive experience from the first linear collider, the Stanford Linear Collider (SLC), as well as other modern accelerators and numerous test facilities including ASSET, the Final Focus Test Beam (FFTB) and the NLC Test Accelerator (NLCTA) at SLAC, and the Accelerator Test Facility (ATF) at KEK. In particular, the polarized electron source and the positron production system are modest extensions of the SLC sources. The damping rings are similar to third-generation synchrotron light sources and are required to produce an equilibrium emittance that is only a factor of two below what has been achieved at the Advanced Light Source (ALS) in Berkeley or the ATF at KEK. The bunch compressor is based on experience from the SLC bunch compressor and is similar to, although not as difficult, as the bunch compressors for the new SASE-based short wavelength FEL drivers. Finally, a prototype X-band rf system has been operated successfully at the NLCTA since 1997. In principle, this system could be used today to build a 500-GeV c.m. collider, but there is active R&D on a next generation of components that are more efficient and less expensive to build and operate.

To preserve the small beam emittance during acceleration, the X-band structures must be designed to minimize wakefields, and both the structures and the focusing quadrupoles must be aligned to very tight tolerances. Structures fabricated in Japan and the United States already meet construction tolerances tighter than those required for JLC-X/NLC.
The wakefield properties of these prototype structures have been measured precisely in the ASSET test facility and agree well with the calculations. The required alignment accuracy has also been demonstrated in ASSET. Beam-based alignment techniques developed for the SLC and FFTB quadrupoles have achieved close to the necessary accuracy, and extensive simulations indicate that these techniques are capable of preserving the emittance through a 14-km linac using diagnostics and correction hardware which needs to be only a factor of 2-3 better than that used at the FFTB. The FFTB also demonstrated the validity of the final-focus optics and achieved a demagnification of the beam size greater than required for JLC-X/NLC. All of these results have led to improvements in the design and increased confidence in its capabilities.

The JLC-X/NLC will be described in the following sections. It should be noted that although the JLC and NLC have the same rf system designs and the same beam parameters, small differences still exist between the two designs. The JLC would likely operate at a repetition rate that is a multiple of the 50 Hz line frequency while the NLC would operate at 120 Hz—this leads to different luminosities for the same beam parameters and requires slightly different damping rings. Finally, many of the detailed optical designs differ, partly because the NLC designs have continued to be refined while many of the JLC designs have not been revisited since the 1997 JDS. To address this problem, this chapter will present only the optics of the current NLC design but will note the differences where they exist. Finally, the optical decks contain detailed information on the placement of the diagnostic and control equipment which is essential for operating the collider, but these systems will not be discussed because of space limitations.

1.2 Parameters and Layout

The JLC-X/NLC collider parameters and layout have evolved over the last five years. These changes have been motivated by a desire to provide additional physics opportunities and to reduce the capital costs of the facility. The facility is designed for optimal performance at a c.m. energy of 1 TeV, but with flexibility to begin operation at 500 GeV and be upgraded to match the needs of physics as they evolve. Key areas and systems are designed for energies above 1 TeV. In particular, by reducing the beam current, the presently envisioned linac that would deliver beam for 1 TeV collisions, would still be able to deliver substantial luminosity at a c.m. energy of 1.3 TeV.

The collider configuration is shown schematically in Figure 1. The 1 TeV collider is roughly 30 km in length. The main linac rf systems are capable of generating 250 GeV beams (500 GeV c.m. collisions) in one half of the two 14-km long linac tunnels that are part of the initial configuration. The upgrade to 1 TeV c.m. energy can be achieved by completing the main linacs with replicas of the rf components used in the initial construction, or, more likely, with improved versions of those components. Bypass lines along the main linac allow beams of various energies to be transported to the experiments, fully covering the energy range from 90 GeV to 1.3 TeV. The beam sources and damping rings that make up the injectors for the main linacs are designed to meet specifications for 1.5 TeV collisions.

To accommodate the physics demands for energy flexibility, the design includes two interaction regions. One is optimized for high energy, 250 GeV to 1.5 TeV, and is configured so that it is ultimately upgradeable to multi-TeV. The other is designed for precision measurements at lower energy, 90 to 500 GeV, although it could be upgraded to operate at ∼1 TeV as well. The final focus can actually accommodate beams of up to 2.5 TeV in a length of about
800 meters. To capitalize on the multi-TeV potential of the new design, it was also necessary to eliminate other bending between the linac and the high energy IP. In the NLC design, a 20 mrad crossing angle at the IP is used to avoid parasitic interactions of one bunch with the later bunches in the opposing train and to ease the extraction line design. The linacs are not collinear but are oriented with a shallow 20 mrad angle between them to produce the desired crossing angle at the high-energy IR without additional bending. The beams to the second IR are bent by about 25 mrad, which is acceptable for energies up to \( \sim 1 \) TeV. The low-energy IR has a larger 30 mrad crossing angle for compatibility with a possible \( \gamma/\gamma \) option. Finally, in the JLC design, the primary IP has a crossing angle of 7 or 8 mrad and the non-collinear linac layout has not been planned. However, the crossing angle of the second IP is 30 mrad as in the NLC design.

The primary \( e^+ / e^- \) parameters for the JLC-X/NLC are listed in Table 1. The beams consist of bunch trains with 192 bunches separated by 1.4 ns. The repetition rate would be 150 Hz for Stage I and 100 Hz at Stage II in Japan while, in the US, the repetition rate would remain 120 Hz at both stages. Although not listed, the collider is also designed to operate with 96 bunches of \( 1.5 \times 10^{10} \) particles and a 2.8 ns bunch spacing—this later option might be preferred for \( \gamma/\gamma \) collisions but also provides higher \( e^+ / e^- \) luminosity while increasing the beamstrahlung and emittance dilution. During the initial stage, the center-of-mass energy is assumed to be 500 GeV with a luminosity of \( 2.5 \times 10^{34} \) cm\(^{-2}\)s\(^{-1}\) (\( 2.0 \times 10^{34} \) cm\(^{-2}\)s\(^{-1}\)) at the repetition rate of 150 Hz (120 Hz), although the collider might be started with a lower initial energy depending on the physics interest. The second stage assumes the installation of the full rf system to reach a center-of-mass energy of 1 TeV with a luminosity of \( 2.5 \times 10^{34} \) cm\(^{-2}\)s\(^{-1}\) (\( 3.0 \times 10^{34} \) cm\(^{-2}\)s\(^{-1}\)) at a repetition rate of 100 Hz (120 Hz). In addition, sets of nominal parameters for operation of the low-energy IR are listed in Table 2.

It should be noted that the JLC-X/NLC traveling wave accelerator structures are tested to the full unloaded gradient of 65 MV/m; this differs from the testing of the standing-wave superconducting structures which are only tested to the maximum \textit{loaded} gradient of 23 to 35 MV/m. Because the cavities are tested to the full unloaded gradient, the JLC-X/NLC collider could operate at an energy roughly 25% higher than nominal with 30% of the nominal luminosity by reducing the average beam current. Thus, without modification to the rf system, the Stage II JLC (NLC) could deliver a luminosity of \( 7 \times 10^{33} \) cm\(^{-2}\)s\(^{-1}\) (\( 9 \times 10^{33} \) cm\(^{-2}\)s\(^{-1}\)) at a c.m. energy of 1.25 TeV. A plot of the luminosity versus energy for the Stage II NLC is plotted in Figure 2; using the bypass lines and the two interaction regions,
the collider is designed to fully cover the energy region between 90 GeV and 1.3 TeV.

The beam parameters listed in Table 1 and Table 2 have been chosen to balance total luminosity against the fraction of luminosity close to the center-of-mass energy and the bremsstrahlung-related backgrounds. The luminosity spectrum can be described by two parameters, the number of beamstrahlung photons radiated per incident electron $n_\gamma$ and the average energy lost to the beamstrahlung $\delta_B$. These parameters can be traded against each other to optimize the total luminosity and the luminosity spectrum for any given experiment. The parameters presented in Table 1 and Table 2 are only an illustrative set.

Detailed emittance and beam-jitter budgets are shown in Table 3; these are discussed in Section 1.6 along with the beam-based alignment and jitter-stabilization techniques. The design luminosities, listed in Table 1, include 5% luminosity degradation beyond the explicit emittance dilutions to account for beam jitter and beam tuning. It is important to emphasize that the JLC-X/NLC has been designed with generous margins throughout to facilitate attaining the design luminosity rapidly.

It should also be noted that the ultimate luminosity of the collider is roughly a factor of two higher than the design. This higher luminosity might be attained if the beam-based alignment techniques can be pushed to even higher precision and the beam-beam limitations due to the high disruption parameter that impact the TESLA design can be overcome; the disruption parameter for these high luminosity parameters is roughly 20 which is still less than the TESLA values of 25-28. The ultimate luminosity, referred to as the ‘intrinsic luminosity,’ is determined by physical limitations such as the finite damping time of the damping rings and synchrotron-radiation emission in the bunch compressors and final focus. These intrinsic

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**Table 1: Parameters for Stage I and Stage II of the JLC-X/NLC.**

<table>
<thead>
<tr>
<th></th>
<th>Stage I</th>
<th>Stage II</th>
</tr>
</thead>
<tbody>
<tr>
<td>c.m. Energy [GeV]</td>
<td>500</td>
<td>1000</td>
</tr>
<tr>
<td>Site</td>
<td>Japan</td>
<td>US</td>
</tr>
<tr>
<td>Luminosity [10^{33}] incl. dilutions</td>
<td>25 20</td>
<td>25 30</td>
</tr>
<tr>
<td>Repetition Rate [Hz]</td>
<td>150</td>
<td>120</td>
</tr>
<tr>
<td>Luminosity within 1% of E_{c.m.} (%)</td>
<td>64 58</td>
<td></td>
</tr>
<tr>
<td>Bunch Charge [10^{10}]</td>
<td>0.75</td>
<td>0.75</td>
</tr>
<tr>
<td>Bunches/RF Pulse</td>
<td>192</td>
<td>192</td>
</tr>
<tr>
<td>Bunch Separation [ns]</td>
<td>1.4</td>
<td>1.4</td>
</tr>
<tr>
<td>Lum. Dilution for tuning and jitter [%]</td>
<td>5 5</td>
<td></td>
</tr>
<tr>
<td>Injected $\gamma\epsilon_x / \gamma\epsilon_y$ [10^{-8} m-rad]</td>
<td>300 / 2</td>
<td>300 / 2</td>
</tr>
<tr>
<td>$\gamma\epsilon_x / \gamma\epsilon_y$ at IP [10^{-8} m-rad]</td>
<td>360 / 4</td>
<td>360 / 4</td>
</tr>
<tr>
<td>$\beta_x / \beta_y$ at IP [mm]</td>
<td>8 / 0.11</td>
<td>13 / 0.11</td>
</tr>
<tr>
<td>$\sigma_x / \sigma_y$ at IP [nm]</td>
<td>243 / 3.0</td>
<td>219 / 2.1</td>
</tr>
<tr>
<td>$\sigma_z$ at IP [µm]</td>
<td>110</td>
<td>110</td>
</tr>
<tr>
<td>Upsilon average</td>
<td>0.13</td>
<td>0.28</td>
</tr>
<tr>
<td>Pinch Enhancement</td>
<td>1.49</td>
<td>1.42</td>
</tr>
<tr>
<td>Beamstrahlung $\delta_B$ [%]</td>
<td>4.6</td>
<td>7.5</td>
</tr>
<tr>
<td>Photons per $e^+/e^-$</td>
<td>1.3</td>
<td>1.3</td>
</tr>
<tr>
<td>Loaded Gradient [MV/m]</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>Linac Length [km]</td>
<td>6.9</td>
<td>13.8</td>
</tr>
</tbody>
</table>
Table 2: Low energy operation parameters for the NLC.

<table>
<thead>
<tr>
<th>c.m. Energy [GeV]</th>
<th>92</th>
<th>250</th>
<th>350</th>
</tr>
</thead>
<tbody>
<tr>
<td>Luminosity [$10^{33}$]</td>
<td>3.5</td>
<td>9.4</td>
<td>13.2</td>
</tr>
<tr>
<td>Luminosity within 1% of E$_{c.m.}$ (%)</td>
<td>92</td>
<td>75</td>
<td>65</td>
</tr>
<tr>
<td>Repetition Rate [Hz]</td>
<td>120</td>
<td>120</td>
<td>120</td>
</tr>
<tr>
<td>Bunch Charge [$10^{10}$]</td>
<td>0.75</td>
<td>0.75</td>
<td>0.75</td>
</tr>
<tr>
<td>$\sigma_x / \sigma_y$ at IP [nm]</td>
<td>630 / 6.2</td>
<td>380 / 3.8</td>
<td>320 / 3.2</td>
</tr>
<tr>
<td>Beamstrahlung $\delta_B$ [%]</td>
<td>0.18</td>
<td>1.1</td>
<td>2</td>
</tr>
<tr>
<td>Photons per e$^+$/e$^-$</td>
<td>0.49</td>
<td>0.79</td>
<td>0.92</td>
</tr>
<tr>
<td>Polarization loss [%]</td>
<td>0.08</td>
<td>0.21</td>
<td>0.34</td>
</tr>
</tbody>
</table>

Figure 2: Energy versus luminosity for Stage II NLC rf system.

beam emittances and luminosity are listed in Table 4 for comparison with the design values.

Next, possible parameters for operation as a $\gamma/\gamma$ collider are listed in Table 5. These parameters are based on the JLC-X/NLC beam with a 2.8 ns spacing and 96 bunches as noted earlier. The $\gamma/\gamma$ interaction region would be located in the ‘Low Energy IR’ (LEIR) which has a large crossing angle of 30 mrad to facilitate extracting the disrupted e$^-$ beams. To take full advantage of the photon interaction, the horizontal and vertical beta functions have been reduced at the IP which has been verified with tracking simulations.

Finally, as described, the JLC-X/NLC is designed to operate with center-of-mass energies up to $\sim$1.5 TeV. The next logical step for electron-positron facilities would then be a linear collider that operates in the 3-TeV to 5-TeV center-of-mass range with a luminosity of $10^{35}$ or more, using a design such as CLIC. The history of accelerator laboratories makes one point clear: the investment in the infrastructure of the accelerators, including the beamline housings, is significant and therefore the infrastructure should be used and reused for as long as possible. This has led to the use of existing synchrotrons as injectors for new synchrotrons, and in some cases to the decommissioning of existing accelerators so that the tunnels or components can be recycled for use in new accelerators. It is this history that has shaped the decision to make the design as compatible as possible with future energy upgrades.
Table 3: NLC Design Emittance and Jitter budgets for 500 GeV c.m. parameters.

<table>
<thead>
<tr>
<th>Region</th>
<th>$\gamma\epsilon_x [\mu\text{m-rad}]$</th>
<th>$\gamma\epsilon_y [\mu\text{m-rad}]$</th>
<th>X jitter $[\sigma_x]$</th>
<th>Y jitter $[\sigma_y]$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Damping Ring</td>
<td>3.0</td>
<td>0.020</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>Injector (8 GeV)</td>
<td>0.2</td>
<td>0.002</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>Main Linac</td>
<td>0.1</td>
<td>0.010</td>
<td>0.1</td>
<td>0.3</td>
</tr>
<tr>
<td>Beam Delivery</td>
<td>0.3</td>
<td>0.008</td>
<td>0.1</td>
<td>0.3</td>
</tr>
<tr>
<td>Final Doublet</td>
<td>0.1</td>
<td>0.25</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total at IP</td>
<td>3.6</td>
<td>0.04</td>
<td>0.22</td>
<td>0.51</td>
</tr>
</tbody>
</table>

Table 4: Intrinsic versus design emittances and luminosity for JLC-X/NLC at 1 TeV.

<table>
<thead>
<tr>
<th>Intrinsic Design</th>
<th>Intrinsic $\gamma\epsilon_x / \gamma\epsilon_y [10^{-8} \text{ m-rad}]$</th>
<th>Design $\gamma\epsilon_x / \gamma\epsilon_y [10^{-8} \text{ m-rad}]$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Damping rings</td>
<td>300 / 1</td>
<td>300 / 2</td>
</tr>
<tr>
<td>Main Linac</td>
<td>315 / 1</td>
<td>330 / 3</td>
</tr>
<tr>
<td>Beam delivery</td>
<td>330 / 1</td>
<td>360 / 4</td>
</tr>
<tr>
<td>Luminosity [10^{33}]</td>
<td>63</td>
<td>30</td>
</tr>
</tbody>
</table>

While it is too early to determine the technologies that will be used at a multi-TeV linear collider, a general review of the issues discussed above reveals many of the requirements of such a facility. The JLC-X/NLC configuration has been developed with these requirements in mind. For example, the multi-TeV linear collider will require a site with low levels of ground motion, a crossing angle of at least 20 mrad, beam delivery systems with weak bend magnets, and in all probability a main-linac tunnel that can accommodate a second beamline for the “drive beam.” All of these features are included in the design. In many cases, the requirements are identical to those of a future facility. In other cases, configuring the design to accommodate a future linear collider did not cause additional financial or technical penalties. This permits the injectors, beam delivery systems, and main-linac housings to be used in a multi-TeV collider, although the main-linac accelerator structures and rf power sources would need to be replaced and some upgrades of the damping rings, bunch compressors, and final-focus beamlines would be required.

Table 5: Parameters for $\gamma/\gamma$ collisions at the JLC-X/NLC.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam Energy</td>
<td>250 GeV</td>
</tr>
<tr>
<td>Luminosity incl. dilutions</td>
<td>$3.2 \times 10^{33}$</td>
</tr>
<tr>
<td>Repetition Rate</td>
<td>120 Hz</td>
</tr>
<tr>
<td>Bunches/RF Pulse x Bunch Separation</td>
<td>$96 \times 2.8$ ns</td>
</tr>
<tr>
<td>Bunch Charge</td>
<td>$1.5 \times 10^{10}$</td>
</tr>
<tr>
<td>$\gamma\epsilon_x / \gamma\epsilon_y$ at IP</td>
<td>$360 / 7.1 \times 10^{-8}$ m-rad</td>
</tr>
<tr>
<td>$\beta_x / \beta_y$ at IP</td>
<td>$4 / 0.065$ mm</td>
</tr>
<tr>
<td>$\sigma_x / \sigma_y$ at IP</td>
<td>$172 / 3.1$ nm</td>
</tr>
<tr>
<td>$\sigma_z$ at IP</td>
<td>$156$ $\mu$m</td>
</tr>
<tr>
<td>Conversion point $\rightarrow$ IP</td>
<td>2 mm</td>
</tr>
</tbody>
</table>
Figure 3: Schematic of the JLC-X/NLC linac layout; each sector contains 20 rf units in a length of 520 meters.

1.3 Main Linacs and RF Systems

The main JLC-X/NLC linac tunnels are each 13.8 km long and contain the necessary rf system as well as three diagnostic regions and three extraction sections that feed the bypass line (see Figure 3). The tunnels are designed to be long enough to hold the full complement of accelerating structures to reach 1 TeV in the center-of-mass at the design luminosity, although, in the first stage of the project, only the first half of the tunnels would be filled with structures. The installation would start from the low-energy end of the tunnel to allow maximum flexibility in choosing the appropriate energy upgrade steps to match physics interests and funding profiles.

The JLC-X/NLC linac would contain 254 rf units at Stage I (500 GeV c.m.). Each rf unit contains one solid-state induction modulator driving eight 75-MW 1.6-μs klystrons arranged in pairs. Each of the four klystron pairs powers a dual-mode SLED-II pulse compression system which feeds an rf girder with six 0.9-m accelerator structures. The linac beam-line enclosure would contain the accelerator structures while the modulators and klystrons will be installed in a separate utility enclosure. This simplifies access and maintenance which is essential to ensure the desired reliability and collider availability. The SLED-II lines could be placed in either the main linac tunnel or in the utility tunnel—both options have advantages: the main linac tunnel has better temperature control however the utility tunnel allows easy access for upgrades and maintenance of the SLED-II systems.

Because of the transverse wakefields of the accelerator structures, it is undesirable to transport the beam through a large number of unpowered structures. In order to maximize luminosity at lower energy, a non-accelerating ‘bypass’ line is provided to bring the low-energy beams to the end of the linac. The bypass line will share the main-linac tunnel, and will be installed at the same elevation as the main beamline. The design includes three transfer points where the beam can be diverted into the bypass line at 50, 150 and 250 GeV, and a return at the end of the linac to bring the beam back into the collimation section. These are sufficient to support a continuous variation of beam energy over the whole range.

The linac transport optics were chosen to minimize the dispersive and wakefield-related beam emittance growth. In the NLC design, quadrupole magnets, in a FODO configuration, are located after every (one, two, or three) rf girders at the (beginning, middle, or end) of each linac. The quadrupoles in the rf regions will have 12.7-mm-diameter apertures and vary in length from 0.32 m to 0.96 m. The rf girders and quadrupoles will be supported on movers that will be remotely adjusted during beam operation based on signals from the structure manifolds and beam position monitors (BPMs) in the quadrupole magnets.
As will be discussed in Section 1.6, extensive effort has been made to ensure that the beam emittance can be preserved along the linac. The signals from the structure manifolds will be used to directly align the accelerator structures to the beam; as discussed in Section 1.3.5 measurements using the manifolds in prototype structures have already shown the required precision. The BPMs located at the quadrupole magnets will be used to align the quadrupoles. Although the required quadrupole alignment is roughly 25 times smaller than that achieved in the SLC and about 3 times smaller than in FFTB, the BPMs are specified to have resolutions of 0.3 $\mu$m which has been demonstrated in prototype rf BPMs and is 50 times smaller than that in the SLC linac and 3 times smaller than that in the FFTB. Because the expected alignment precision scales with the diagnostic resolution, using the quad-shunting beam-based alignment technique utilized at the FFTB with the improved BPM resolution should attain the desired alignment.

Simulations indicate that the desired alignment precision will be attained. However, to provide additional safety margin, provision has been made to utilize two other beam-based alignment techniques pioneered at the SLC: dispersion-free steering and emittance correction bumps. These techniques are relatively sensitive to details of the energy profile along the linac and the beam optics. To monitor the beam energy, energy spread, and emittance, there will be four diagnostic regions along the length of the linac where these parameters can be measured parasitically. In addition to being needed for the beam-based alignment and emittance correction techniques, continuous, non-invasive monitoring was found to be essential during the SLC operation because it facilitates rapid diagnosis of faults and makes it possible to correlate disparate effects.

In the following sections, the rf system will be described in greater detail and then, in Section 1.6, the emittance preservation and luminosity performance issues will be discussed.

### 1.3.1 RF Systems

Outstanding progress has been made in applying and extending the science and engineering of microwave power and acceleration systems from S-band, the enabling technology for the SLAC linac, to X-band, which can provide the significant performance improvements and cost reductions needed for a high-energy linear collider. New modulators, klystrons, microwave power distribution systems, and accelerator structures that can meet the challenging demands of a linear collider are in the final stages of development. The R&D on these components has been pursued as a joint effort between SLAC and KEK as part of the International Study Group (ISG) developing designs for an X-band linear collider.

The 11.424-GHz rf systems are similar in character to those in the SLAC linac. Electrical energy is transformed in several stages: the induction modulators convert AC power to high-voltage pulsed DC; the klystrons transform the pulsed DC to high-power rf; the SLED-II pulse compression system combines the power from two klystrons with pulse lengths of 1.6- $\mu$s and, by storing the power, compresses it into pulse lengths of 400 ns and sends it to sets of six accelerator structures; and finally, the six structures on each rf girder accelerate the beam. The baseline JLC-X/NLC rf system is illustrated in Figure 4.

Because the AC power required to drive the accelerator is high, especially at a c.m. energy of 1 TeV, much effort has been focused on maximizing the efficiency of the conversion and transfer of energy at every stage of the rf system. Both the JLC and NLC design teams have been investigating alternate pulse compression systems with higher efficiency than the SLED-II rf system. In particular, the Delay Line Distribution System (DLDS) will be pursued as a
Figure 4: Schematic of a JLC-X/NLC linac rf unit (one of 254 per linac); the SLED-II delay lines could be located in either the linac or utility tunnels.

possible high efficiency option to the SLED-II pulse compression system. However, because of the simpler topology of the SLED-II system, it will be faster to demonstrate a SLED-II pulse compression system at the full JLC-X/NLC power specifications than it will be to test a full DLDS system. In addition, the JLC-X/NLC SLED-II pulse compression system is based on the SLED-II systems that have operated at the NLCTA for over five years, providing confidence in the design. We believe that, by first pursuing the SLED-II-based baseline rf design and then moving toward a higher efficiency system, we will be able to demonstrate the feasibility of the X-band rf system while still working to improve the system efficiency.

The parameters of the JLC-X/NLC major rf subsystems (klystrons, modulators, rf distribution, and accelerator structures) are listed in Table 6. The unloaded gradient ($G_U$) of 65 MV/m is close to optimal in the tradeoff between energy-related costs (e.g., modulators and klystrons), which scale roughly as $G_U$, and length-related costs (e.g., structures and beam-line tunnel), which scale roughly as $1/G_U$. However, the overall linac cost has a fairly weak dependence on unloaded gradient in the range of interest for the JLC-X/NLC (50 to 100 MV/m). The beam parameters were chosen as a tradeoff between increasing rf-to-beam efficiency and easing tolerances related to both short-range and long-range transverse wakefields effects.

A brief description of each major rf subsystem follows including design choices and R&D progress.

1.3.2 Modulators

The 75-MW PPM klystrons require pulses of roughly 500-kV and 260-A. Initially, conventional line-type modulators like those used in the SLAC linac were considered for this purpose. These modulators contain pulse-forming networks that are slowly charged and then rapidly
Table 6: JLC and NLC rf system parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>JLC</th>
<th>NLC</th>
</tr>
</thead>
<tbody>
<tr>
<td>RF Units per Linac (500 GeV c.m.)</td>
<td>254</td>
<td></td>
</tr>
<tr>
<td>AC Power for Modulators per Linac</td>
<td>65.9 MW</td>
<td></td>
</tr>
<tr>
<td>AC Power for Other RF + Cooling RF System per Linac</td>
<td>9.6 MW</td>
<td></td>
</tr>
<tr>
<td>Total AC Power Related to RF per Linac</td>
<td>75.5 MW</td>
<td></td>
</tr>
<tr>
<td>Beam Power per Linac</td>
<td>6.9 MW</td>
<td></td>
</tr>
<tr>
<td>AC-to-Beam Power Efficiency</td>
<td>8.8%</td>
<td></td>
</tr>
<tr>
<td>Modulator Type 1:1 Linear Induction</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Modulator Efficiency</td>
<td>80%</td>
<td>80%</td>
</tr>
<tr>
<td>Number of RF Modulators per RF Unit</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Klystron Type</td>
<td>PPM</td>
<td></td>
</tr>
<tr>
<td>Beam voltage/current</td>
<td>490 MV / 260 A</td>
<td></td>
</tr>
<tr>
<td>Output Power</td>
<td>75 MW</td>
<td></td>
</tr>
<tr>
<td>Klystron Pulse Length</td>
<td>1590 ns</td>
<td></td>
</tr>
<tr>
<td>Klystron Efficiency</td>
<td>55%</td>
<td></td>
</tr>
<tr>
<td>Number of Klystrons per RF Unit</td>
<td>8</td>
<td></td>
</tr>
<tr>
<td>Type</td>
<td>SLED-II</td>
<td></td>
</tr>
<tr>
<td>Modes</td>
<td>TE01 &amp; TE02</td>
<td></td>
</tr>
<tr>
<td>Power Gain = Number of Feeds per RF Unit</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>Switching Time</td>
<td>8 ns</td>
<td></td>
</tr>
<tr>
<td>RF Pulse Length per Feed</td>
<td>396 ns</td>
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</tr>
<tr>
<td>Compression Efficiency</td>
<td>75%</td>
<td></td>
</tr>
<tr>
<td>RF Phase Advance per Cell</td>
<td>150 degrees</td>
<td></td>
</tr>
<tr>
<td>Structure Input Group Velocity</td>
<td>5.1% c</td>
<td></td>
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<tr>
<td>Structure Length</td>
<td>0.90 m</td>
<td></td>
</tr>
<tr>
<td>Field Attenuation Factor (tau)</td>
<td>0.510</td>
<td></td>
</tr>
<tr>
<td>Number of Structures per RF Feed</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>Fill Time</td>
<td>120 ns</td>
<td></td>
</tr>
<tr>
<td>Average Acceleration Shunt Impedance</td>
<td>81.2 Mohm/m</td>
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<tr>
<td>Loading Shunt Impedance</td>
<td>82.4 Mohm/m</td>
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<tr>
<td>Peak RF Power into Structure</td>
<td>75.0 MW</td>
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<tr>
<td>Unloaded Accelerator Gradient ($G_u$)</td>
<td>64.8 MV/m</td>
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</tr>
<tr>
<td>Beam Loading</td>
<td>23%</td>
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<tr>
<td>Multibunch Loading</td>
<td>14.7 MV/m</td>
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</tr>
<tr>
<td>Single Bunch Loading</td>
<td>0.30 MV/m</td>
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</tr>
<tr>
<td>Loaded Accelerating Gradient</td>
<td>49.8 MV/m</td>
<td></td>
</tr>
<tr>
<td>Average RF phase</td>
<td>11.0 degrees</td>
<td></td>
</tr>
<tr>
<td>RF Overhead (3% BNS + 3% Failed + 2% FB)</td>
<td>8%</td>
<td></td>
</tr>
<tr>
<td>Length of Powered Linac</td>
<td>6.6 km</td>
<td></td>
</tr>
<tr>
<td>Length of unpowered Linac (for upgrade to 1 TeV c.m.)</td>
<td>6.6 km</td>
<td></td>
</tr>
<tr>
<td>Total Length of Diagnostic And Bypass Regions</td>
<td>0.6 km</td>
<td></td>
</tr>
<tr>
<td>Total Length of Each Linac Tunnel</td>
<td>13.8 km</td>
<td></td>
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</table>
Figure 5: Photograph of the NLC induction modulator with three of the SLAC 5045 klystrons that are used as a load.

discharged, via a thyratron, through a step-up transformer to generate the high-voltage pulse. These modulators have several drawbacks including low efficiency and the use of thyratrons, which have relatively short lifetimes (10,000-20,000 hr) and require periodic adjustments. As an alternative, the idea of a solid-state induction-type modulator was explored, based on recent advances in high-power, solid-state switches (Insulated Gate Bipolar Transistors or IGBTs). The concept is to sum many low-voltage sources (2-4 kV) inductively to yield the desired klystron voltage. This has been implemented by having each source drive a toroidal-shaped transformer made with Metglass or Finemet cores. The cores are stacked so secondary windings, which sum the output voltages, can be threaded through them. Each source is essentially a capacitor that is slowly charged and then partially discharged through an IGBT switch to generate the pulse.

The solid state NLC modulator is designed to power eight klystrons. It is constructed from 42 Metglass cores, each driven by two 6.5 kV IGBTs operating at 4 kV and 3 kA. These drive a 3-turn secondary winding for an output pulse of 500 kV, 2160 Amps that is 1.6 µs long. The modulator is roughly 2 meters high and consists of two stacks of 21 cores. A full-scale prototype based on 4.5 kV IGBTs is shown in Figure 5. The JLC modulator, referred to as the Linear Induction Modulator, is similar except that it uses a single-turn secondary to produce 500 kV and 2 kAmps to eliminate the production and installation of the secondary windings. The design has three times the number of cores although, on average, cores are smaller.

For fast pulse performance, the IGBT drivers must be operated in a regime where they are not well modelled. The drivers are designed for locomotive traction, requiring continuous high power operation at a few kV and 600-800 A. The pulsed-power requirements of the modulator are very high dI/dt, peak currents that nearly saturate the bipolar switch, high voltage lasting only for a few microseconds, and inductive connections through the drivers to capacitive loads (klystrons). After each pulse, the core has to be reset, and stored energy recovered. This must be done without producing transients on the gate of the IGBT sufficient to exceed its ratings and destroy the transistor. Several key technical challenges encountered
in bringing the designs from concept to working prototype include:

- IGBTs have a known susceptibility to neutron radiation induced from cosmic rays, or accelerators, which can cause a Single Event Upset (SEU) that latches and destroys the bipolar transistor. Shielding solves this problem in the JLC-X/NLC applications.

- Many studies have been conducted to develop circuits that will protect the IGBTs under conditions of a short circuit to the load and of core saturation. Some wiring layout changes have been made in the transistor itself to minimize unwanted transients.

- To protect the stack if one IGBT fails, a circuit was developed that assures that, on failure, the device is shorted and disconnects its drive voltage from the cell primary single turn. Therefore, the stack suffers an incremental drop in voltage due to the loss of the one cell, which could be compensated by either slightly raising the supply voltage on each cell or by turning on spare ‘hot’ IGBT cards which will be installed in each modulator. This fail-soft feature will enable longer periods of continuous operation without interruptions for maintenance.

- Two approaches are being adopted to limit the energy delivered if one of the klystrons arcs. Passive inductance from the stack to each tube, and between tubes, is used to slow the transfer of charge to the faulting tube. In addition, the entire stack is designed to sense the fault and shut off in about 400 ns, drawing most of the load’s stored charge and shunting it to ground. Klystron faults have been studied on pairs of X-Band klystrons in NLCTA at SLAC, so far with no apparent degradation.

- Recently, current and voltage distribution in the two commercial IGBT hybrid packages currently being used have been modelled on a 3D simulator. The commercial hybrid circuits consist of between 9 and 16 bonded dies, each with multiple IGBTs, on a single substrate mounted on a heat sink. The cause of observed failures in one of the layouts has been traced to the highly non-uniform distribution of high $dI/dT$ current densities as a function of chip location on the die, due to unsymmetrical placement with respect to buses, and uneven wire bonding. During the fast risetime transient currents in different bond wires and single chips vary by more than 10:1. A new symmetrical geometry has been modelled which eliminates this effect entirely. Also some simple bond wire changes with the present layout will improve distribution by a factor of 2-3. While the IGBTs now in hand are totally sufficient to support the present program, development of a more robust device for fast pulse applications is being pursued with manufacturers.

At SLAC, a full-scale prototype induction modulator has been built using 3.3 kV IGBTs and a stack of 76 ferrite cores. Testing began in October 2001 (Figure 5) and proceeded to full voltage at low power using a water load. The modulator was then tested to near full power, but less than full voltage, using three 5045 S-band klystrons operating as diodes. These klystrons are the only loads available that permit testing close to the full power. To study the modulator in extreme conditions, the voltage was further raised to deliberately arc the 5045 klystrons. During the arc testing, damage occurred to the IGBTs. This problem was solved by adding ‘snubber’ circuits to damp the high frequency reflections and upgrading the IGBTs to 4.5 kV models. This prototype modulator has now been moved to the NLCTA to power the SLED-II pulse compression system and demonstrate the JLC-X/NLC baseline
X-band rf system. Another 8-pack modulator using 6.5 kV IGBTs is under construction at the Lawrence Livermore Laboratory and should be completed in 2003. At KEK, the design for the Linear Induction Modulator, shown in Figure 6, is nearing completion and a full prototype should be operating in 2003.

1.3.3 Klystrons

The X-band power required for the JLC-X/NLC has driven the development of klystrons much further than those available commercially. The designs first considered were similar in concept to the solenoid-focused S-band klystrons used in the SLAC linac. The general design goal was to achieve the highest peak power and the longest pulses possible while minimizing the overall klystron cost. As a first step, the XL4 klystron was designed in the early 1990s and achieved its target power of 50 MW. Thirteen of these XL4s have been built. They are used as X-band rf sources for R&D at the SLAC Klystron Test Laboratory and the Next Linear Collider Test Accelerator (NLCTA). They reliably generate 1.5-\(\mu\)s, 50-MW pulses with a 43% beam-to-rf efficiency. In a test, one XL4 klystron was run at 120 Hz with 75-MW, 1.5-\(\mu\)s pulses which were produced with 48% efficiency. An XL4 has also been operated at 2.4 \(\mu\)s and 50 MW without difficulty. At KEK, two similar klystrons (XB72K-9 and XB72K-10) also operate with 1.5-\(\mu\)s pulses at 50 MW. The integrated running time of the XL4/XB72K klystrons is around 40,000 hours, during which there have been no major failures (the JLC-X/NLC lifetime goal is 20,000 hours).

With the success of these solenoid focused klystrons, attention turned to developing a permanent magnet focusing system which would consume no power. In the Periodic Permanent Magnet (PPM) design, many magnet rings with alternating polarities are interleaved with iron pole pieces to generate a periodic axial field between the gun anode and beam collector. The resulting focusing strength is about 2 kG, which is smaller than the 5-kG field in the solenoid-focused klystrons. The weaker PPM field has led to a klystron design with a higher voltage-to-current ratio, which reduces the space charge defocusing and increases the klystron efficiency; the micropervance of the 75 MW PPM klystrons is between 0.70 and 0.80 and the klystrons operate at roughly 500 kV and 250 A.

The first PPM klystron was built at SLAC in 1996 to generate 50-MW pulses, like the XL4s. It worked well, producing 1.5-\(\mu\)s, 50-MW pulses with an efficiency of 55%, close to
the predicted performance. The next klystron, referred to as the XP1, then was designed for 75 MW. After modification, the klystron delivered over 90 MW in a 0.7-µs pulse length and 79 MW at 2.8 µs with 60% efficiency. The repetition rate was limited to 1-Hz due to heating of the uncooled magnet stack. The most recent klystron at SLAC, the XP3, has been designed to operate at a 60 Hz repetition rate at 75 MW and a 3.2 µs pulse length; the 3.2 µs pulse length, which is twice the rf system requirement, was chosen to increase the energy output from each klystron and thereby reduce the required number of klystrons by a factor of two. Two of these klystrons have been built however neither reached the desired output power due to fabrication errors; a third is being constructed.

At KEK, three PPM klystrons have been designed and built by industry. The first, PPM-1, was completed in 2000 and produced 56 MW with pulse lengths of 1.5 µs and roughly 50% efficiency. The second, PPM-2, was completed in 2001 and produced 70 MW in a pulse length of 1.5 µs with a 55% efficiency before a modulator problem halted testing. This klystron was operated at 25 Hz. The most recent klystron, PPM-3, is being tested. It has operated at 68 MW with a 1.5-µs pulse length and 53% efficiency. The repetition rate is limited by the modulator to 50 Hz, however, thermal measurements show that the tube could safely operate at 100 Hz without additional cooling. With further testing it is expected that the klystron will produce the desired 75-MW power with an efficiency of about 55%.

Finally, next-generation klystrons are being designed at SLAC and KEK. At KEK, the PPM-4 is a version of the PPM-3 optimized for mass production and should be delivered in February 2003. At SLAC, the XP4 is being designed for completion in 2003. The goal of both programs is to produce a number of klystrons to be lifetime tested.

1.3.4 RF Pulse Compression

Using the klystron output power to drive the accelerator structures is complicated by the different pulse-length and peak power requirements. While long, relatively low power klystron pulses are optimal from a klystron cost perspective, shorter pulses are needed to power the structures to minimize overall cost. An rf pulse compression system is used to match these conditions.

The goal in compressing the pulse (and increasing the peak power) is to make the transition efficiently with as little waveguide as possible. The Delay Line Distribution System (DLDS), proposed at KEK, is a very efficient system. Other options include the Binary Pulse Compression system, which has comparable efficiency, and the SLED-II system, which is less efficient but requires less waveguide. All of these rf distribution systems are characterized by the ratio of the klystron to structure pulse length or the compression ratio. In the JLC-X/NLC design, a compression ratio of four is needed. The rf system is based on a dual-moded SLED-II compression system which was chosen for two reasons. First, while other pulse compression systems are more efficient, they are more complicated and, unfortunately, this will delay the demonstration of the system. Second, the NLC Test Accelerator group has a lot of operational experience with SLED-II pulse compression whose technology has been established for years. The only challenge is that the full power JLC-X/NLC version must produce 400 ns pulses of 450 MW—the SLED-II systems at the NLC Test Accelerator and the Klystron Test Laboratory have generated 240 ns pulses of 270 MW and 150 ns pulses of 480 MW. The new over-moded components that have been developed are expected to have no trouble operating at the higher field levels. Finally, the routing of the rf power is controlled with the klystron phases. An 8-ns period is allotted for each phase shift, making the total
klystron pulse length needed to accelerate the JLC-X/NLC bunch train equal to 1.59-μs.

To fully demonstrate the SLED-II system, the prototype NLC solid state modulator has been moved to the NLC Test Accelerator. Four 50-MW klystrons will be used to power a dual-moded SLED-II system as illustrated in Figure 7. With four times pulse compression, the SLED-II system will be able to produce 600-MW in a 400 ns pulse; this is 33% higher power than required in the JLC-X/NLC, giving confidence in the SLED-II design. The system could also be operated with a 2.4-μs input pulse and six times compression to deliver over 800 MW. The high power tests will be complete by mid-2003 at which point the rf power will be directed into the NLCTA enclosure to power one rf girder of accelerator structures.

To prevent significant attenuation while transmitting the power through the long waveguides, the rf power is transported in low-loss circular modes. A low-power transmission test of the three circular modes in a 55-m delay line was performed at KEK to verify the expected power attenuation per unit length of the modes. The results of the test confirm the viability of any of the TE01, TE02, or TE12 modes for a pulse compression system. At the present time, the JLC-X/NLC SLED-II delay lines use two circular modes, the TE01 and TE02.

Finally, two tunnel configurations have been considered: a Cut and Cover construction, where the klystron galleries can be much shorter than the linac tunnel, and a dual tunnel construction, where the klystrons and modulators are placed in the parallel tunnel. These layouts have an impact on the pulse compression scheme. In the SLED-II pulse compression scheme, the rf units can be configured in either a distributed or localized manner, although, if the rf units are localized, additional waveguide is needed to direct the power to the respective rf girders which will reduce the efficiency of the system.
1.3.5 Structures

The JLC-X/NLC linacs will each contain about 5 km of X-band accelerator structures to increase the beam energy from the 8 GeV at injection to 250 GeV for collisions at the IP. There are three basic requirements on the structure design: it must transfer the rf energy to the beam efficiently to keep the machine cost low; it must be optimized to reduce the short-range wakefields which depend on the average iris radius; and it must suppress the long-range transverse wakefields to prevent multibunch beam breakup.

As part of the JLC-X/NLC development, many X-band accelerator structures have been constructed ranging in length from 20 cm to 1.8 meters. Originally, the focus of the structure R&D was on controlling the long-range wakefields. The acceleration gradient was not a major concern—short structures had quickly reached gradients much higher than needed in the JLC-X/NLC design and the longer structures were not tested because there was insufficient rf power available.

The long-range wakefield suppression was challenging because the wakefields must be reduced by two orders-of-magnitude within an inter-bunch spacing of 1.4 ns. The solution is to use a combination of detuning and damping. The detuning is generated by choosing the frequencies of the lowest (and strongest) band of dipole modes so that the modes excited by an off-axis bunch do not add constructively. This detuning produces an approximately Gaussian falloff in the net wakefield generated by each bunch. Detuning works well to suppress the wakefield for about the first 30 ns, after which the amplitude increases due to a partial recoherence of the mode excitations. To offset this rise, weak mode damping was introduced. The damping is achieved by coupling each cell through a longitudinal slot to four TE11 circular waveguides that run parallel to the structure. Two of the circular waveguide manifolds are in the horizontal plane and couple to the vertically deflecting dipole modes while two are in the vertical plane and couple to the horizontally deflecting modes. At the ends of the structures, the circular manifold waveguide makes a transition to rectangular waveguide, which transports the power out of the structure to processing electronics so the signals can be used for beam position monitoring.

Until recently, the JLC-X/NLC design choice was a traveling-wave 1.8-m Rounded Damped Detuned Structure (RDDS) with 206-cells. The rf group velocity varies from 12% c at the upstream end to 3% c at the downstream end to achieve a nearly constant gradient along the structure. The basic parameters were defined primarily by the choice of average cell iris size, which determines the strength of the short-range (intra-bunch) transverse wakefield. The phase advance was chosen to be 120 degrees per cell, the same as in the SLAC S-band structure. This value gives a high shunt impedance per unit length for good efficiency. An average iris radius equal to 18% of the rf wavelength was chosen to limit the wakefield-related bunch emittance growth in the JLC-X/NLC linacs.

To build a structure, disks and cells are first rough-machined using regular lathes and milling machines. At this stage, more than 40 μm of extra copper are left on all surfaces except the coupling slots and manifolds. Final machining is done to micron accuracy and 50 nm surface finish using single crystal diamond turning. The cells are carefully cleaned and rinsed with ozonized water, and then stacked in the V-block of a special fixture. The whole stack is pre-diffusion bonded at 180°C and final-diffusion bonded at 890°C. The final assembly including flanges, vacuum ports, WR90 waveguides for the fundamental mode, and WR62 waveguides for the dipole modes are brazed in a hydrogen furnace at 1020°C. The brazed section is then installed on a strongback for final mechanical measurement and straightening.
in a CMM (Coordinate Measuring Machine). Straightness at the ±20 μm level has been achieved over the length for some of the 1.8-m structures; this exceeds the JLC-X/NLC requirements.

During the assembly process, microwave quality control is used to evaluate the cell and structure properties at several steps. This is particularly important since the cells are not designed to be tuned. As the cells are fabricated, the fundamental and dipole modes are measured to look for significant cell-to-cell deviations. Stacks of cells are also measured to verify that the phase advance is correct at 11.424 GHz. If the net phase error deviates by more than several degrees, the dimensions of subsequent cells are modified to compensate the phase shift. After the structure is assembled, a semi-automated bead pull system is used to measure the field phase and amplitude along the structure.

To determine if the long-range wakefield of the structure is as predicted, the wakefield is measured in the Accelerator Structure SETup (ASSET) facility in the SLAC Linac. The positron beam passes first through the structure and induces a wakefield the effects of which are then observed with a trailing electron bunch. A comparison of the measurements and prediction is shown in Figure 8 for the RDDS1 structure. Although the agreement is excellent, the wakefield is larger than originally designed and is not acceptable for JLC-X/NLC. This is due to a defect in the final assembly procedure. Several cells of the structure were distorted by a support ring during the final braze of the vacuum manifolds onto the outside of the structure. This changed their frequency by about 30 MHz. To estimate the effect of this error, the phase advance of the fundamental mode was measured after assembly. A corresponding change in the dipole frequencies was then included in the wakefield prediction. Despite this localized defect, the random dipole frequency error of the rest of the cells is less than 1 MHz, which is demonstrated by the fact the wakefield dips to the 0.1 V/pC/m/mm level at about 25 ns. In earlier structures (DDS1 and DDS3), smaller wakefields were achieved.

Centering tests were also performed in ASSET using the dipole signals from the manifolds. The measured positions along the structure from the manifolds were compared with the results of mechanical measurements of the relative cell misalignments. The agreement was...
excellent at the 1-2 μm level. In another test, two dipole readings were used as a guide to position the positron beam; this models the beam-based alignment technique proposed for the JLC-X/NLC. Measurements of the resulting short-range wakefield (< 300 ps) indicated that the beam had been centered to less than 12 μm rms in the structure. This measurement incorporates both the precision of the dipole mode measurement (estimated to be 1-2 μm rms) and the internal structure misalignments. The resulting precision is close to the requirement for JLC-X/NLC operation.

The original design for the NLC Test Accelerator only delivered ~100 MW to each 1.8-m accelerator structure to produce a gradient of roughly 50 MV/m—this was essentially the design described in the 1996 NLC ZDR. Four of the 1.8-m long structures that had been developed for the wakefield suppression studies were installed in the NLCTA and processed up to the desired 50-MV/m gradients.

The gradient limitations in the JLC-X/NLC prototype structures were only seen in 1999 when higher-power X-band sources were installed with the goal of generating gradients in excess of 70 MV/m. During this period, a 1.3-m JLC structure was also tested at the Klystron Test Laboratory at SLAC and it achieved gradients up to 85 MV/m with 150-ns pulses. However, the phase profiles from before and after processing of the JLC structure showed that the net phase shift through the structure had changed by 25 degrees, indicating significant changes to the cell dimensions. This shift occurred only in the upstream two-thirds of the structure with most of it at the upstream end. A visual inspection showed pitting along the rises of these upstream cells.

A similar pattern of damage was also observed when processing one of the 1.8 m damped, detuned structures to 70 MV/m with 240-ns pulses in the NLCTA. During about 1,000 hours of operation at high gradient, the net phase shift increased by 90 degrees. Once this degradation was seen, bead-pull measurements were made on the remaining three 1.8-m structures. All of these had about 500 hours of operation at gradients less than 55 MV/m. Although the phase shifts were much smaller, the same pattern of damage was observed.

Based on these results, it was hypothesized that the damage causing the phase shifts was related to the higher group velocity at the upstream end of the structures. To study the factors contributing to the damage, a series of six structures were built (called the T-Series) with different lengths (20, 53 and 105 cm) and lower group velocities (5% c and 3% c at the upstream ends). In addition, various improvements were made to the structure cleaning, handling and processing procedures to determine their impact on high-gradient performance.

The rf processing of the T-Series structures started at higher gradients (55-65 MV/m) than that (35-45 MV/m) for the 1.8 m structures. In addition, much less damage was observed in these structures at gradients above 70 MV/m than in the 1.8 m structures at gradients of 50-65 MV/m. After processing to 80-85 MV/m, the breakdown rate at 70 MV/m was dominated by events in the input and output couplers. The breakdown rates in the body of the structures (i.e., excluding the couplers) at 70 MV/m were close to acceptable for the JLC-X/NLC at the design pulse width of 400 ns. For the three 53 cm, 3% c initial group velocity structures that were tested, the breakdown rates were < 0.1, 0.2 and 0.3 per hour, respectively, while the goal is < 0.1 per hour.

An autopsy of the input coupler on one of the structures revealed melting along the edges of the waveguide openings to the cell, and extensive pitting near these edges and on the coupler iris. The waveguide edges see large rf currents that are a strong function of their sharpness, and the associated pulse heating can be significant. By design, the edges in the T-Series structures were sharper (76-μm radius) than those in the 1.8-m structures (500-μm radius).
radius. Recent calculations have shown that the pulse heating for the T-Series structures is in the 130-270°C range, well below the copper melting point, but high enough to produce stress-induced cracking, which might enhance the heating.

Based on these observations, a 53 cm, 3% c structure was built with couplers designed to have much lower pulse heating. This structure is currently being tested and has performed very well, with no obvious enhancement of the coupler breakdown rates relative to the other cells. For the full structure, breakdown rates of about 1 per 25 hours at 73 MV/m and 1 per hour at 92 MV/m have been measured with 400 ns pulses. All future structures will be made with couplers similar to those used in this test.

Although the results from the T-Series structures are very encouraging, their average cell iris radii are too small to meet JLC-X/NLC short-range wakefield requirements. To increase the iris size while maintaining a low group velocity, a structure design with thicker irises and a higher phase advance per cell (150° instead of 120°) design has been adopted. Two such structures (H-Series) have been built, one 60 cm long with an initial group velocity of 3% c, and the other 90 cm long with an initial group velocity of 5% c. Both are detuned for wakefield suppression, but do include manifolds for wakefield damping.

Unfortunately, these structures have the earlier, T-Series type couplers since they were built before the coupler pulse heating problem was discovered. Making the problem worse, the H-Series structures have lower shunt impedance than the T-Series structures, so the pulse heating is relatively high. During their processing at NLCTA, the coupler breakdowns have indeed limited the gradient to values lower than that achieved with the T-Series structures. In addition, at short pulse lengths where the coupler events did not dominate, the processing rate was much slower than that for the T-Series structures. The larger iris thicknesses of the H-Series structures are certainly a contributing factor, but they do not explain the full difference.

The best results to date in an H-series structure have been achieved with the 60 cm, 3% c structure, which has been processed to 72 MV/m with 400 ns pulses. At 65 MV/m, the current JLC-X/NLC design gradient, the breakdown rate in the body of this structure meets the goal of < 1 per 10 hours. The program until Summer 2003 is to test several H-Series structures with improved couplers, culminating in one that is fully damped and detuned for wakefield suppression. Later, 5.4 m of such structures will be powered with the SLED-II rf source to demonstrate full system integration and to improve performance statistics.

1.4 Injectors

The NLC Injector System is designed to produce low emittance, 8 GeV electron and positron beams at 120 Hz for injection into the main linacs. Each beam consists of a train of 192 bunches of $0.75 \times 10^{10}$ particles spaced by 1.4 ns. The horizontal and vertical emittances are specified to be $\gamma \epsilon_x = 3.2 \mu \text{m-rad}$ and $\gamma \epsilon_y = 0.022 \mu \text{m-rad}$ at injection into the main linacs, and the bunch length is in the range of 90 to 150 µm. Electron polarization of greater than 80% is required. Electron and positron beams are generated in separate accelerator complexes, each of which contains the source, damping ring systems, L-band, S-band, and X-band linacs, bunch length compressors, and collimation regions.

The need for low technical risk, reliable injector subsystems has been a major consideration in the design effort. Technologies chosen for the design of the injector systems are solidly based on experience with previously built and operated high energy colliders and with third-generation synchrotron light sources. Polarized electrons are produced using a dc
photocathode gun which is very similar to the successful SLC polarized source. Unpolarized positrons are generated using multiplexed target systems which will be run in parallel; the peak energy deposition in each target assembly is designed to be identical to that of the SLC positron system, which ran for more than 5 years without incident. The parameters of the two main damping rings are similar to the present generation of synchrotron light sources and the B-Factory colliders in that they must store high-current beams (∼1 A) while attaining small normalized emittances. The acceleration gradient in the injector S-band linacs is only modestly higher than the gradient in the SLC linac and the S-band klystrons are based on the 65 MW SLAC 5045 klystrons. Injector L-band linacs have been designed with low gradients to avoid problems associated with high fields in the structures or ancillary rf distribution systems. The X-band rf for the bunch length compressors is adapted from the main linac rf development.

There are two separate injector complexes to produce the low-emittance trains of electron and positron bunches for injection into the main linac. The electron injector includes a polarized photocathode gun, a bunching system and an S-band booster linac to deliver a 1.98 GeV beam to the damping ring. For the positron injector, an unpolarized electron gun and bunching system followed by a 6 GeV (10 GeV) drive linac provides the electron beam needed to produce positrons in the NLC (JLC) design. Multiple positron targets are required to keep the energy deposited in each target below the threshold for material damage. The electrons are split by an rf separator and directed onto 3 out of 4 multiplexed targets and positron capture sections. The bunches are then recombined into the desired bunch train format and accelerated in a 1.98 GeV L-band (S-band) linac to the positron pre-damping ring in the NLC (JLC) design. Because of the large emittance of the captured positrons, large-aperture L-band rf is used for acceleration and a pre-damping ring is required to reduce the emittance of the positrons before injection into the main damping ring. Two identical rings are used to damp the positron and electron bunch trains from the injectors to a normalized emittance of 3 μm-rad in the horizontal and 0.02 μm-rad in the vertical for the nominal 1.4 ns bunch spacing.

After extraction from the damping rings, the beam passes through a spin rotator system that can be used to orient the electron spin in an arbitrary direction to ensure longitudinal polarization of the beams at the IP. In the baseline design, the spin rotating solenoids are only installed in the electron beamline. However, the positron beamline is identical so that additional solenoids can easily be installed later for operation with either polarized positrons or with polarized electrons.

After the spin rotators, the bunch length must be compressed from 4 mm to 110 μm before injection into the main X-band linacs. This is accomplished in a 2-stage bunch compressor that is identical for the two beams. The first stage uses an L-band rf section followed by a wiggler to compress the bunch to a length of about 0.5 mm. This is followed by a 6 GeV S-band pre-linac and the second-stage bunch compressor with a 180° arc, an X-band rf section and a chicane. The second stage can produce a bunch length between 90 and 150 μm. In the present layout, the electron booster and pre-linac are housed in the same tunnel to minimize infrastructure costs. The positron drive linac, booster and pre-linacs also share a common tunnel and support buildings.

Descriptions of the choice of injector layouts, the polarized electron source, the positron system, damping ring systems, and bunch length compression systems follow.
1.4.1 Polarized Electron Source

The electron injector source system creates polarized electron beams of the required energy and emittance for injection into the electron damping ring system. The polarized electron beams are produced with a DC photocathode electron gun, bunched in a 714 MHz sub-harmonic rf system and accelerated in an S-band linac to 1.98 GeV, the energy of the damping ring. Each beam consists of a bunch train of 192 bunches with $0.8 \times 10^{10}$ particles per bunch that are spaced by 1.4 ns. The electrons at the end of the source booster linac are predicted to have an rms emittance of 50 $\mu$m-rad from PARMELA simulations. To ensure reliable operation, the system is required to produce beams with rms emittances that are less than twice the simulated value, i.e. 100 $\mu$m-rad. In addition, the transverse jitter is specified to be less than the rms beam size and the energy jitter less than 1%. Finally, the spin polarization is specified to be 80%. All of these requirements are similar to those attained during operation of the SLC. A summary of the design parameters is given in Table 7.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bunch Spacing</td>
<td>1.4 ns</td>
</tr>
<tr>
<td>Number of Bunches</td>
<td>192</td>
</tr>
<tr>
<td>Particles/Bunch</td>
<td>$0.8 \times 10^{10}$</td>
</tr>
<tr>
<td>Energy</td>
<td>1.98 GeV</td>
</tr>
<tr>
<td>Energy Adjustability</td>
<td>±5%</td>
</tr>
<tr>
<td>Bunch Energy Variation</td>
<td>1% Full Width</td>
</tr>
<tr>
<td>Single Bunch Energy Spread</td>
<td>1% Full Width</td>
</tr>
<tr>
<td>Emittance $\gamma \epsilon_{x,y}$ [rms]</td>
<td>100 $\mu$m-rad</td>
</tr>
<tr>
<td>Bunch Length $\sigma_z$</td>
<td>&lt;10 mm</td>
</tr>
<tr>
<td>Train Population Uniformity</td>
<td>1% Full Width</td>
</tr>
<tr>
<td>Bunch-to-Bunch Pop. Uniformity</td>
<td>2% rms</td>
</tr>
<tr>
<td>Repetition Rate</td>
<td>120 Hz</td>
</tr>
<tr>
<td>Horizontal Beam Jitter $\Delta \gamma J_x$</td>
<td>50 $\mu$m-rad</td>
</tr>
<tr>
<td>Vertical Beam Jitter $\Delta \gamma J_y$</td>
<td>50 $\mu$m-rad</td>
</tr>
<tr>
<td>Polarization</td>
<td>80%</td>
</tr>
<tr>
<td>Beam Power</td>
<td>58 kW</td>
</tr>
</tbody>
</table>

The polarized electron source consists of a polarized high-power laser and a high-voltage dc gun with a semiconductor photocathode. Many of the performance requirements for the injector are similar to those in the SLC and the design of the injector is based on the successful SLC injector. The SLC polarized source generated 80% beam polarization. As long as ultra high vacuum conditions were maintained, the cathode lifetimes exceeded thousands of hours, and system availability approached 99%. The most notable differences between the present and the SLC design are the increase in gun high voltage from the SLC value of 120 kV to 175-200 kV and the use of 714 MHz rf for sub-harmonic bunching. For comparison, a 200 kV polarized electron gun is being developed at Nagoya University.

Improvement of the SLC photocathodes is required for the JLC-X/NLC operation because of the higher pulse charge requirements; the SLC source operated with a single polarized bunch of $\sim 5 \times 10^{10}$. Efforts by SLAC and the University of Wisconsin, and at Nagoya University are concentrating on developing cathodes with a highly doped surface layer to
permit rapid dissipation of surface charge that builds up as beam is extracted. Recent tests using a strained layer cathode with a 75 Ångström surface layer are extremely promising. Operating at 120 kV, up to \(8 \times 10^{11}\) electrons have been extracted by illuminating a 1 cm radius spot on the cathode. The polarization of the electrons was measured to be about 78% and no evidence of surface charge limit was observed. The maximum charge extracted was limited by available laser energy in the test laboratory. After being moved to the CID gun in the SLAC linac, the cathode has produced roughly \(10^{13}\) \(e^-\) in 300 ns, many times the JLC-X/NLC requirement of \(2 \times 10^{12}\) \(e^-\) in 267 ns from the gun. This cathode has been routinely operating for 6 months during the E-158 physics run. The polarization measured during the E-185 run was about 85%.

An S-band linac is used to accelerate the captured electrons up to the damping ring energy of 1.98 GeV. The loaded gradient of the linac is 17 MeV/m. This linac will use KEK-style SLED systems for rf pulse compression which have been designed and operated at higher field levels than the original SLAC-style SLED systems. Beam emittance growth through the booster linac is not a problem because of the low charge per bunch (in comparison to SLC operation) and because of the relatively large damping ring design acceptance. Standard quadrupole focusing elements are employed together with discrete steering dipoles along the length of the booster linac. Multibunch beam loading in the linac is compensated using the \(\Delta T\) method in which the beam is injected into the accelerator before the rf has fully filled the structures. Fine tuning of the amplitude of the rf in a prescribed fashion after the beam has been injected provides additional control over the energy spread. An energy compression system has been included in the transport line that leads from the end of the linac to the main damping ring to further stabilize the energy and reduce the energy spread of injected bunches by a factor of roughly 2.

To measure the beam emittance, 4-wire parasitic emittance diagnostics are located after the \(e^-\) source (at 80 MeV) and before injection into the main damping ring. In addition, energy, energy spread, and bunch length diagnostics are located in a chicane at the 80 MeV point and in the 60° arc before injection into the main damping ring. To preserve electron helicity, the spin must be rotated into the vertical direction prior to injection into the damping ring. The 60° arc also rotates the polarization vector from the longitudinal direction into the \(x-y\) plane and a subsequent superconducting solenoid then orients the polarization vertically. To stabilize the trajectory and preserve the emittance, all the quadrupoles have BPMs with 10 \(\mu\)m resolution and horizontal or vertical steering correctors depending on the focusing plane.

### 1.4.2 Positron Source

The positron injector source system creates positron beams of the required energy and emittance for injection into the positron damping rings. In the NLC design, positrons are produced by colliding 6.2 GeV electrons into three separate high Z material targets, capturing the resulting positrons, and accelerating them to the 1.98 GeV energy of the pre-damping ring system. Each beam consists of a bunch train of 192 bunches with \(0.9 \times 10^{10}\) particles that are spaced by 1.4 ns (or 96 bunches with twice the charge that are spaced by 2.8 ns). As required by the pre-damping ring acceptance, the positrons have an edge emittance of 0.03 m-rad and a transverse jitter that is less than 0.015 m-rad; this jitter corresponds to about a 7 mm oscillation at the damping ring entrance. Table 8 lists the positron beam parameters required for injection into the pre-damping ring system.
Table 8: Beam parameters delivered by the positron source system to the positron pre-
damping ring system for the 1.4 bunch spacing option.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bunch Spacing</td>
<td>1.4 ns</td>
</tr>
<tr>
<td>Number of Bunches</td>
<td>192</td>
</tr>
<tr>
<td>Particles/Bunch</td>
<td>$0.9 \times 10^{10}$</td>
</tr>
<tr>
<td>Energy</td>
<td>1.98 GeV</td>
</tr>
<tr>
<td>Energy Adjustability</td>
<td>±5%</td>
</tr>
<tr>
<td>Bunch Energy Variation</td>
<td>1% Full Width</td>
</tr>
<tr>
<td>Single Bunch Energy Spread</td>
<td>2% Full Width</td>
</tr>
<tr>
<td>Emittance $\gamma \epsilon_{x,y}$ (edge)</td>
<td>30,000 µm-rad</td>
</tr>
<tr>
<td>Bunch Length $\sigma_z$</td>
<td>&lt;10 mm</td>
</tr>
<tr>
<td>Train Population Uniformity</td>
<td>1% Full Width</td>
</tr>
<tr>
<td>Bunch-to-Bunch Pop. Uniformity</td>
<td>2% rms</td>
</tr>
<tr>
<td>Repetition Rate</td>
<td>120 Hz</td>
</tr>
<tr>
<td>Horizontal Beam Jitter $\Delta \gamma J_x$</td>
<td>15,000 µm-rad</td>
</tr>
<tr>
<td>Vertical Beam Jitter $\Delta \gamma J_x$</td>
<td>15,000 µm-rad</td>
</tr>
<tr>
<td>Beam Power</td>
<td>65 kW</td>
</tr>
</tbody>
</table>

The design of the positron system is based on the system used for the SLC, which demonstrated excellent reliability over many years of operation. The total number of positrons required for the JLC-X/NLC bunch train is almost two orders of magnitude greater than the number of positrons in the single SLC bunch. The design goal is to build a target system which is expected to survive a 9 month run (120 Hz, 24 hours per day, 7 days per week, with no scheduled outages for maintenance). Targets can be replaced/repaired annually in a scheduled 3 month maintenance period.

Positrons are produced by targeting a 6.2 GeV electron beam onto a WRe target to create an electro-magnetic shower. The positrons produced in the shower are collected using a 5.8 Tesla magnetic flux concentrator, accelerated to 250 MeV in L-band structures encased in a 0.5 Tesla solenoidal magnetic field, and then injected into an L-band linac and accelerated to 1.98 GeV. The average deposited power is handled by rotating the target and removing the excess heat through water cooling. Of critical concern for target damage is the instantaneous energy deposition per unit volume.

After approximately 1000 days of operation (~5 calendar years), the SLC positron system failed. Upon examination it was found that a water-to-vacuum leak had occurred in one of the target cooling tubes. In addition, cracking and material ejection were found on the exit face of the target.

The peak energy deposition in the SLC target was about 50 J/g under the conditions at which the target failed. This level produces an instantaneous mechanical shock in the WRe target material which is about a factor of two below the expected ultimate tensile strength of pristine material. However, material hardening of a factor of about 2 from target entrance to target exit was measured along the beam path. The calculated radiation damage to the material is in excess of 3 dislocations per atom (dpa) and the target embrittlement and subsequent loss of material integrity are consistent with the calculated exposure level.

Because of the consistency of the observed damage with expectations from the simulations, it has been decided to limit the shock in the targets to that of the SLC system. In particular, the peak energy deposition and irradiation fluences will be kept by design to less than 50
6.2 GeV e\(^-\) – 250 MeV e\(^+\) RF Separater

3 out of 4 target system scheme

Figure 9: Schematic of the conventional e\(^+\) production system.

J/g and 1 dpa. Investigations into the connection between radiation damage due to electrons with that from neutron/proton exposure are continuing. It is useful to tap into the data on material property degradation due to neutron/proton damage since the database of electron induced damage is comparatively limited. Beam tests at SLAC are underway to determine the threshold for material damage and a model of the expected damage is being developed. To date, samples of Ti, Cu, GlidCop, Ni, Ta, W, and WRe have been irradiated in the FFTB area at SLAC. Additional studies will be aimed at developing an optimized target material. Induced damage to candidate target materials will be studied using the E158 beam at SLAC (5 \times 10^{11} e^-/pulse at 45 GeV, 200-300 ns pulse width, and focusable to small spots).

In order to keep the peak shock stress in the target below the threshold for damage, three e\(^+\) targets operating in parallel are planned to produce the JLC-X/NLC beam. To assure overall system availability, a layout has been adopted where there are 4 target/capture modules, 3 of which are operating at any one time as illustrated in Figure 9. The bunches are separated using an rf separator and then directed to the desired targets using dc bending magnets. Access is possible to the fourth target/capture module for maintenance and repair while the other 3 modules are in operation.

The 6.2 GeV electron drive beam, which is used to create the positrons, is based on S-band technology. Because of the need to use three quasi-independent target/capture sections for positron production, the electrons will be generated using a photocathode based source. Fine tuning of the individual electron bunch populations within the drive train is possible through bunch-to-bunch intensity adjustments at the source laser. The unpolarized electron source system is essentially identical to the polarized electron source with the exception that shorter laser wavelengths and photocathodes with higher quantum yields will be used.

Positron yield is defined as the number of positrons captured in the pre-damping ring divided by the number of electrons incident on the target. The NLC has adopted the use of L-band (1.4 GHz) for both the initial 250 MeV capture and 1.73 GeV booster linacs. The larger aperture and longer wavelength of the L-band affords a factor of about 30 increase in acceptance over an S-band system. Yield into the pre-damping ring acceptance is calculated based on the initial e\(^+\) distribution, generated using EGS4. The calculated yield is about 1.5, but experience with the SLC shows that this yield can be rapidly degraded by alignment and optical errors in the transport between the e\(^+\) source and the damping rings. It is believed that a 50% margin in the yield should be sufficient. If necessary, the population of the drive e\(^-\) beam can be increased somewhat to produce the desired number of e\(^+\).

To measure the beam emittance, 4-wire parasitic emittance diagnostics will be located after the 250 MeV point in the e\(^+\) beam line and before injection into the pre-damping ring. In addition, energy, energy spread, and bunch length diagnostics are located in a chicane at
the 250 MeV point and in the 60° arc before injection into the pre-damping ring. To stabilize the trajectory and preserve the emittance all of the quadrupoles have BPMs with 10 µm resolution and horizontal or vertical steering correctors depending on the focusing plane.

1.4.3 Damping Rings

The JLC-X/NLC damping rings are designed to damp the incoming electron and positron beams to the small emittances needed for collisions. The rings have three purposes: (1) damping the incoming emittances in all three planes, (2) damping incoming transients and providing a stable platform for the downstream portion of the accelerator, and (3) delaying the bunches so that feed-forward systems can be used to compensate for charge fluctuations. To meet these goals, three damping rings have been designed: two identical main damping rings, one for the electrons and one for the positrons, and a pre-damping ring for the positrons. The pre-damping ring is needed because the emittance of the incoming positrons is much larger than that of the electrons. Each damping ring will store multiple trains of bunches at once. At every machine cycle, a single fully damped bunch train is extracted from the ring while a new bunch train is injected. In this manner, each bunch train can be damped for many machine cycles.

At the SLC, the damping rings were one of the most problematic subsystems. This was because the downstream systems are extremely sensitive to small changes in the injected beams, and because the beams are stored in the rings for a relatively long time, which makes them more sensitive to subtle accelerator physics effects. The parameters of the JLC-X/NLC main damping rings are similar to the present generation of synchrotron light sources and the B-Factory colliders in that they must store high-current beams (∼ 1 A) while attaining small normalized emittances. Table 9 compares the damping ring parameters with those of the SLAC B-Factory Low-Energy Ring (PEP-II LER), the Advanced Light Source (ALS) at Lawrence Berkeley National Laboratory, and the Accelerator Test Facility (ATF) damping ring at KEK in Japan. In particular, the stored beam currents are less than half of what the PEP-II LER has achieved, while the emittance, energy, and size of the rings are similar to those of the ALS and the ATF. These other rings have been largely successful in meeting their design parameters, and have been able to test and verify many of the accelerator physics and technology issues that will arise in the damping rings. We believe that this provides confidence that the JLC-X/NLC rings will operate as required.

Table 9: Comparison of NLC main damping rings with design parameters of other rings.

<table>
<thead>
<tr>
<th></th>
<th>NLC MDR</th>
<th>PEP-II LER</th>
<th>LBNL ALS</th>
<th>KEK ATF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy [GeV]</td>
<td>1.98</td>
<td>3.1</td>
<td>1.5</td>
<td>1.54</td>
</tr>
<tr>
<td>Circumference [m]</td>
<td>300</td>
<td>2200</td>
<td>197</td>
<td>139</td>
</tr>
<tr>
<td>Current [A]</td>
<td>0.8</td>
<td>2.16</td>
<td>0.4</td>
<td>0.6</td>
</tr>
<tr>
<td>Equilib. γεₓ [µm-rad]</td>
<td>2.17</td>
<td>400</td>
<td>12</td>
<td>2.8</td>
</tr>
<tr>
<td>Equilib. γεᵧ [µm-rad]</td>
<td>0.014</td>
<td>12</td>
<td>0.12</td>
<td>0.028</td>
</tr>
</tbody>
</table>

Issues associated with the very small beam emittances, such as intrabeam scattering and ion trapping, continue to be studied in the ALS and ATF. The ATF has achieved emittances of γεₓ=2.8 µm-rad and γεᵧ=0.028 µm-rad, close to those desired in the main damping rings; work continues to improve the performance, which is primarily limited by the diagnostics in that machine. Experiments have also been performed at low energy (1 GeV) in the ALS,
where the measured emittances of $10^9$ particles are $\gamma\epsilon_x=4\ \mu\text{m-rad}$ and $\gamma\epsilon_y=0.07\ \mu\text{m-rad}$. These measurements, combined with theoretical modelling, are designed to improve the understanding of the process of intrabeam scattering in electron storage rings, and to increase confidence in the predictions for the damping rings.

In addition, the PEP-II LER at SLAC, the KEK-B LER at KEK, and the Advanced Photon Source (APS) at Argonne have been used to study the electron-cloud instability and have shown success in controlling and understanding the phenomenon. Simulations based on a simple circular vacuum chamber predict that the growth times of transverse instabilities driven by the electron cloud are greater than $100\ \mu\text{s}$ and can be controlled with a broadband feedback system. The NLC vacuum system design includes an ante-chamber in which synchrotron radiation is absorbed, significantly reducing the number of photoelectrons in the beam duct and the chamber will likely use a TiN or similar coating to reduce the number of secondary electrons.

The similarities with other rings have also simplified the design process, and experience at these other accelerators will continue to be applied to benefit the damping rings designs. For example: the damping ring rf system is based on the higher-order-mode damped cavity designs successfully operating at the SLAC B-Factory and the ATF damping ring, the multibunch feedback systems are based upon the feedback systems successfully verified at the SLAC B-Factory and the ALS, and the vacuum system is similar to that used by the ALS. Furthermore, the design uses “C” quadrupole and sextupole magnets similar to those used at the ALS and the APS, a high-field permanent magnet wiggler similar to those in use at third generation light sources, and a double kicker system for extraction similar to one operational in the ATF. The successful demonstration of these and other systems and components allows a high degree of confidence in achieving the damping ring parameters.

The NLC damping ring complex is designed to operate with the parameters listed in Table 10 and the positron damping ring complex is illustrated schematically in Figure 10; the JLC design is similar although the repetition rate is slightly different. These design parameters satisfy the requirements of all presently considered NLC upgrades. The rings produce extracted electron and positron beams with emittances $\gamma\epsilon_x=3\ \mu\text{m-rad}$ and $\gamma\epsilon_y=0.02\ \mu\text{m-rad}$, at a repetition rate of 120 Hz. Designs have also been developed which allow repetition rates as high as 180 Hz; in this case, the use of two main damping rings is proposed. The beams in the damping rings consist of multiple trains of 192 bunches with an injected single bunch charge of $0.8 \times 10^{10}$. To provide operational flexibility, the rings have been designed to also accommodate trains of 96 bunches spaced by 2.8 ns with maximum single bunch charge of $1.6 \times 10^{10}$ in the main rings ($1.8 \times 10^{10}$ in the pre-damping ring), and to operate with a peak current roughly 15% higher than the nominal peak current. In addition, the electron source has been designed to provide additional charge to allow for at least 10% losses during injection into the electron damping ring. Similarly, the positron source has been designed to produce at least 20% additional charge to provide for losses during injection into the pre-damping ring. Finally, the rings have been designed to operate at 1.98 GeV, with an energy range of 5%—1.98 GeV corresponds to a spin tune of 4.5 where depolarizing spin resonances are expected to be small. The energy adjustability will allow the damping rate and/or spin tunes to be shifted if necessary.

**Main Damping Rings** The NLC main damping rings are roughly 300 m in circumference and they measure roughly 60 m by 100 m with a nominal energy of 1.98 GeV. The rings are designed in a racetrack form with two arcs separated by straight sections. The main
damping rings are designed to damp beams with injected emittances $\gamma \epsilon_x, \gamma \epsilon_y = 1.5 \times 10^{-4}$ m-rad to give extracted beam emittances of $\gamma \epsilon_x = 3 \times 10^{-6}$ m-rad and $\gamma \epsilon_y = 2 \times 10^{-8}$ m-rad. The rings will operate at 120 Hz. They provide sufficient damping to decrease the injected emittance by four orders of magnitude. The parameters are summarized in Table 11 for the main damping rings (MDR), and the positron pre-damping ring (PPDR). The main damping ring lattice is based on detuned Theoretical Minimum Emittance (TME) cells, which were chosen because of efficiency in generating low emittance and eased requirements on the combined-function bending magnets. The chromaticity is corrected with two families of sextupoles and the dynamic aperture is more than sufficient to ensure lossless injection. The damping is performed using both high-field bending magnets and ten 4.6 m sections of damping wiggler. The dynamic aperture, including effects of errors, is predicted to be in excess of 15 times the injected beam size. Potential limitations due to the contribution from the 46 m of wiggler magnet have been studied. Analytical expressions of arbitrary three-dimensional wiggler fields have been developed, and tracking including the non-linear components of the wiggler field will be used to determine the minimum pole width requirement for the 2.15 T hybrid wiggler magnet. Preliminary analysis indicates that the wiggler with a magnet pole width of 11 cm does not seriously impact the dynamic aperture.

The rings operate with three trains of 192 bunches spaced by 1.4 ns or 96 bunches spaced by 2.8 ns. The bunch trains are injected onto and extracted from the closed orbit using pulsed kickers and DC septa. The bunch trains are separated by 65 ns to allow for the rise and fall times of the injection and extraction kickers. To avoid coupled-bunch instabilities the rf cavities use higher-order-mode damping, based on the PEP-II design, and a transverse bunch-by-bunch feedback system. As stated, the rings are designed to operate with maximum bunch charges of $1.6 \times 10^{10}$ particles; this is roughly 10% more than the maximum needed at the IP with a 2.8 ns bunch spacing.

Table 10: Requirements for NLC main damping rings.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Repetition rate [Hz]</td>
<td>120</td>
</tr>
<tr>
<td>Bunches per train</td>
<td>192</td>
</tr>
<tr>
<td>Bunch spacing [ns]</td>
<td>1.4</td>
</tr>
<tr>
<td>Bunch population</td>
<td>$0.8 \times 10^{10}$</td>
</tr>
<tr>
<td>$\gamma \epsilon_x$ equilib. / $\gamma \epsilon_x$ extract. [10$^{-6}$ m-rad]</td>
<td>3.0 / 3.0</td>
</tr>
<tr>
<td>$\gamma \epsilon_y$ equilib. / $\gamma \epsilon_y$ extract. [10$^{-8}$ m-rad]</td>
<td>1.4 / 2.0</td>
</tr>
</tbody>
</table>

Figure 10: Schematic of NLC positron damping ring complex.
Table 1: Parameters for main damping rings and the pre-damping ring.

<table>
<thead>
<tr>
<th></th>
<th>MDR</th>
<th>PPDR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Circumference [m]</td>
<td>299.792</td>
<td>230.933</td>
</tr>
<tr>
<td>Energy [GeV]</td>
<td>1.98</td>
<td>1.98</td>
</tr>
<tr>
<td>Max. Current [A]</td>
<td>0.8</td>
<td>0.75</td>
</tr>
<tr>
<td>Max. Rep. Rate [Hz]</td>
<td>120</td>
<td>120</td>
</tr>
<tr>
<td>Bunch trains x Bunches per train</td>
<td>3 x 192</td>
<td>2 x 192</td>
</tr>
<tr>
<td>Train / Bunch separation [ns]</td>
<td>65 / 1.4</td>
<td>100 / 1.4</td>
</tr>
<tr>
<td>$\nu_x, \nu_y, \nu_z$</td>
<td>27.26, 11.13, 0.0035</td>
<td>11.45, 5.45, 0.0114</td>
</tr>
<tr>
<td>$\gamma \epsilon_x$ equilib. [\mu m-rad]</td>
<td>2.17</td>
<td>60</td>
</tr>
<tr>
<td>$\gamma \epsilon_x$ extract., $\gamma \epsilon_y$ extract. [\mu m-rad]</td>
<td>3.0, 0.02</td>
<td>127, 70</td>
</tr>
<tr>
<td>$\sigma_{\Delta E/E}$, $\sigma_z$</td>
<td>0.09%, 3.6 mm</td>
<td>0.08%, 5.1 mm</td>
</tr>
<tr>
<td>$\xi_x$ uncorr., $\xi_y$ uncorr.</td>
<td>-37.12, -28.24</td>
<td>-10.39, -12.23</td>
</tr>
<tr>
<td>$\tau_x$, $\tau_y$, $\tau_\epsilon$ [ns]</td>
<td>4.76, 5.00, 2.60</td>
<td>5.85, 5.81, 2.90</td>
</tr>
<tr>
<td>$U_{\text{sr}}$ [kV/turn]</td>
<td>777</td>
<td>525</td>
</tr>
<tr>
<td>$\alpha_p$</td>
<td>$2.95 \times 10^{-4}$</td>
<td>$2.00 \times 10^{-3}$</td>
</tr>
<tr>
<td>$V_{\text{RF}}$</td>
<td>1.1 MV, 714 MHz</td>
<td>1.5 MV, 714 MHz</td>
</tr>
<tr>
<td>Lattice</td>
<td>36 TME cells</td>
<td>10 DBA cells</td>
</tr>
</tbody>
</table>

Finally, because the rings must generate extremely small beam emittances, there are tight jitter and alignment tolerances. Extensive effort has been made to include cancellations and tuning procedures in the design that will ease the tolerances to reasonable levels. Skew quadrupole windings will be incorporated in sextupole magnets to facilitate coupling correction. Quadrupoles and sextupoles will have independent trim control, and magnet movers will be used to facilitate beam-based alignment. BPMs, having a 1 \mu m resolution for single turn measurements and < 0.3 \mu m resolution for the stored orbit, will be located at every quadrupole. In addition, a synchrotron radiation port will be used for bunch length and initial beam size measurements and, a laser wire, like the system commissioned at the ATF at KEK, will likely be used to measure the damped beam. There will be a 4-wire parasitic emittance measurement as well as energy and energy spread diagnostics located in the extraction line before the spin rotator and first stage bunch compressor. Additional emittance, energy spread and bunch length diagnostics will be located in and after the first stage bunch compressor.

**Positron Pre-Damping Ring**  The pre-damping ring is roughly 230 m in circumference and has 10 dispersion-free straight sections for injection, extraction, rf, circumference correction chicanes, and damping wigglers; the latter have a total length of roughly 50 m. The ring has a radius of roughly 40 meters. It stores two bunch trains which are separated by more than 100 ns to allow for the rise and fall times of the injection and extraction kickers—these kickers must provide larger deflections than those in the main damping rings. To minimize rf transients during injection and extraction, a new bunch train will be injected one half turn after a train is extracted. In addition, the rf cavities are placed downstream of the injection kicker and upstream of the extraction kicker so that the injection/extraction process will not interrupt the beam current seen by the cavities.

The positron pre-damping ring is designed to damp the large emittance beam from the
positron source to an emittance of less than $\gamma \epsilon_{x,y} = 1.5 \times 10^{-4}$ m-rad; the parameters are summarized in Table 11. The extracted positrons are then injected into the main damping ring where they are damped to the desired final emittances. The pre-damping ring allows the large aperture requirements for the incoming positron beams to be decoupled from the final emittance requirements of the linear collider.

The magnets and vacuum systems are designed to provide sufficient aperture to accept a 2-GeV beam with an edge emittance of $\gamma \epsilon_{x,y} = 0.03$ m-rad and momentum spread of $|dp/p| = 1.5\%$ plus betatron-action jitter of $\Delta \gamma J_{x,y} = 0.015$ m-rad for misalignments and missteering; this provides a substantial margin for injection and internal mismatches. In addition, the injector specifications allow significant overhead for injection losses into the pre-damping ring. The pre-damping ring is designed to operate with a maximum bunch charge that is roughly 20% greater than the maximum required at the IP.

Like the main damping rings, quadrupoles and sextupoles will have independent trim control, and magnet movers will be used to facilitate beam-based alignment as well as matching of the lattice functions, which is especially important in the pre-damping ring because of the limited aperture. BPMs will be located at every quadrupole and will have a resolution better than 15 \( \mu \)m for a single turn and 5 \( \mu \)m after averaging the stored orbit. In addition, a synchrotron radiation port will be used for bunch length and beam size measurements. There will be a beam size as well as energy and energy spread diagnostics located in the transfer line to the main damping ring.

### 1.4.4 Bunch Length Compressors

The bunch compressors must reduce the \( \sim 4 \) mm rms length of the bunches extracted from the damping rings to the 90 to 150 \( \mu \)m bunch length required for the main linacs and final focus systems. A two-stage compressor system has been designed in which the first stage follows the damping ring and the second stage is at the exit of the S-band pre-linac at a beam energy of 8 GeV. Electron and positron bunch compression systems are identical. The bunch compressor system has been designed to meet the following additional goals: (1) Multibunch phase variations in the damping ring of up to \( \pm 5 \) mm should not produce relative energy variations that are larger than \( \pm 0.1\% \) in the final focus systems. (2) The system should include a 180\( ^\circ \) turn-around arc to permit future main linac extensions and to allow beam abort and feedforward systems. (3) The transverse emittances must be preserved to within a reasonable budget with diagnostics and correction elements included in the design. (4) The compression systems should not depolarize the beams.

The two-stage system has a number of advantages over a single-stage compressor. In particular, it keeps the rms energy spread less than about 2\% and the bunch length is more naturally matched to the acceleration rf frequency so that energy spread due to the longitudinal wakefields can be cancelled locally. The disadvantage of the two-stage design is that it is more complex and lengthy than a single-stage compressor. The first stage rotates the longitudinal phase by $\frac{\gamma}{2}$ while the second stage performs a $2\pi$ rotation. In this manner, phase errors due to the beam loading in the damping rings and energy errors due to imperfect multibunch energy compensation in the 6 GeV S-band pre-linacs do not affect the beam phase at injection into the main linac.

Assuming an incoming rms energy spread of $\sigma_\delta = 1 \times 10^{-3}$ and rms bunch length of $\sigma_z = 5$ mm, the first stage compresses the damping ring beam to a bunch length of about 0.6 mm. This stage consists of a 140 MV L-band (1.4 GHz) rf section followed by a long pe-
period wigglers which generates the momentum compaction needed for the bunch compression. The second bunch compression stage follows the 6 GeV pre-linac. The nominal configuration compresses the beam to a bunch length of 110 $\mu$m. This compressor is a telescope in longitudinal phase space which rotates the phase space by $2\pi$. It consists of a 180° arc which is followed by a 600 MeV X-band (11.4 GHz) rf section and a chicane. Adjustments to either the low-energy or the high-energy compressors permit control of the final bunch length over the specified range of 150 to 90 $\mu$m.

One of the rationales behind the compressor design has been to utilize naturally achromatic magnetic lattices wherever the beam energy spread is large. In particular, the optics is chosen so that quadrupoles are not placed in regions of large dispersion and strong sextupoles are not needed. This choice arises from experience with the second-order achromats in the SLC bunch compressors in which quadrupoles are located in dispersive regions and strong sextupoles are used to cancel the chromatic aberrations. Unfortunately, the SLC design was difficult to operate and tune because of large nonlinearities and sensitivity to multipole errors in the quadrupoles; over the years additional nonlinear elements were added (skew sextupoles and octupoles) to help cancel the residual aberrations but tuning remained problematic. To facilitate tuning, orthogonal tuning controls and diagnostics have been explicitly designed into the NLC system, which should make it relatively straightforward to operate. Details of the diagnostic equipment can be found in the optics decks.

Finally, although the tolerances on components in the bunch compressor systems are not nearly as tight as in the main linacs or the final focus systems, the same methods of beam-based alignment and tuning have been adopted. In particular, to ease the alignment procedures, all of the quadrupoles will be mounted on magnet movers and each quadrupole will contain a BPM with a resolution of $< 2\mu$m. Similarly, all of the accelerator structures will be instrumented with rf BPMs to measure the induced dipole modes and each rf girder will be remotely movable for minimization of wakefields. There will be 4-wire parasitic emittance measurement sections and subsequent tune-up dumps after the first-stage bunch compressors, the 6 GeV pre-linacs, and the second-stage bunch compressors before injection into the main linac. There will also be synchrotron radiation-based bunch length and energy spread diagnostics in the first-stage wigglers, the second-stage arcs, and the second stage chicanes and there will be rf deflector-based bunch length monitors before injection into the main linac.

1.5 Beam Delivery

The beam delivery system (BDS) must both reduce the beams to the sizes required to produce luminosity and remove any particles that are far enough from the beam core to produce unacceptable detector backgrounds. In addition, the BDS must provide protection for the detector and beamline components against missteered beams emerging from the main linacs, and must safely transport the collided beams to water-cooled dumps which can absorb the high beam power density without damage. Finally, the BDS must provide instrumentation that can monitor the parameters of the collided beams, such as the energy spread and polarization after collision, which are required by the particle physics experiments.

Although the parameters of the JLC-X/NLC BDS are far beyond anything that has been achieved in a storage ring, the SLC demonstrated the viability of a fully-integrated linear collider beam delivery system with millimeter-sized betatron functions and routine collision of beams with rms sizes of under 1 $\mu$m. The FFTB at SLAC was a single-beam demonstration...
of a linear collider beam delivery system with IP betatron functions comparable to those in the JLC-X/NLC. The BDS design is based upon experience from these two facilities. In addition, a vigorous R&D program on passive and active magnet position stabilization, ground motion, materials damage thresholds, and instabilities driven by collimators close to the beam have all yielded insights which have been incorporated into the design of the system.

The layout of the BDS components is shown in Figure 11. The six main subsystems of the beam delivery, from upstream to downstream, are: the emittance diagnostic and skew correction region, which provides parasitic measurement of the beam emittance and an orthogonal set of four skew quadrupoles to correct all sources of betatron coupling in the beam; the IR transport, which separates the beamlines to the low and high-energy IRs; the collimation system, which provides protection from errant beams and removes particles which might cause backgrounds; the final focus (FF), which focuses the beams down to the small spots; the IRs, which provides detector masking and specialized supports for the final doublet quadrupoles of the final focus; and the extraction line, which transports the spent beams to their respective dumps and provides the post-collision beam measurements. In addition, a high-power pulsed beam dump, which is not shown, is located in the energy collimation region to allow the full-power linac beam to be tuned before sending the beam through the final focus.

The beamline for the high energy IR is 1.8 km long. This distance includes a 1.4 km long collimation and final focus region, a 150 meter region where the beamlines for the low-energy IR diverge, and a 200 meter emittance diagnostic and skew correction section. The low-energy IR beamline splits off at the end of diagnostic region and includes arcs that bend the beam by about 25 mrad and a shorter 800 meter collimation region and final focus. The two IRs are separated by about 35 m transversely and 150 m longitudinally to provide vibration isolation and shielding so either IR hall may be accessed while the other is in operation.
1.5.1 Final Focus

The role of the final focus is to reduce the size of the beam at the IP sufficiently to provide the required luminosity. The small beam sizes are achieved using strong quadrupole magnets close to the IP to focus the low emittance beams and reducing $\beta^{\star}_{x,y}$ to 8 x 0.11 mm. Unfortunately, the final quadrupoles also generate a huge chromaticity which, if uncorrected, would increase the spot sizes by one to two orders of magnitude.

Correcting the chromaticity of the final quadrupole doublet is the issue that drives much of the design. In the final focus systems used at the SLC and the FFTB, which were also the basis of the 1996 NLC ZDR final focus design, the chromaticity correction was accomplished in dedicated “chromaticity correction sections.” In these sections, a combination of bend magnets and sextupoles generated a chromaticity equal-and-opposite to that of the final doublet. Once the chromaticity of the final focus was corrected, the principal aberration to be cancelled was generated by the sextupoles that were required for chromaticity correction. This was accomplished by placing additional sextupoles in the beamline, with optical transformations between sextupoles which caused the geometric aberrations of the sextupoles to cancel while the chromatic aberrations remained.

In the SLC and FFTB, each of the sextupoles in a matched pair contributed 50% of the chromaticity correction. The combined effect of the chromaticities of the sextupoles, the quads between the sextupoles, the quads between the last sextupole and the final doublet, and the doublet chromaticity caused these designs to provide correct focusing to only a narrow range of particle energies. The 1997 JLC design by Oide ameliorated this limitation by generating as much of the chromaticity correction as possible in the sextupoles closest to the IP, rather than splitting it equally among the pairs of sextupoles in a given family.

The present NLC final focus design uses an extreme form of Oide’s asymmetric solution which places the chromaticity correction sextupoles in the final doublet itself. This configuration requires a horizontal dispersion through the final doublet, which is tuned to be exactly zero at the IP. The optics of the combined NLC final focus and the upstream collimations system are shown in Figure 12.

There are three clear advantages of the new final focus optics: first, the system requires many fewer magnets and is conceptually simpler. Second, it addresses a limitation of the earlier designs where the energy loss from synchrotron radiation between the last sextupole and the IP had to be minimized to avoid causing a breakdown of the chromaticity correction. Because of this requirement the bending magnets in the conventional final foci were weak, and the systems were correspondingly long. The present NLC configuration is much shorter than previous final-focus systems: less than 0.4 km is required for 750-GeV beams as compared to 1.8 km in the NLC ZDR design and the present length of 0.7 km will handle 2500-GeV beams; the energy reach of the final focus is shown in Figure 13. Third, in the new design, off-energy particles tend to have small amplitudes in the final doublet magnet, whereas nonlinearities in the traditional final-focus systems tended to drive off-energy particles to very large amplitudes in the final doublet. The effect of the nonlinear amplitudes has not been considered in the past but the new design will simplify the beam collimation requirements significantly.

1.5.2 Collimation System

The collimation system must remove particles in the beam tails that can generate backgrounds in the detector and it must protect the final focus and detector from errant beams. As is well known, the population and distribution of the beam tails can be very hard to calculate
Figure 12: Optics of the NLC collimation and final focus systems.

Figure 13: Energy reach of the NLC final focus where $L_0$ is the luminosity without the pinch enhancement, $L$ is the nominal luminosity, and $L_s$ is the luminosity after scaling the bending magnets. By scaling the bending magnets in a manner to maintain the IP position the present system can accommodate beam energies well above 1500 GeV.
and, because the backgrounds can severely limit the luminosity recorded by the detector, the collimation system must be designed quite conservatively. Beam collimation was one of the limiting factors in the SLC operation.

The collimation system must remove all primary beam particles which could be lost near the detector. However, tighter constraints arise due to the synchrotron radiation produced by the large amplitude particles in the final doublet focusing magnets. Because of the high beam energy, the photons emitted as the beam is focused in the final doublet have energies that are too high to be able to shield the detector with masking in the IR. Ray tracing shows that to prevent any synchrotron radiation photons from hitting in the IR, the angular divergence of the beam at the IP cannot exceed a rectangular aperture of 570 µrad horizontally by 1400 µrad vertically. This restriction on the beam tails is significantly tighter than that to prevent primary particles from hitting the vacuum apertures.

Another important consideration is the muons produced by the collimators when the high energy tails are removed. Simulation studies have shown that as many as $10^9$ primary electrons or positrons per train can be removed by a collimation system located well upstream of the final focus without producing an unacceptable muon flux in the detector, although this number depends somewhat upon the exact configuration of the beamline. The number of primary particles that can be stopped within the final focus without unacceptable muon production is only $10^4$.

The most easily estimated source of beam tails in the linac is elastic scattering off the residual gas in the vacuum system; this process generates less than $10^5$ large amplitude particles per bunch train. Transverse wakefields have little effect on a beam with a gaussian longitudinal profile unless the trajectory has huge oscillations that will also lead to unacceptably large (~ 2000%) emittance dilutions. Unfortunately, the beam will not likely have a gaussian longitudinal distribution on exit from the damping rings and the bunch compressors, but it is difficult to estimate the exact form of the distribution until better estimates of the ring impedance and sources of nonlinearity in the bunch compressors are obtained. Generous estimates of these effects would still limit the number of particles in the beam tails to be less than $10^6$ per train. Other possible sources of tails are parasitic rf buckets that are populated in the bunch compressors or the damping rings. Parasitic bunches with charges as high as a few percent of the primary beam were seen in the SLC damping rings. Because of the uncertainties and the importance of limiting the backgrounds, the NLC has been designed to remove $10^9$ primary particles per bunch train which is a tail population that is 0.1% of the beam—this is the halo population that was observed during the last run of the SLC, which is thought to be a generous over-estimate of the possible load.

Because of the muon generation, the NLC collimation system is designed in four stages. First, there will be a transverse collimation section immediately after the damping rings at 1.98 GeV. This is desired because beam-gas and intrabeam scattering will generate beam tails that fill the damping ring vacuum aperture and it is pointless to accelerate all of these particles to high energy. This system has not yet been designed but is thought to be straightforward. Second, after the pre-linacs at 8 GeV, the longitudinal phase space is collimated. This system removes many of the particles in the longitudinal tails, preventing them from being deflected into the transverse phase space by wakefields during the subsequent acceleration. Next, the primary collimation system is located at the end of the main linac. This system collimates both the transverse and longitudinal phase spaces with an efficiency of ~ $10^5$—thus for $10^9$ incident tail particles, only $10^4$ will pass through the system. Finally, both the longitudinal and transverse phase spaces are collimated in the final focus itself. This is necessary to remove
particles that escape the primary collimation system as well as additional particles scattered by the residual gas downstream of the collimation section; the latter is estimated to be less than $10^3$ particles per bunch train.

All of these systems have dual purposes: they must collimate the beam tails and they form an integral part of the machine protection system (MPS). Because the particle beams have such high charge densities, a single bunch at the end of the linac or a few bunches at the linac entrance will damage almost any material unless the beam size is increased to very large values. Unfortunately, this requires an optics which is itself chromatic and can generate more halo particles. In practice, to limit the betatron functions in the collimation region, the collimation systems rely on thin spoilers (0.25-0.5 radiation length) which scrape the halo and which, if accidentally struck by the full power beam, will enlarge the spot size via multiple Coulomb scattering. The scattered halo and enlarged beam are then stopped on thick (20 radiation length) absorbers. Although the damage threshold of the spoilers is considerably higher than that of the absorbers, the design outlined above still requires an enlarged beam size at the spoiler location if the spoiler itself is to survive damage from an errant bunch train.

The betatron collimation system scrapes the beam halo and provides machine protection against infrequent orbit disruption of on-energy beams. Based on the SLC experience, very few of these events are expected to occur in each run. A lattice with relaxed tolerances has been designed that uses the concept of “consumable spoilers.” These are cylindrical spoilers or scrapers that can be rotated to present a clean surface to the beam if damaged by an errant pulse. Their circumference is such that approximately 1000 damaging pulses can be permitted before replacement is necessary. Tracking studies indicate that this system gives the 5 orders of magnitude of halo reduction required.

In contrast, the energy collimators are designed to be capable of surviving hits from a full bunch train because klystron trips causing off-energy beams may be relatively frequent events and can occur with only microseconds of warning. As seen in Figure 12, the system combines a large horizontal dispersion and a large vertical betatron function to ensure that the transverse size of beam pulses at the 0.5 radiation length spoilers is large enough that the charge density is below the damage threshold. Multiple Coulomb scattering in the spoiler further increases the beam size before the spoiled bunch train is stopped in an absorber downstream.

Because of the above difficulties, the collimation spoiler has been the subject of a substantial research program. There are three elements in the R&D program. The first is the fabrication of a prototype consumable spoiler from beryllium and copper to investigate the engineering challenge of providing accurately aligned surfaces in a piece of moving machinery that must operate under vacuum. A configuration in which each collimator jaw is a rotating wheel has been selected and a prototype has been constructed. This prototype has pointed the way to minor design modifications and demonstrated that collimation devices of this type can be incorporated reliably into any final system design.

The second element of the collimator R&D effort is a series of beam damage experiments. Samples of various materials have been exposed to single shots of 30-GeV beam of 3 and $20 \times 10^9$ electrons with rms transverse areas of $50 - 200 \mu m^2$ at the FFTTB. The samples were then inspected to help understand the resulting damage. To date, thin samples of copper, nickel, titanium, and tungsten-rhenium alloy have been tested. The tests have indicated that, for targets which are less than 1 radiation length in thickness, the damage threshold which is naively calculated is a considerable underestimate of the instantaneous heating which the
materials can tolerate. This is believed to be due to the fact that in thin targets the heated material is not fully constrained. Further tests of samples that more completely approximate an NLC spoiler are planned.

The third element of the collimation system R&D effort is a series of experiments to measure the collimator wakefields. The collimator gaps are on the order of 500 µm. Wakefield effects due to the collimator shape, resistivity or smoothness may produce enough jitter amplification to adversely impact luminosity. A movable vacuum enclosure holding four collimator samples plus a standard large-diameter round beam pipe has been installed at the SLAC linac. Two sets of measurements have been performed: a set of tapered copper collimator jaws to study the geometric wakefields of such objects and a set of graphite collimates designed and built by the TESLA collaboration. Future tests will focus on additional resistive and geometric wakefields and on the surface roughness.

Finally, a recent development in the collimation system is the use of octupole doublets which permit the beam halo in one betatron phase to be reduced in amplitude, while leaving the beam core nearly unaffected. A pair of these doublets, located in the beta match section at the beginning of the final focus, has been shown to reduce the halo in the critical final doublet betatron phase by a factor of 4, which in turn would permit equivalently larger collimator apertures in that phase. This would also dramatically decrease the impact of collimator wakefields, as the wakefields are believed to scale with the inverse square of the gap size. There are plans to verify this concept in the FFTB or the LINX test facility at the SLC final focus.

1.6 Beam Dynamics and Luminosity Performance Studies

As described in Table 3, the JLC-X/NLC injectors are designed to produce 8 GeV bunch trains with normalized emittances of 3.2 µm-rad in the horizontal and 0.022 µm-rad in the vertical. The main linac and beam delivery regions must preserve these small emittances, and must collide beams with very small transverse sizes in order to achieve the luminosity goals. The main-linac and beam-delivery system designs must ensure that the dual goals of emittance preservation and colliding of ultra-small bunches are achievable. The emittance and jitter budgets for these subsystems are listed in Table 3.

Because of the relatively strong wakefields and tight tolerances, the topics of emittance preservation and jitter control have been studied extensively in the X-band designs. To ensure the collider will attain the performance goals, generous emittance and jitter budgets have been applied and multiple redundant emittance control solutions have been incorporated into the design. Furthermore, the diagnostic and controls required to preserve the beam emittance have been explicitly designed into the facility and the required diagnostic performance has either been demonstrated or is a reasonable extrapolation from demonstrations in operating accelerators or test facilities. The performance of the systems has been studied extensively using simulation tools that were benchmarked with the SLC.

When discussing the luminosity performance, it is also important to separate the timescales. There are three regimes which are determined by the ability to feedback on the trajectory motion: beam jitter, which occurs at high frequencies \( f \gtrsim \text{few Hz} \) where the feedback systems have little impact and thus the beam overlap at the IP is degraded; emittance control, which occurs at low frequencies \( f \lesssim 0.01 \text{ Hz} \) where the trajectory errors increase the beam emittance and thereby the spot size at the IP; and the intermediate regime. Fortunately, the intermediate regime is not important in the JLC-X/NLC because the motion tends to be
well correlated and beam-based feedbacks can easily damp any residual. The tolerances in these two regimes typically differ by two to three orders of magnitude. Furthermore, while the horizontal and vertical beam sizes at the IP are both quite small, the large IP aspect and emittance ratios (both approximately 100:1) imply that the challenges in the vertical plane will be 1 to 2 orders of magnitude more difficult than those in the horizontal.

An example of the vertical tolerances in the final focus can be seen in Figure 14 where the emittance control tolerances correspond to the ‘drift’ tolerances. Without emittance correction and beam-based alignment techniques, the typical beam-to-quad random alignment tolerance throughout the JLC-X/NLC is between 1 µm and 10 µm, and the typical quadrupole random jitter tolerance is between 1 nm and 10 nm. These tolerances are very tight by the standards of today’s accelerators, however, when discussing tolerances, it is also important to consider the correlation of the motion and the response of the optics. In general, the beam is very insensitive to misalignments with wavelengths long compared to the betatron wavelength—this is ∼ 100 meters in the main linacs and beam delivery system. As an example, the luminosity impact of aligning the linear collider to follow the earth’s curvature is minimal although this implies a ‘misalignment’ of roughly 10 meters at the IP. Fortunately, the micro-seismic ground motion tends to be highly correlated at low frequencies where its amplitude is large and tends to have small amplitudes at high frequencies where the correlation length is short. Similarly, both beam and mechanical alignment techniques tend to have good resolution over relatively short distances and much poorer accuracy over longer baselines.

In the following, we will first discuss the diagnostics and controls that are essential to the emittance preservation. Then, we will discuss the sources of beam jitter and, finally, we will cover the beam emittance control that is necessary for the luminosity.
Table 12: Requirements for JLC-X/NLC diagnostic and correction devices, compared with achieved capabilities of existing equipment.

<table>
<thead>
<tr>
<th>Item</th>
<th>Specification</th>
<th>Achieved</th>
<th>Improvement Needed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quadrupole BPMs</td>
<td>0.3 µm resolution</td>
<td>1 µm resolution (FFTB striplines)</td>
<td>3×</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.025 µm resolution (FFTB cavities)</td>
<td>None</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.23 µm resolution (NLC prototype cavity)</td>
<td>None</td>
</tr>
<tr>
<td>RF structure BPMs</td>
<td>5.0 µm resolution</td>
<td>2 µm resolution</td>
<td>None</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(DDS3 and RDDS1 structure prototypes)</td>
<td></td>
</tr>
<tr>
<td>Magnet Movers</td>
<td>0.05 µm step size</td>
<td>0.3 µm step size (FFTB magnet movers)</td>
<td>6×</td>
</tr>
<tr>
<td>RF Girder Movers</td>
<td>1 µm step size</td>
<td>0.3 µm step size (FFTB magnet movers)</td>
<td>None</td>
</tr>
<tr>
<td>Laser Profile Monitor</td>
<td>1 µm rms beam size</td>
<td>1 µm rms beam size (SLC laser wire)</td>
<td>None</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.06 µm rms beam size (FFTB laser interferometer profile monitor)</td>
<td>None</td>
</tr>
<tr>
<td>Magnet/Girder Supports</td>
<td>&lt; 3 nm vibration w.r.t. tunnel floor</td>
<td>~ 2 nm vibration w.r.t. tunnel floor (FFTB quadrupole supports)</td>
<td>None</td>
</tr>
</tbody>
</table>

1.6.1 Diagnostics and Controls

The JLC-X/NLC alignment tolerances can only be achieved through the use of beam-based diagnostics and corrections. For this reason, all subsystems in the accelerator have been designed to permit the use of beam-based techniques to measure the misalignments, and precision remotely controlled translation stages to position misaligned magnets. Use of beam-based techniques allows a tremendous improvement in the alignment precision over conventional survey methods. In the FFTB, for example, magnet alignment of 50 µm was achieved by mechanical survey, but beam-based alignment achieved resolutions as small as 1 µm; independent techniques have been used to set an upper bound on the quadrupole misalignments of 7 µm. These beam-based techniques are only possible with adequate diagnostic and control equipment. The diagnostic and correction devices needed to meet these tolerances are shown in Table 12. In general, the required capabilities are at most an incremental improvement upon existing hardware.

In addition to the devices listed in Table 12, the JLC-X/NLC will require a set of tuning algorithms that will convert the measurements of the diagnostics into new settings of the correction elements. Here again, the design will rely upon widely-used and well-understood techniques in accelerator physics: quadrupole shunting, which has achieved beam-to-quad resolutions as small as 1 µm in the FFTB; dispersion-free steering (DFS), which enabled both SLC and LEP to achieve record luminosities; and closed orbit bumps for global emittance tuning, which have been used routinely in the SLAC linac for many years. Because the JLC-X/NLC builds on the demonstrated success of existing colliders and test facilities, it is
expected that modest advances in a few areas of the technology are all that will be required
to achieve the performance goals.

1.6.2 Beam Jitter and Vibration

Beam jitter will arise from the motion of the quadrupole magnets along the beamline. This
relatively high frequency motion of the beam has two effects: first, it causes the beams to be
offset at the IP, directly reducing the luminosity, and, second, it degrades the performance
of the beam position and beam size diagnostics. The direct impact of the beam jitter on
the luminosity is straightforward to evaluate and is not the largest concern. Instead, the
beam jitter will reduce the effectiveness of the beam-based alignment and tuning techniques
without which it will not be possible to attain reasonable luminosity.

The motion of the magnets will be driven by natural ground motion, vibrations caused
by accelerator equipment such as pumps and cooling water, and other human-made “cultural
noise.” Other phenomena, such as the tendency of mechanical supports to amplify vibrations
in some frequency band, can also make the problem significantly more difficult. The natural
characteristics of the micro-seismic ground motion are that low-frequency motion, which
typically accounts for hundreds of nanometers of rms motion, is highly coherent, while high-
frequency motion, which is nearly incoherent, accounts for only a few nanometers of motion.
Figure 15 shows a series of measurements of the power spectrum of micro-seismic motion,
which have been taken at various sites around the world. Included are measurements taken
in the SLAC tunnel at 2 AM during a period when the beam and rf structures were off but
cooling water was flowing normally, data taken in the LEP, HERA and UNK tunnels, and
data taken in the Hiidenvesi cave in Finland. All of the measurements indicate that the power
density of natural micro-seismic motion is a strong function of frequency, with a characteristic
$1/\omega^4$ dependence. Although high frequencies are potentially the most deleterious from the
point of view of beam-beam jitter, Figure 15 shows that natural ground motion contains
very little power in frequencies above 1 Hz while the large amplitude peak at 0.15 Hz has a
wavelength of $\sim$10 km. The JLC-X/NLC beam-beam jitter sensitivity favors a deep tunnel in
relatively strong material at a location with minimal cultural noise, but these characteristics
can be traded off against each other. A shallow tunnel site at a relatively deserted location
can have noise characteristics comparable to a deep tunnel in a populated area. The most
important lesson to be learned from the power spectral density measurements is that not all
sites are equally viable for the JLC-X/NLC.

In order to minimize the ‘cultural’ noise from the accelerator equipment vibrations and
the impact of magnet supports, it will be necessary to subject every piece of hardware in
the accelerator complex to carefully developed engineering criteria, in essence to establish
a “vibration budget” for the equipment similar to the “impedance budget” of modern-day
storage ring vacuum system. While achieving the vibration goals will require appropriate
planning and design, as a proof-of-principle, magnets on the FFTB magnet supports were
measured to have motions that were only 2 nm larger than that of the underlying ground.
Comparable measurements have been made on NLC prototype quadrupoles which were also
attached to rf structures. Other sources of cultural noise, for example the use of motor vehicles
on site, will be addressed through appropriate selection of a site and of a tunnel depth. The
LEP tunnel measurements in Figure 15 show that even a tunnel in a suburban area can
be made relatively free of cultural noise sources. Thus, while many sources of accelerator
component misalignment can be minimized or eliminated through engineering, the natural
Figure 15: Power spectrum of ground motion, in units of $\mu m^2/Hz$, from several accelerator tunnels and a cave. The strong peak at 0.15 Hz in all spectra is from ocean waves. The shoulder at 4 Hz in the HERA data is most likely due to “cultural noise,” vibration sources within the accelerator complex and from the surrounding urban area.

ground motion of the site is a potential source of misalignments that is not itself amenable to direct engineering.

When the influences of beam-based steering feedback, lattice response, and correlated motion are considered, it can be shown that quadrupole motion at frequencies below approximately 1 Hz will generally not contribute significantly to beam-beam jitter at the IP. For most of the quadrupoles in the JLC-X/NLC, considered as an ensemble, uncorrelated rms motion of 10 nm in the frequency range above 1 Hz will be acceptable. For example, Figure 14 shows that, with the exception of the final doublet, typical jitter tolerances in the final focus are on the order of 10 nm for incoherent motion of the magnets while the sensitivity of the luminosity to correlated motion is much smaller. If the SLAC integrated ground motion and the FFTB quadrupole supports are used as a basis, the rms quadrupole motion will be less than 4 nm in this frequency range. Thus, for a reasonable choice of site and magnet support technology, it will be possible to provide stability for most of the quadrupole magnets in an entirely passive manner.

In contrast, the jitter tolerances of the final doublet quadrupoles, QD0 and QF1, are roughly an order of magnitude tighter than those in the rest of the final focus. The final doublet quads are the only ones in the JLC-X/NLC that cannot meet their tolerances through passive stabilization alone. However, because the final doublets contain a small number of elements in a reasonably compact space, it is possible to contemplate solutions to the doublet motion problem that are too complex to be applied to a larger number of elements. Thus, jitter suppression for these magnets must include a combination of passive and active methods. Passive methods include locating the IR hall sufficiently far from cultural sources
of vibration, minimizing potential vibration sources that can be controlled through proper engineering, and engineering to ensure that the detector, magnet technology, and doublet support girders are stable and do not amplify motion. Active vibration suppression techniques are based on feedback systems to control piezoelectric movers or other fast translation-stage technology which would allow constant position adjustment of the magnets at frequencies far above the beam repetition rate. Two different technologies for measuring the motion of the magnets with high resolution over a wide frequency band are under consideration: an optical anchor, which measures the positions of the final doublet magnets with respect to a fixed point on the detector floor; and inertial sensors which can measure the accelerations of the magnets directly. Both technologies would allow the additional vibrations of the detector to be suppressed, and would allow one doublet to be held fixed in position with respect to the other.

The measures described above are expected to limit luminosity loss from beam-beam jitter to a few percent, which is acceptable. An additional measure, which can potentially provide further reduction, is a feedback at the interaction point that operates within a single bunch train. An intra-train collision feedback would use the beam-beam deflection to estimate the relative offset of the two bunch trains from the measured deflections of the first few bunches and would then be used to steer subsequent bunches back into collision. Such a feedback has been studied for the TESLA bunch train. The JLC-X/NLC implementation for such a feedback is made more complicated by the fact that both the bunch train and the intra-bunch spacing are much shorter than in TESLA. Nonetheless, a design of the system using available components has been developed and the system will be tested in the NLCTA.

1.6.3 Beam Emittance Control

The beam emittance dilutions primarily arise from misalignments of the beamline components. The BNS damping mechanism, a technique proven at the SLC, suppresses the Beam BreakUp instability (BBU) and eliminates emittance dilution from coherent (betatron) oscillations of the beam but requires a large energy spread of 0.7-1% which will make the beam more sensitive to incoherent misalignments of the quadrupole magnets. Similarly, incoherent rf-structure misalignments will lead to emittance dilution from short-range dipole wakefields, and construction errors in the structures can introduce substantial multibunch emittance dilution. The most serious sources of emittance dilution are single-bunch effects due to misaligned magnets and rf structures. As discussed, the relevant scale in this case is about 1000 times larger than that for beam jitter and is microns. These misalignments are due to slow motion $0.01 \text{ Hz} \lesssim f \lesssim \text{d.c.}$ and are referred to as static misalignments.

The alignment requirements are beyond what can be achieved by conventional survey techniques. Fortunately, it is possible to use beam-based alignment algorithms to achieve the most challenging tolerances in the main linac. Figure 16 shows the beamline hardware associated with beam-based alignment: remotely controlled translation stages for quadrupoles and rf girders, and high resolution BPMs in the quads and the rf structures. The equipment and instrumentation builds on the successful prototypes demonstrated at the FFTB and in ASSET as discussed in Section 1.6.1.

There are several sources of multibunch emittance dilution in the main linac which cause the various bunches in a given bunch train to follow different trajectories down the beamline. Provided the BBU due to the long-range wakefield is kept small by the combination of detuning and damping, the jitter amplification will be negligible. In this case, the rf structure
defects will generate a set of bunch-by-bunch deflections. The tolerances on the structure alignment to limit the multibunch dilutions are loose compared to those imposed by the single bunch effects; tolerances for 10% emittance dilution are shown in Figure 17. In addition, the multibunch dilutions will be nearly constant in time, and, as a result, they will be amenable to a feedback that corrects bunch positions within a train. Such a feedback is simultaneously fast (i.e., its BPMs and correctors have a bandwidth of several-hundred MHz) and slow (i.e., the system applies nearly the same set of corrections to each train). The linac design includes several sub-train feedback systems that utilize high-bandwidth BPMs and stripline kickers similar in many ways to the high-bandwidth transverse feedbacks of modern storage rings. Analytic estimates indicate that such systems can reduce the emittance dilution from multibunch sources by roughly a factor of 10, limited by the system bandwidth and the signal-to-noise performance of the BPMs.

Given that the emittance dilution is dominated by the single bunch effects, the primary issue is to attain and maintain the alignment of the quadrupoles and the rf girders. The procedure to be used to do this is summarized below.

1. Determine the “gold orbit” of the linac. This is the set of quadrupole BPM readings that corresponds to high luminosity. In the absence of BPM-to-quad offsets, the gold orbit would simply be zero on all BPMs.

2. Move the quadrupole magnets using the magnet movers until the gold orbit is achieved and then move the rf girders using the rf structure BPMs to align these to the beam trajectory.

3. Use a set of discrete steering feedback loops in the main linac to minimize the orbit drift due to component motion as a function of time. The steering feedback can operate quickly (at the level of 1 Hz or faster), and is entirely compatible with colliding for luminosity.

4. As diffusive ground motion moves the accelerator components, the luminosity will gradually decline. This is because the misalignments between the feedback correctors will become sufficiently large that the feedback can no longer maintain a reasonable approximation of the gold orbit. At this time, recover the gold orbit by returning to Step 2. This procedure should be compatible with colliding for luminosity if the magnet mover step sizes are small and the steering feedback loops are operating.
Alignment Length [Structure Length]

Tolerance for 10\% \Delta \varepsilon / \varepsilon

\begin{align*}
\text{Alignment Length [Structure Length]} & \\
\text{Tolerance for 10\% \Delta \varepsilon / \varepsilon} & \\
0.5 & 1 & 1.5 & 2 & 2.5 & 3 & 5 & 10 & 50 & 100 & 500 & 1000
\end{align*}

Figure 17: Misalignment amplitude leading to 10\% \Delta \varepsilon / \varepsilon as a function of the accelerator structure length (90 cm) for the long-range (solid) and short-range transverse wakefields. An alignment length of one structure corresponds to random rigid misalignments of individual structures while lengths of less than one structure correspond to random piecewise misalignments of the structures. With the S-BPM and structure mover system, the JLC-X/NLC essentially eliminates the short-range wakefield tolerances.

5. Over even longer time scales, the gold orbit will gradually cease to provide good luminosity. This is because the electrical centers of the Q-BPMs, the magnetic centers of the quadrupoles, and other parameters are subject to change over time. Once this has happened, return to step 1 and determine a new gold orbit using invasive procedures.

Determining the gold orbit is a crucial step in the algorithm as the quality of the gold orbit will determine the maximum luminosity performance of the collider. Ideally, the BPM-to-quad offsets can all be measured by the beam with sufficient accuracy by varying the focusing strength of each quadrupole and measuring the resulting deflection of the beam on downstream BPMs. This allows determination of the beam-to-quad offset, and the quad-to-BPM offset of the nearest BPM can then be deduced by subtraction. This procedure was demonstrated at the FFTB. For the main linac, a resolution of 1 \mu m would be straightforward to achieve for each quad, if the technique were not limited by systematic errors. The primary systematic error arises if the quadrupole center moves as the quadrupole strength is varied. Measurements of the quadrupole center motion, implies that electromagnetic quadrupoles could be aligned at the tolerance level of 2 \mu m while the alignment would be roughly 10 times worse with permanent magnets; permanent magnets have been considered for the main linac due to reliability and cost considerations.

Because the accurate determination of the BPM offsets will still provide the most local (hence most stable) correction of the emittance, the quad-varying technique remains the method of choice for determining the gold orbit. However, because of the sensitivity to quad-center variation, this technique may not be adequate by itself. An alternative technique for generating a gold orbit is Dispersion Free Steering (DFS), in which the dispersion is measured by varying the energy of the beam or beamline and measuring the change in the trajectory.
This technique is less local than varying a single quadrupole at a time and measuring the resulting deflection, but it directly measures the dispersion. Furthermore, DFS relies only upon the BPM resolution to achieve an acceptable trajectory, and the BPMs will have a resolution that is much better than the knowledge of the BPM-to-quad offset under almost any imaginable circumstances. The emittance dilution after convergence is 20% with a 0.3 \( \mu m \) BPM resolution.

Additional improvement to the emittance can be achieved by applying closed-orbit bumps over a small region of the linac. These bumps generate dispersion or wakefields at a particular phase and in a particular location, which can cancel any existing dispersion at that phase and location. A simulation has been performed in which a set of dispersion bumps was applied to the main linac after DF steering. In the case where 0.3 \( \mu m \) BPM resolution was assumed for DFS, the final DFS + bumps emittance dilution is 5%.

As suggested in Step 5, the emittance obtained by repeatedly steering to the gold orbit in Step 2 will increase, as the BPM-to-quad offsets change with the passage of time. Once this has happened, it is necessary to repeat the procedure that was used to determine the gold orbit in the first place. The length of time between determinations of the gold orbit is difficult to estimate. Unfortunately, determining the gold orbit can be invasive and incompatible with colliding for luminosity. Measurements of the BPM centers in the FFTB stripline BPMs suggest that the gold orbit will not have to be re-measured more often than once a month and aggressive use of emittance bumps can further extend the life of a gold orbit.

As discussed in Step 3, another important technique for maintaining the luminosity is the use of steering feedback loops which stabilize the beam trajectory at frequencies up to \( \sim 1 \) Hz. The main linac will use several discrete sets of fast, weak dipole correctors to provide steering feedback at 5 to 10 locations within the beamline. The main linac feedback provides partial reduction of the emittance dilution arising from diffusive ground motion. Figure 18 shows the emittance as a function of time at the end of the main linac due to ATL motion, assuming a coefficient \( A \) of \( 5 \times 10^{-7} \) \( \mu m^2/m/s \), both with and without steering feedback in the main linac. Without feedback, the emittance dilution in the main linac would become unacceptable within minutes, while the addition of steering feedback preserves the emittance for hours. After this time period, it is necessary to recover the gold orbit throughout the linac.
by moving all of the quadrupoles on their magnet movers. The steering feedbacks also reduce
the luminosity dilution that happens while the quadrupoles are being moved. Figure 18
suggests that the time-averaged luminosity loss from the slow completion of mover steering
will be on the order of 2%.

Finally, Table 13 shows a tentative distribution of the main linac emittance budget
amongst the various sources of dilution. Since the studies were performed with the 1 TeV c.m.
configuration of the JLC-X/NLC, the lower-energy configurations, which have fewer rf structures
and thus less challenging beam dynamics, should be substantially more tolerant. In
addition, Table 13 assumes that DFS + bumps must be used for generation of a gold orbit,
and that only a 1.0 \( \mu \)m effective BPM resolution is achieved which is 3 times worse than the
design specification.

Table 13: Distribution of the main linac emittance budget and resulting engineering toler-
arances. Dilutions are applied to the vertical plane except where indicated. Beam-to-quad
misalignment is an “effective misalignment” assuming DFS + bumps with 1.0 \( \mu \)m effective
BPM resolution. Multibunch sources assume factor of 10 suppression via sub-train feed-
back. Note that the tolerance on structure dipole frequencies is for the worst-case error mode
(random cell-by-cell frequency errors which are reproduced in every structure), and all other
distributions of frequency errors have considerably looser tolerances.

<table>
<thead>
<tr>
<th>Effect</th>
<th>Tolerance (effective)</th>
<th>Resulting Emittance Dilution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam-to-quad Misalignments</td>
<td>2.0 ( \mu )m</td>
<td>25%</td>
</tr>
<tr>
<td>Quad Strength Errors</td>
<td>0.1%</td>
<td>0.7% (x) / 0.5% (y)</td>
</tr>
<tr>
<td>Structure-to-girder Misalignments</td>
<td>30 ( \mu )m</td>
<td>8%</td>
</tr>
<tr>
<td>Structure-to-girder Tilts</td>
<td>30 mrad</td>
<td>4%</td>
</tr>
<tr>
<td>Quadrupole Rotations</td>
<td>200 mrad</td>
<td>4%</td>
</tr>
<tr>
<td>Structure BPM Resolution</td>
<td>5 ( \mu )m</td>
<td>3%</td>
</tr>
<tr>
<td>Mover Steering Interval</td>
<td>30 minutes</td>
<td>2%</td>
</tr>
<tr>
<td>Structure Straightness (bow)</td>
<td>50 ( \mu )m</td>
<td>1% (incl. feedback)</td>
</tr>
<tr>
<td>Cell-to-cell Misalignments</td>
<td>3.5 ( \mu )m</td>
<td>1% (incl. feedback)</td>
</tr>
<tr>
<td>Structure Dipole Frequencies</td>
<td>1 MHz</td>
<td>1%</td>
</tr>
<tr>
<td>Synchrotron Radiation</td>
<td></td>
<td>3% (x)</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td>3.7% (x) / 50% (y)</td>
</tr>
</tbody>
</table>

The procedure described above works well for the main linac. However, the beam dynam-
ics in the final focus can be different from that in the main linac. The number of quadrupoles
and the rms beam energy spread are both quite small, so phase mixing in the final focus is
not a serious problem. This in turn implies that global knobs of various kinds will be more
effective than in the linac. The final focus also contains horizontal bend magnets, so it is
possible to adjust the dispersion with normal or skew quads at high-dispersion points rather
than by varying the beam trajectory, as is done in the linac. On the other hand, the final fo-
cus contains many strong aberrations, such as chromaticity, sextupoles, and skew quadrupole
effects, which typically are delicately balanced against one another. Therefore, the BDS has
looser tolerances on the conditions that must be met before global corrections are applied
than the main linac has, but the tolerances on stability over time are much tighter than in
the main linac.

Of course, the final focus of the JLC-X/NLC, like the main linacs, is designed with power-
ful diagnostic capabilities and robust correction devices. Every quadrupole and sextupole is on a remotely controlled magnet mover, similar to those in the main linac. Each quadrupole is paired with a BPM with submicron resolution, and in some critical locations ultra-high resolution cavity BPMs with resolutions better than 100 nm are also used. Laser-based beam-size monitors are installed at critical locations. All sextupoles, bends, and quads except for the final doublet are iron-dominated electromagnets, with high-precision power supplies. In addition, the final focus has two powerful diagnostics not available at other locations, the luminosity and the beam-beam deflection, each of which will be measured on every pulse in order to provide signals for feedback systems.

The tolerances for the final focus components are shown in Figure 14. Although these are small, it is important to note that these are so-called “bare” tolerances—tolerances in the absence of feedback systems or other non-invasive correction algorithms which can stabilize accelerator performance. Understanding the real performance of the final focus requires simulation studies that include the planned diagnostic and correction systems, and their algorithms. As an example, one of the most serious potential sources of emittance dilution is beamline magnet misalignments driven by diffusive ground motion. Figure 19 is the result of a simulation that misaligns the elements of the 1-TeV BDS configuration according to the ATL law with $A = 5 \times 10^{-7} \, \mu m^2/m/s$. The curves show that luminosity would degrade under ATL motion in approximately 2 minutes if only the beam-beam deflection collision stabilization feedback was present. If, in addition, orbit control feedback is allowed to steer the beam through the centers of critical quadrupole and sextupole magnets, the time for luminosity degradation increases to approximately 1 day. Finally, if direct optimization of the main aberrations via global knobs is added to the system, the luminosity lifetime increases to several months, after which a disruptive realignment procedure would be required.

Figure 19: Degradation of alignment under ATL ground motion with IP beam-beam deflection based feedback only, with orbit feedback added, and with direct luminosity optimization added.
2 JLC-X/NLC Energy Upgrades

As described in the Overview (Section 1), the JLC-X/NLC linear collider has been designed to facilitate the upgrade to energies greater than 1 TeV. The baseline upgrade is accomplished by installing additional rf modules into the second half of the linac tunnel which is empty in the initial Stage I (500 GeV) configuration. The upgrade could either be completed using modules of the baseline rf system, identical to those for 500 GeV, or it could use higher efficiency rf units which will likely be developed over the next few years. To ensure the feasibility of the upgrade, all of the luminosity studies have been performed for the Stage II (1 TeV) configuration and the component tolerances have been specified for the Stage II design. In particular, the beam properties for the Stage II operation are identical to those for Stage I. Thus, no modification of the injector system is required and only the permanent magnet final doublet needs to be replaced in the beam delivery system. The expected cost for the full energy upgrade is roughly 25% of the initial total project cost (TPC).

The Stage II parameters can be found in Table 1 of the JLC-X/NLC Overview. As in Stage I, the beams consist of bunch trains with 192 bunches separated by 1.4 ns. The repetition rate would be decreased to 100 Hz in Japan and would remain at 120 Hz in the US. Although not listed, the collider is also designed to operate with 96 bunches of $1.5 \times 10^{10}$ particles and a 2.8 ns bunch spacing—this latter option provides higher luminosity but also more beamstrahlung and emittance dilution. The luminosity would be $2.5 \times 10^{34} \text{ cm}^{-2} \text{s}^{-1}$ ($3.0 \times 10^{34} \text{ cm}^{-2} \text{s}^{-1}$) in Japan (US) at the nominal center-of-mass energy of 1 TeV.

The energy reach of Stage II is roughly 1.3 TeV without modification of the rf system. This is possible because the JLC-X/NLC traveling-wave accelerator structures are tested to a full unloaded gradient of 65 MV/m; this differs from the testing of the standing-wave superconducting structures which are only tested to the maximum loaded gradient of 23 to 35 MV/m. The luminosity versus energy for the Stage II JLC-X/NLC is plotted in Figure 20. Thus, as discussed in the Overview, the JLC-X/NLC linear collider is designed to fully cover the energy region between 90 GeV and 1.3 TeV.

To accommodate the physics demands for energy flexibility, the design includes two in-
teraction regions. One is optimized for high energy, 250 GeV to 1.3 TeV, and is configured so that it is ultimately upgradeable to multi-TeV. This final focus can actually accommodate beams of up to 2.5 TeV in the length of about 800 m. The other interaction region is designed for precision measurements at lower energy, 90–500 GeV, although it could be upgraded to operate at ∼1 TeV as well.

To capitalize on the multi-TeV potential of the new design, it was also necessary to eliminate other bending between the linac and the high energy IP. In the NLC design, a 20 mrad crossing angle at the IP is used to avoid parasitic interactions of one bunch with the later bunches in the opposing train and to ease the extraction line design. The linacs are not collinear but are oriented with a shallow 20 mrad angle between them to produce the desired crossing angle at the high-energy IR without additional bending. The beams to the second IR are bent by about 25 mrad, which is acceptable for energies up to 1 TeV. The low-energy IR has a larger 30 mrad crossing angle for compatibility with a possible γ/γ option. Finally, in the JLC design, the primary IP has a crossing angle of 7 or 8 mrad and the non-collinear linac layout has not been planned. However, the crossing angle of the second IP is 30 mrad as in the NLC design.

As stated, the luminosity listed for the Stage II design is based on the same injector and beam delivery system as for Stage I. Of course, it will likely prove possible to further increase the luminosity by upgrading the performance of the injector systems to decrease the extracted vertical beam emittance. It is expected that the emittance transport through the linacs will perform better than required as described in Section 1.6. In this case, the primary limitations will be stabilization of the pulse-to-pulse jitter due to the high disruption parameter which will start to approach the values in the TESLA design. An estimate of the ultimate luminosity from the collider can be found in Table 4 of the JLC-X/NLC Overview.

Finally, ongoing R&D at KEK, SLAC, FNAL, and LLNL is aimed at improving the efficiency of the rf units. The three places where significant improvements might be expected are the modulator, the klystron, and the pulse compression system which have design efficiencies of 80, 55, and 75%, respectively, in the baseline design. Working in collaboration with the IGBT manufacturers, the modulator efficiency might be increased to 85% by improving the rise and falls times of the IGBTs. Similarly, simulations have indicated that ∼65% efficiency for the klystrons may be possible either with improved single beam PPM klystron designs or by developing a sheet beam or multibeam klystron; the sheet beam concept is being pursued at SLAC while the multibeam klystron design is being studied at KEK. Lastly, the biggest improvement might come from improvements to the pulse compression system. The SLED-II baseline system has an efficiency of roughly 75%. An optimized Delay Line Distribution System (DLDS) or Binary Pulse Compression system (BPC) might have efficiencies of ∼90%. Work investigating the viability of a four times single-moded DLDS compression system will begin at SLAC and KEK after the demonstration of the SLED-II compression system. If found viable, this DLDS system could simply replace the SLED-II without changes to the other rf system components.

Similarly, ongoing R&D at many laboratories, including SLAC, KEK, and CERN, is aimed at higher acceleration gradients. The maximum gradient that can be supported in copper accelerator structures is not clearly known. With the development of a new coupler design, a recent X-band test structure has operated at 90 MV/m with a breakdown rate of less than 1 per 24 h—the maximum allowable rate for JLC-X/NLC operation being 1 per 10 h. Additional design modifications might support still higher gradients. In addition, R&D at CERN and SLAC studying different materials has shown that as much as a 50% increase
in the gradient may be possible by using Tungsten, Molybdenum, or Stainless Steel in the accelerator structure irises.

If structures that support ~100 MV/m can be developed over the next decade, the upgrade to Stage II could have an energy reach well in excess of 1.5 TeV and approaching 2 TeV. Looking further into the future, as described in the Overview, the JLC-X/NLC facility has been configured to simplify the evolution to a multi-TeV collider with c.m. energies of roughly 3-5 TeV. It is likely that much of the infrastructure could be reused and the injectors and beam delivery systems would need relatively straightforward upgrades. Only the main linac structures and rf sources would need to be replaced. Furthermore, and perhaps more importantly, the knowledge gained from operating a normal conducting linear collider would be indispensable for the design and construction of a multi-TeV linear collider.

3 JLC-X/NLC Test Facilities

The primary rf R&D program is centered around the NLC Test Accelerator with the accelerator structure development and the SLED-II demonstration. However, the JLC-X/NLC incorporates a very broad R&D program on luminosity related issues as well. These include the ATF prototype damping ring at KEK, the ASSET and Collimator Wakefield Test facilities at SLAC, and the Stabilization Demonstrations. In addition, the largest linear collider test facility that has been constructed was the Stanford Linear Collider (SLC). This facility was built with the dual purpose of demonstrating the feasibility of a linear collider while studying the $Z^0$ boson.

The SLC contained all of the same subsystems that exist in the next-generation linear colliders: a positron source, a polarized electron source, damping rings, bunch compressors, a main linac, a beam collimation system, and final foci with beam extraction lines. In addition, as will be needed in a future collider, the SLC contained extensive emittance diagnostics and many beam feedback loops that automated much of the required beam tuning. A schematic is shown in Figure 21.

The SLC was proposed in 1980 and construction started in 1983 with commissioning beginning in 1987. After two difficult years of commissioning, the first $Z^0$ was seen at the IP in 1989. A steady stream of improvements were made to the collider over the following decade including: over 50 beam size (wire) monitors to diagnose the sources of emittance dilution, beam collimators and muon spoilers to reduce backgrounds in the detector, new damping ring vacuum chambers to improve the extracted beam stability, and constant replacements of hardware that was not sufficiently reliable or stable. In addition, many new techniques were developed including: BNS damping to control the Beam BreakUp instability, new beam steering methods such as Two-Beam Dispersion Free Steering, and beam-beam deflection scans and dither feedbacks to tune the beam delivery system. In the end, the collider was operating near its design luminosity but in a parameter regime very different from that initially conceived; a plot of the beam sizes at the IP is shown in Figure 22. The success of the SLC is a true credit to the creativity and dedication of the large number of people who worked on it, as well as the inventiveness and audacity of its progenitors. It is also worth noting that, although the difficulties encountered when commissioning the SLC were much larger than anticipated, the single best measurement of $\sin^2\theta_W$ was still made at this facility.

Many of the detailed experiences from the SLC are either not applicable or have already been incorporated into the next-generation designs. However, it should be noted that the
tolerances in the SLC were *looser* than in *any* of the current linear collider proposals and the difficulties of these future colliders should not be minimized. In particular, there are still a number of more global ‘lessons’ that are important to remember. First, a linear collider lacks the inherent stability of the storage ring—every rf pulse differs from the previous, making hardware and beam stability, especially from the sources and the damping rings, essential. Next, reliable hardware is mandatory as demonstrated by the experience with the SLC, and more recently with the Tevatron and HERA. If the hardware interruptions are too frequent, the collider is not up long enough to make effective progress on the luminosity. It was only after the SLC achieved reasonable reliability that the many beam tuning challenges for a linear collider could be addressed. Third, noninvasive diagnostics are needed often to determine hardware problems as well as beam physics issues. Of course, BPM’s are placed throughout in all designs but the 50+ beam size monitors in the SLC allowed rapid localization and diagnosis of subtle hardware problems that would have been hard to trace otherwise. Finally, simulations do not accurately represent the true difficulty of operating the beams and tuning the luminosity. It is important to allow for multiple backup tuning solutions as well as parameter flexibility because the biggest difficulties that will likely be encountered are those that are not yet considered or simulated.

Beyond the SLC, many additional test facilities have been created at KEK and SLAC to specifically validate the X-band linear collider design. These include: the NLC Test Accelerator (NLCTA), which is an rf systems test; the Final Focus Test Beam (FFTB), which studied the issue of focusing the beam to the very small spot sizes needed to attain the desired luminosity; the Accelerator Test Facility, which is a prototype damping ring for a normal-conducting linear collider; the Accelerator Structure SETup (ASSET), which is used to directly measure the long-range transverse wakefields; the Collimator Wakefield Test, which is used to measure the short-range wakefields from beam collimator-like devices; and the Stabilization Demonstrations, which have quantified the expected stability, have stabilized a 100 kg block, and will demonstrate the required stabilization in an IR-like environment.

It should be noted that most of these facilities are dedicated to studying issues related to luminosity—only the NLCTA is devoted to the rf system goals. Although the rf system is the most visible of the technological components required for a linear collider, it is also relatively straightforward to validate. A small systems test of 0.1 to 1% of the rf system is all that is really needed. In contrast, validating the damping ring concepts, the particle sources, the emittance preservation, or the beam delivery system could be a much more daunting task. Fortunately, the normal-conducting designs allow the linear collider subsystems to be based on other operating accelerators or accelerator subsystems as well as making use of the essential experience from the SLC. In particular, the polarized electron source and the positron production system are modest extensions of the SLC sources. The damping rings are similar to third-generation synchrotron light sources and are required to produce an equilibrium emittance that is only a factor of two below what has been achieved at the Advanced Light Source (ALS) in Berkeley or the ATF at KEK. The bunch compressor is based on experience from the SLC bunch compressor and is similar to, although not as difficult, as the bunch compressors for the new SASE-based short wavelength FEL drivers. Much of the emittance preservation techniques and the final focus systems were demonstrated at the SLC and the Final Focus Test Beam (FFTB).
Figure 21: Schematic of the Stanford Linear Collider.

Figure 22: Spot sizes and cross-sectional area at the SLC IP as a function of time from 1990 through 1998; the design spot sizes were 1.7 \( \mu m \) by 1.7 \( \mu m \).
3.1 NLC Test Accelerator

The Next Linear Collider Test Accelerator (NLCTA) has been a testing ground for the X-band rf system components and has demonstrated the viability of an early version of the NLC rf system. The facility was proposed in the early 1990s to provide system integration testing of the NLC X-band rf components being developed at SLAC and KEK while these systems were still in an early stage of development. The design philosophy was to make it large enough to yield meaningful operating statistics, and to make it capable of accelerating an NLC-like beam to verify performance, especially in regard to the beam loading compensation. The system was rapidly commissioned and in 1997 accelerated beam to 350 MeV while demonstrating the desired beam loading compensation. The system was upgraded in 1999 to deliver twice the rf power to structures to be able to generate higher acceleration gradients, and the rf control system was upgraded to allow around-the-clock unmanned operation.

The rf system design of the NLCTA is similar to that proposed in the 1996 NLC ZDR. The initial implementation of the NLCTA contained four rf stations (including the injector), each of which consisted of a modulator powering a single 50 MW klystron which drove a SLED-II pulse compression system. The SLED-II pulse compression systems compressed the 1.5 µs klystron pulses by a factor of six in time and gained a factor of four in peak power. The resulting 200 MW, 240 ns pulses in the NLCTA powered two 1.8 m long X-band accelerator structures (100 ns fill time) to produce ∼ 50 MV/m unloaded gradients.

A schematic of the NLC Test Accelerator is shown in Figure 23. The fourth rf station shown in the figure was later eliminated from the plan. The first rf station is used to power the injector, which was designed to generate beams with NLC-like currents (∼1 A), but with the bunch spacing equal to the X-band period (88 ps). The beam source is a 150 kV, thermionic DC gun, and the injector is followed by a chicane that allows for collimation of the longitudinal bunch tails generated by the direct DC-to-X-Band bunching. The two accelerator structures used in the injector are half the nominal length to reduce the beam loading and allow for higher currents which compensate the collimation losses in the chicane (typically 1/3). To improve the bunching efficiency, the first structure has a low beta section in its upstream end and is preceded by two pre-bunching cavities, all powered from the SLED-II pulse.

The injector was commissioned in late 1996 and, by the end of 1997, both linac rf stations were operational and the pairs of 1.8 m structures were typically run at unloaded gradients of 44 MV/m in the first station and 37 MV/m in the second station. At these levels, beam-loading compensation measurements were made that demonstrated 17% compensation to within the 0.3% level required for the NLC. The facility delivered beam with a peak energy of roughly 350 MeV. A photograph of the beam line, with the four 1.8-m accelerator structures
Subsequent operation brought the gradients up to the 50 MV/m design value but the maximum gradients were limited by rf breakdown. The standard processing technique is to process to higher than nominal gradient and then reduce the gradient for operation. However, to achieve higher gradients, upgrades to the rf stations were required. During a two to three year period, both of the linac modulators were partially rebuilt, some of the SLED-II components replaced with ones capable of handing higher peak power, and a second 50 MW XL4 klystron was added to each station. Also, an automated rf processing system was developed and the machine protection system improved to allow for around-the-clock, unmanned structure processing.

During this period, the NLCTA program focused on processing one of the Damped-Detuned Structures (DDS) to 73 MV/m with 240 ns pulses. After roughly 1000 hours of processing at 60 Hz, it became clear that stable operation at such a gradient would not be attainable. Also, in situ beam-based measurements of the structure phase advance profile revealed large changes, suggesting substantial erosion of copper, in the upstream structure irises. The 1.8-m accelerator structures are nearly constant-gradient structures and thus the iris radii and the rate of rf power flow is large at the upstream end. Subsequent measurements of the other structures in the NLCTA showed similar patterns of damage occurring at gradients as low as 50 MV/m. This prompted an aggressive program to develop more robust high-gradient structures.

Before operating the relatively long 1.8-m prototype structures, many shorter X-band accelerator structures had been processed to much higher gradients. Single cell standing-wave cavities had operated at 150-200 MV/m and a short 20 cm structure had operated at 120-150 MV/m. In addition to being much shorter than the prototype 1.8-m structures, all of these structures had much lower rates of rf power flowing through the structure. Given this
previous experience and the observed pattern of damage in the 1.8-m structures, where only the upstream end seemed to be affected, it was hypothesized that the damage was related to the group velocity of the rf power flowing through the structure. To study this idea, the first test structure was constructed by cutting off the last 1/3 of the DS2 structure, so that the maximum group velocity was 5% instead of 12% of \( c \), and brazing on a new input coupler. This structure rapidly processed \( \sim 65 \) MV/m.

Next, a series of test accelerator structures were constructed to explore the dependence of the damage and breakdown on both the structure length and on the group velocity of the rf power through the structure. Both travelling-wave and short standing-wave structures were built and tested. In addition, new processing, cleaning, and handling procedures were implemented. While these tests confirmed the initial hypothesis that there is a strong correlation between the group velocity and the breakdown/damage gradient levels, the test structures were still limited to operating at gradients of \( \sim 70 \) MV/m due to the breakdown rate in the input and output couplers.

Most recently, it was found that pulsed heating in the input and output couplers may have been limiting the true performance of these test structures. Sharp edges in the coupler design were observed to have significant damage while the rest of the structures looked fine. Figure 25 is a photograph of one of these edges which shows damage that looks like melting of the copper although the expected temperature rise was relatively low.

The latest test structure was constructed with new input and output couplers. This structure was rapidly processed to 80 MV/m and then operated stably at 73 MV/m with a breakdown rate much less than required for JLC-X/NLC operation. It was subsequently processed up to 92 MV/m and has been operating at 90 MV/m with less than one breakdown event per day, a factor of two better than the JLC-X/NLC specification. The gradient performance of a number of the test structures is shown in Figure 26. Clearly, the latest structure, with the improved couplers, is performing well above the gradients desired for the JLC-X/NLC. Note, however, that the T-structures do not yet include the damping slots and manifolds.

The structure testing for the gradient program has been done exclusively at NLCTA using the four accelerator slots in the two linac rf stations. To date, 12 structures have been tested.
in the two rf stations, which have been run in parallel for about 7000 hours at 60 Hz. As part of this testing, the SLED-II pulse compression systems have operated stably, producing up to 280 MW, 240 ns pulses. Although there have been klystron failures due to cracked windows and vacuum leaks, none have failed for more fundamental reasons (e.g., chronic beam interception) after more than 30,000 hours of operation.

While the NLCTA essentially demonstrated an X-band rf system, construction of the facility began in 1993 when the rf components were still at an early stage of development. For example, the modulators that were built were of a line-type design, like the SLAC Linac modulators, with PFN’s, thyatron and transformers, rather than the current design which is based on solid-state switches. Similarly, the XL4 klystrons that were installed are solenoidal focused and not the periodic permanent magnet (PPM) focused tubes that are envisioned for the NLC. The SLED-II pulse compression system that was built was an improved version of the one initially tested to 200 MW in the SLAC Klystron Test Lab but is a single-moded design with components whose ultimate power handling capability is probably more limited than that currently needed. Finally, the original accelerator structures were of the DS and DDS design that had been built to test long-range wakefield suppression methods but were limited to operating at $\sim 40$ MV/m by rf breakdown and damage.

To test the present generation of X-band rf components, the NLC Test Accelerator is being upgraded. A solid-state modulator has been installed and will power four additional XL4 klystrons. These will feed a dual-mode SLED-II pulse compression system to produce roughly 600 MW in 400 ns by the middle of 2003; this is 30% greater than the present JLC-X/NLC specification. Finally, the rf power will be delivered to the NLCTA enclosure and will power 5.4 m of accelerator structure. In parallel, further testing of the PPM klystrons at KEK and SLAC will complete the demonstration of the JLC-X/NLC rf power source. During this period, the original NLCTA rf stations will continue to be used for high gradient testing. Full JLC-X/NLC prototype structures with the short-range and long-range wakefield control
(HDDS1/HDDS2) will be tested in the middle of 2003 to verify the gradient performance.

### 3.2 Accelerator Structure SETup

The Accelerator Structure SETup (ASSET) is a facility dedicated to measuring the long-range transverse wakefield from an accelerator structure. The facility was constructed in 1995 and is located in Sector 2 of the SLAC linac. It uses the 1.19 GeV damped electron and positron beams from the SLC damping rings; the positron bunch comes first and excites the cavity, and the electron beam is then used to measure the resulting transverse wakefield. A chicane directs the positron beam to a dump, and the wakefield deflection of the electron beam can be detected using the ~30 BPMs along Sector 2 which yield a resolution on the transverse wakefield measurements of roughly 0.1 V/pC/mm, more than sufficient for the JLC-X/NLC beam dynamics. The timing of the two beams can be adjusted so that the wakefield can be measured in the time domain, exactly as the bunch train would sample the wakefield, without resorting to a scan in frequency space that can miss high-Q resonances or the impact of higher frequency bands. A schematic of the facility is shown in Figure 27.

The facility has been used to measure the wakefields in five JLC-X/NLC X-band accelerator structures as well as a JLC-C choke-mode structure from KEK and an X-band structure from CERN that was designed to study strong damping of the transverse wakefield as proposed for CLIC. The accuracy of the measurements has been used to benchmark the wakefield calculation codes as illustrated in Figure 8 of the JLC-X/NLC Overview. The facility has also been used to verify the dipole-mode Beam Position Monitor (S-BPM) concept which would be used to align the X-band accelerator structures in the JLC-X/NLC linear collider. The resolution of the S-BPM is sub-micron and the accuracy appears to be similar.

The ASSET facility will continue to be used to measure the long-range wakefields of the JLC-X/NLC prototype structures. The next structure to be tested, the HDDS2, will be ready in mid-2003. This structure design will be tested in both the NLCTA to demonstrate the gradient performance as well as ASSET to verify the wakefields. In parallel, a dual-wire measurement is being developed as an alternate technique of directly measuring the transverse wakefield. This technique should prove to be much simpler and speedier to implement than mounting the structures in the ASSET facility and then measuring the wakefields using a beam. The ASSET facility will be used to benchmark this alternate approach.

### 3.3 Collimator Wakefield Test

To keep the background levels in the detectors manageable, the beam tails will have to be collimated with very high efficiency in all of the linear collider designs. Unfortunately, the transverse wakefields from any components that are placed close to the beam, such
as a collimator, may amplify the beam jitter or dilute the beam emittance. There are few quantitative measurements of the collimator wakefields and it is difficult to model or calculate the high-frequency impedance due to a tapered planar collimator.

The collimator wakefield test facility is a dedicated facility that was designed to measure the short-range transverse wakefields induced by collimators or similar components that must be placed close to the beam. It is located in Sector 2 of the SLAC linac, close to the ASSET facility, and uses the damped 1.19 GeV beams from the electron damping ring. The apparatus consists of a large vacuum vessel roughly 1.7 x 0.6 x 0.3 m into which an insert with up to five collimator apertures is placed. The vessel and insert can be moved vertically in 1 µm steps over a distance of ±1.5 mm. The wakefield measurements are performed by moving the collimator and measuring the resulting deflection of the beam on ∼30 downstream BPMs. The resulting resolution of the transverse wakefield is better than 0.1 V/pC/mm. A photograph of the facility and a typical measurement are shown in Figure 28.

At this time, two inserts have been measured: a set of copper collimators to measure the geometric wakefields and benchmark the analytic approximations and a set of graphite collimators constructed at DESY. In 2003, it is planned to measure a set of collimators that will study the resistive wakefields and another set to study geometric wakefields in a regime that is closer to that expected in the JLC-X/NLC. Depending on the results, future studies can be scheduled as needed.

3.4 KEK Accelerator Test Facility

Aside from the SLAC/SLC beams, the ATF is the only linear collider R&D facility devoted to the production of low emittance beams, a critical challenge in LC beam dynamics and technology. All other LC test facilities, with the exception of the FFTB, are directed toward linac technology RD. The ATF, consisting of a 1.5 GeV S-band injection linac, a damping ring and an extraction line for beam analysis, is also by far the largest of the linear collider test facilities.

The purpose of the ATF is to demonstrate the feasibility of the linear collider low emit-
tance source complex. As such it is focused primarily on beam dynamics issues rather than technology. Experience from the SLC has shown that while technology is an important cost factor, beam dynamics, especially that of the damping ring, is a critical performance limitation. Technology development at ATF is centered on precision beam instrumentation, stabilization and tuning methods.

The ATF international collaboration was formed in 1992 and initially included all major labs then involved in LC R&D. Construction was completed in 1997 and the ATF has operated 20 weeks per year since then. Active members in the ATF collaboration include KEK, eight Japanese Universities, SLAC, LBNL, BINP and Tomsk.

The layout of the ATF is shown in Figure 29.

The design and achieved parameters are summarized in Table 14.

The operation plan to achieve the low emittance goal focused on six areas of investigation: (1) tuning techniques and error correction, (2) single bunch collective effects (e.g. intrabeam scattering), (3) wiggler performance, (4) damping ring acceptance, (5) extracted beam jitter, and (6) multibunch instabilities.

### 3.4.1 Machine Tuning

The tuning procedure to obtain low emittance involves the successive application of steering, dispersion, and coupling corrections. Considerable work has been done to characterize the damping ring optics, resulting in high confidence in the present model. For instance, beam-based magnet field measurements (lattice diagnostics) uncovered quadrupole field-strength errors on the order of 1%. Correcting the optics model to account for these errors produced a model accurate to 0.01%. To correct residual alignment errors, beam-based alignment of fo-
Table 14: The design goals and the achieved accelerator performance of the ATF. The achieved values of the single-bunch emittances quoted above are based on wire scanner measurements on the extracted beam, when the ring is operated at 1.28 GeV in the single-bunch mode. The numbers in parentheses indicate the number of particles per bunch. The quoted errors are estimated based on the fitting analysis of the wire scanner data, together with the observed statistical fluctuations of the measurements.

cusing and sextupole magnets has begun. In late 2002, using new high-resolution ring BPMs, a quick, accurate beam-based alignment procedure is being developed to provide insight into the nature of the optics corrections that are presently used for emittance optimization. We will be able to identify sources of instability and quantify the physical limits on the minimum vertical emittance. This is one of the highest priority beam studies.

The contribution of the wiggler magnets to the damping time has turned out to be consistent with the design. However, they are not used now because of a dynamical problem (the first field integral differs considerably from zero).

The transverse acceptance after tuning turned out to be 0.38×10^{-6} m-rad, which is considerably smaller than the design requirement 0.90×10^{-6} m-rad (3σ of the assumed injected beam) and the SAD simulation value 1.5×10^{-6} m-rad (Δp/p = ±1.5%). However, the measured value is still more than 3σ of the actual injected beam (r.m.s. 0.040×10^{-6} m-rad).

3.4.2 Emittance

The primary damping ring design goal is to obtain a vertical normalized emittance less than 3×10^{-8} m-rad with high intensity (0.7-3.0×10^{10} e⁻/bunch) a multibunch beam (10-40 bunches/train). The ATF damping ring currently operates at 3.125 Hz with one bunch train of 20 bunches with 2.8 ns bunch spacing, 0.1 to 1×10^{10} particles/bunch, at 1.28 GeV beam energy.

Extremely low emittance studies have been done in single-bunch mode, resulting in the
smallest recorded single bunch, low current emittance in the world, $2.8 \times 10^{-8}$ m-rad (vertical, normalized).

The ATF construction included a carefully engineered floor with 14 m deep concrete pilings with a goal of producing a mechanically stable platform for the ring. Early experience with the ring showed sensitivity to thermal and seasonal drift, especially in the circumference. Correction procedures have been developed.

### 3.4.3 Intrabeam Scattering

Single-bunch studies have shown a dependence of the measured emittance on the bunch current and on the longitudinal emittance, indicating strong intra-beam scattering (IBS). The results indicate a stronger effect than current IBS theory suggests, prompting further study. The installation of the rf photo-cathode gun to be described later will allow IBS studies to continue in a higher-current regime, with charge up to $2 \times 10^{10}$ $e^{-}$/bunch.

### 3.4.4 Extraction Kicker

To stabilize extraction from the damping ring, the ATF has a double kicker system in the ring and extraction line which compensates for kick angle jitter in the ring kicker magnet. This scheme has been shown to reduce the extracted beam fractional jitter to $2.8 \times 10^{-4}$ in single-bunch mode. The reduction by the double kicker cancellation is at least a factor of 3.3. The multibunch performance of this system will be verified with a multibunch BPM when the hardware is available (the BPM is currently under development).

### 3.4.5 R&D of Diagnostics Devices

Additional studies at the ATF are aimed at technology associated with accurately measuring very small beams. There are five wire scanners in the extraction line, a laser-wire monitor in the ring, and Optical Transition and Diffraction Radiation (OTR and ODR) monitors under development in the extraction line.

The ATF laser wire closely resembles a design which is expected to be widely used in the LC. In it, a laser beam with a very thin waist is generated in an optical cavity formed by nearly concentric mirrors. The laser intensity is amplified by adjusting the cavity length to meet the Fabry-Perot resonance condition. We have constructed a cavity which produced a beam waist of $12 \mu m$ ($2\sigma$) and an effective power of 100 W, with good long-term stability. The laser wire is installed in the ring at a location with a transverse electron beam size of $\sim 10 \mu m$. In the last year, measurements of the vertical emittance of each bunch in the ring have been done with sufficient accuracy.

Optical Transition Radiation profile monitors are also expected to see widespread use in the LC in order to provide one-shot images of low emittance beams with a resolution well below typical beam sizes. The 2-D image produced by OTR is desirable in order to accurately determine $x$-$y$ and $y$-$z$ coupling and other phase space distortions. We are currently testing a monitor with the resolution required by LC design parameters ($2 \mu m$), well below the current state of the art for such monitors ($20 \mu m$). To date, beam sizes of $5 \mu m$ have been imaged and tests of transition radiation target longevity have been done.

The Optical Diffraction Radiation Monitor, a “proof-of-principle” experiment on the use of optical diffraction radiation (ODR) as a single pulse beam profile monitor has been done
using the electron beam extracted from the DR. We are measuring the yield and the angular distributions of the optical diffraction radiation from a thin metal target at different wavelengths, impact parameters and beam characteristics.

3.4.6 Polarized Positron

Studies are underway at ATF to demonstrate a new method of generating highly polarized positrons through Compton scattering of polarized laser light off relativistic electron beams and successive pair creation. A preliminary experiment has been performed in the ATF extraction line. A polarized $\gamma$-ray yield of $1 \times 10^6$ photons/pulse was measured in 2002.

3.4.7 Multibunch Operation

One of the early studies on multibunch operation was the beam loading compensation system in the injector linac. A new idea using two rf side-bands was applied to compensate for the bunch-by-bunch energy deviation due to beam loading.

Recently (October 2002) we replaced the thermionic gun and buncher system by a Cs2Te cathode rf source for higher injection efficiency to the ring up to $\sim 100\%$ and for better performance of multibunch operation. We succeeded in doubling the stored charge ($6 \times 10^9$/bunch with 19 bunches). The charge uniformity and stability is still poor due to the available laser but it will be improved soon. This will allow more precise studies of single bunch intensity dependent phenomena, such as intra-beam scattering, fast ion instability and impedance effects.

Future plans address the immediate goals of understanding the minimum achievable single bunch emittance and obtaining stable operation with three 20-bunch trains. A program of theoretical and experimental studies has been planned that is focused on understanding the correction and optimization procedures, the stability of the ring component alignment, intra-beam scattering emittance growth and the multibunch beam dynamics mentioned before.

3.5 Final Focus Test Beam

The Final Focus Test Beam (FFTB) at SLAC was constructed during the early 1990s by an international collaboration that included most of the laboratories interested in linear colliders at that time. The primary goal of the facility was to focus the low emittance 50 GeV SLAC electron beam down to a spot of 1 $\mu$m by 60 nm with beta functions of $\beta_x^*=3$ mm and $\beta_y^*=100 \mu$m. This was to demonstrate the optical demagnification that would be required in a future linear collider. A secondary goal of the experiment was to develop and demonstrate some of the high resolution diagnostics, controls, and tuning schemes that would be required in a future collider.

To achieve the small spot sizes, the final focus system is roughly 180 m long with another 180 m of beam line that transports the low emittance beam from the SLAC switchyard to the final focus proper. From the beginning, the FFTB contained 34 quadrupole magnets, 14 dipoles, and 8 sextupoles. The optics was chromatically corrected to third-order by placing the correction sextupoles in pairs, separated by a $-I$ transform, and not interleaving the horizontal and vertical chromaticity corrections. This is quite similar to the correction schemes presently proposed for the future linear colliders.

Each of the quadrupole and sextupole magnets was installed on a remote-controlled magnet mover which had a range of $\pm 1.5$ mm horizontal and vertical motion and $\pm 5$ mrad
rotation about the beam axis, and a step size that was 0.3 µm and 1 µrad, respectively. These magnet movers reduced the need for dipole correctors, and very few correctors were installed. In addition, high resolution BPMs were mounted in the bore of each quadrupole; these BPMs were measured to have pulse-to-pulse resolutions that were 1 µm and drifts of less than 3 µm per week. A set of three 5.7 GHz rf BPMs were also installed at the nearest upstream vertical image of the IP where the nominal beam size was 500 nm; these BPMs were measured to have a resolution of 30 nm. Finally, wire scanners with wire diameters of 3.8 µm were installed and used to measure beam sizes of 0.7±0.1 µm with aspect ratios of 200:1. All of these diagnostic and control devices demonstrated performance close to what will be needed in a future linear collider. Figure 30 shows a schematic of a magnet mover and the reconstructed beam trajectories through the three rf BPMs along with the BPM resolution that can be extracted from the three simultaneous measurements.

The FFTB ran six times between 1993 and 1997 with periods that ranged from a few days to almost two weeks. During the runs, beam-based alignment would be used to align the quadrupoles and sextupoles and verify the quad-to-BPM offsets. The linear optics would then be tuned and finally the nonlinear optical elements would be adjusted to achieve the small spot sizes. The left side of Figure 31 shows a histogram of the measured vertical spot size from the December 1997 run. The measured spot size was 70±7 nm, and was stable over a 48 hour period. The expected spot size at this time was 59±8 nm, including contributions from both the actual rms size of the beam and the rms beam jitter at the focal point, which was measured to be approximately 35 nm; the expected spot size is shown in Figure 31 by the red bar above the histogram. Similar results had been measured during previous runs. The right side of Figure 31 shows the signal from the the Shintake Laser-Interferometer IP beam size diagnostic during the December 1994 run. The beam size is measured with Shintake monitor by detecting the Compton scattered electrons while scanning the beam across the

<table>
<thead>
<tr>
<th>Date</th>
<th>Milestone</th>
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<tbody>
<tr>
<td>1992</td>
<td>ATF Collaboration established</td>
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<tr>
<td>1993</td>
<td>Injector completed (80 MeV)</td>
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<td>1995</td>
<td>Linac completed</td>
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<td>1997</td>
<td>Ring and extraction transport completed</td>
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<td>1998</td>
<td>Vertical emittance measurement using Touschek effect and high resolution synchrotron light interferometer</td>
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<td>2000</td>
<td>Vertical emittance minimization using wire scanners and intra-beam scattering results</td>
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<td>2001</td>
<td>Photo-cathode gun tests showing excellent transmission</td>
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<td>2001</td>
<td>Instrumentation achievements: ring laserwire, high precision OTR, multibunch BPMs and X-ray SR beamline</td>
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<td>2002</td>
<td>Photo-cathode gun installation and BPM upgrade for beam-based alignment</td>
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<td>Multibunch instability studies</td>
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<td>2004</td>
<td>3 pm-rad single vertical emittance (0.75×10⁻⁸ m-rad normalized)</td>
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<tr>
<td>2004</td>
<td>High intensity multibunch operation (1×10¹⁰ e⁻ in each of 20 bunches)</td>
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Table 15: ATF timeline and plans
interference fringes generated by crossing two laser beams at a small angle. This device has a beam size resolution of roughly 40 nm.

Most of the magnets were installed on vibration-damped Anocast stands and there appears to be little amplification of the natural ground motion by the support, mounting, or mover system. In addition, measurements comparing the motion with and without coolant flow show a difference of only 2-3 nanometers. Because they were significantly larger and heavier, the final doublet magnets were mounted on a special table with a separate mover system. Subsequent vibration measurements showed that the table was moving by about 40 nm. This is consistent with independent measurements of the motion of the beam relative to the IP beam size diagnostic.

In summary, the FFTB project demonstrated that the optical demagnification required by the linear collider designs is possible to achieve and maintain. The project also developed and then demonstrated much of the diagnostic and control hardware that will be needed in a future linear collider including the high-resolution beam position monitors, beam size monitors, and magnet movers. Finally, many of the tuning and beam-based alignment techniques that will be needed were demonstrated giving additional confidence in the linear collider designs. At this time, the FFTB enclosure is being utilized for other purposes and there are no plans to revive the beam line as a final focus system.

3.6 Stabilization Demonstrations

The stabilization demonstrations involve work on four different fronts. First, extensive vibration and drift measurements have been made around the world to understand the natural levels of motion. In particular, fast ground motion (relevant for collision stability) has been measured at many laboratories as well as the potential NLC sites in California and Illinois and many of the JLC sites in Japan; the spectra from some of these measurements can be
Figure 31: Histogram of the FFTB vertical spot size measurements (left) with an average of 70±7 nm versus the expected size of 59±8 nm and (right) a plot showing a typical measurement using the Shintake laser interferometer corresponding to a 77 nm beam spot.

seen in Figure 15 of the JLC-X/NLC Overview. Most of the sites considered thus far are sufficiently quiet that there is a significant margin for additional cultural noise. In addition, to understand the tolerances on the cultural noise, transmission measurements from either the surface to the tunnel or between two twin tunnels are being carried out or will be made in 2003. Results of these studies will guide the design of passive vibration protection for the vibration producing equipment. Similarly, the slow motion (relevant for emittance preservation) has been studied extensively at FNAL, SLAC and locations in Japan. These sites are expected to have tolerable slow ground motion, as confirmed either by direct measurements or by comparison with geologically similar sites. As part of the investigation of the slow ground motion a new hydrostatic level system has been developed with submicron resolution. Such a system may also be used as part of the alignment system for a future linear collider.

Second, the effect of cultural vibration sources on the stability of the linac quadrupoles has been studied because, although the jitter tolerances are relatively loose at 10 nm, there are thousands of magnets that require this level of stability. The feasibility of such stability has been demonstrated in several earlier independent measurements, such as those at the FFTB; however in the linacs there may be additional sources of noise. Presently, SLAC and FNAL are studying the vibration transmitted to the quadrupoles from rf structures, which may have large vibration due to the flow of cooling water. Preliminary tests, which used a simplified model of the linac rf girder, showed ~300 nm of motion on the rf structure but little coupling of the structure to the quadrupole and confirmed the feasibility of achieving the required quadrupole stability. Design of a full linac girder prototype is ongoing and will be done with consideration of the stability requirements.

Next, the final doublet magnets, that focus the beams down to the very small spot sizes at the IP, have tolerances of roughly 1 nm, a factor of ten tighter than most of the other quadrupoles. Furthermore, the supports for these magnets are complicated because the magnets are, at least partially, located inside the high-energy physics detector. For these reasons, it is thought that some active stabilization system will be required for these magnets. Although commercial systems are available that can achieve the required stability, they are
Figure 32: Photograph (left) of 100 kg block stabilized in six degrees-of-freedom and (right) of the compact nonmagnetic inertial sensor under development.

Figure 33: Schematic of the FONT experiment in the NLC Test Accelerator.
not well adapted to the details of the interaction region where an extended object must be stabilized in a very compact region with strong magnetic fields. To this end, a program at SLAC has used inertial sensors and electrostatic actuators to stabilize a 100 kg block in six degrees-of-freedom and is developing compact, nonmagnetic, high performance sensors; these are shown in Figure 32. In 2003, this inertial system will be used to stabilize an extended object that more closely represents a final quadrupole magnet, and then the system will be demonstrated in an environment that approximates the real interaction region. In parallel, an ‘optical anchor’, where optical interferometers are used to rigidly anchor an object to an accurate reference, is being studied at the University of British Columbia. This system has the advantage of having better low frequency ($f < 1$ Hz) performance than the inertial systems but must be based on a very stable reference. It is likely that the final system will involve a combination of inertial stabilization and optical anchors.

Finally, a fast intra-train feedback system is being developed to further ensure the stability of the beam at the IP. This feedback system must operate extremely rapidly because the full JLC-X/NLC bunch train is only 270 ns long. Presently, groups from Queen Mary College in London and Oxford University are working on FONT, Feedback On Nanosecond Timescales. This facility uses the NLCTA beam to simulate the beam entering and exiting the IP as illustrated in Figure 33. Tests have shown that FONT is able to reduce the amplitude of an induced oscillation by roughly a factor of 10 with a latency of $\sim 60$ ns. In 2003, new kicker power supplies and improved feedback electronics will be tested with the NLCTA beam to demonstrate improved latency times.