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# Linear Collider Diagnostics*

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**Abstract.** Each major step toward higher energy particle accelerators relies on new technology. Linear colliders require beams of unprecedented brightness and stability. Instrumentation and control technology is the single most critical tool that enables linear colliders to extend our energy reach. In this paper we focus on the most challenging aspects of linear collider instrumentation systems. In the Next Linear Collider (NLC), high brightness multibunch $e^+/e^-$ beams, with $I_{+/-} = 10^{12}$ particles/pulse and $\sigma_{x,y} \sim 50 \times 5$ µm, originate in damping rings and are subsequently accelerated to several hundred GeV in 2 X-band 11424 MHz linacs from which they emerge with typical $\sigma_{x,y} \sim 7 \times 1$µm. Following a high power collimation section the $e^+/e^-$ beams are focused to $\sigma_{x,y} \sim 300 \times 5$ nm at the interaction point. In this paper we will review the beam intensity, position and profile monitors (x,y,z), mechanical vibration sensing and stabilization systems, long baseline RF distribution systems and beam collimation hardware.

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## INTRODUCTION

Linear colliders (LC) extend the general trend of miniaturization[1] for use by accelerators. There are 4 mature LC designs The NLC/JLC, TESLA and CLIC[2] designs involve colliding beams with densities that approach that of solids. For example, at the NLC interaction point (IP), the electronic density of a single bunch is about one fourth that of beryllium. The high density at the IP is required for a usable event rate. Of course, in the bulk of the LC, the density is several orders of magnitude less.

An LC consists of four basic regions: 1) a particle source and pre-accelerator for beam generation, 2) a damping ring that quickly reduces emittance, 3) an high energy linear accelerator and 4) a focusing system complete with aberration correction systems (the latter is known as the 'beam delivery'). With the exception of the source system, each of the regions present major challenges to the instrumentation designer.

The design challenges involve 1) the small characteristic dimensions of the beam, 2) the very large power densities and 3) the high level of stability required to transport and target the beams. In the first case, since the typical dimension of a beamline component is not reduced in proportion to the beam size, simple design scaling is not feasible. For example, a position monitor at the PEP-II B factory[3] is housed in a vacuum chamber measuring a few inches in diameter carrying a beam of a few millimeters with position sensing requirements of a fraction of the beam size, a size/resolution ratio ~ $5 \times 10^{-3}$ . At NLC, with beam duct size of about ½ inch diameter and beam sizes of less than 10 μm, also with a needed precision of ~ $\sigma/5$, the same ratio is $1.5 \times 10^{-4}$, about 30 times smaller. Beam position monitor (BPM) systems under consideration extend and refine the technology of previous systems. The challenge is compounded for transverse and longitudinal profile diagnostic devices by the high charge density of the beam; usually far beyond the threshold of severe single pulse damage to any material. Conventional wire scanners are useful only for beams in the low energy injector systems since in all other locations the wires are cleanly severed by the beam[4]. In contrast to BPM's, profile monitors must use fundamentally new technologies. The laser-based 'fringe' monitor used at the SLAC Final Focus Test Beam[5] and the 'laserwire' used at the SLAC Linear Collider (SLC) interaction point[6] are good examples.

All LC designs rely on the use of flat beams with $\sigma_x/\sigma_y$~10. Table 1 shows some characteristic beam parameters along the collider. Typical single bunch charge is $1 \times 10^{10}$ and bunches are grouped in trains of $n_b$ = 95 bunches, with a total machine pulse intensity of $0.9 \times 10^{12}$ particles per pulse.

**Table 1:** Beam sizes in the NLC/JLC.

| Location | $\sigma_x$ | $\sigma_y$ | $\sigma_z$ |
|---|---|---|---|
| Damping Ring exit | 50 μm | 5 μm | 4.5 mm |
| Linac exit | 7 μm | 1 μm | 100 μm |
| IP | 300 nm | 5 nm | 100 μm |

A third challenge is to provide tools for understanding the pulse to pulse stability of the beam pulses. It includes the application of standard beam instrumentation but, perhaps of equal importance, also includes specialized subsystem instrumentation that may not directly use beam induced signals. In several key components, modern laboratory instrumentation does not adequately provide the stable platform required. Two such subsystems are component position stabilization (vibration / micro seismic) and timing LLRF distribution. In the former case, the challenge is stabilize beamline magnets within extremely severe (few nm) limits over the critical spatial and temporal frequency bands.

In this paper we will first describe uses and functions of LC diagnostics and then introduce approaches to meet the above challenges.

## REQUIREMENTS

The term 'diagnostic' implies an evaluation of substandard performance and a determination of the source of failure. Operational models of all LC under consideration rely heavily on the use of specialized instrumentation, distinct from subsystem monitors such as power converter controllers, for continuous beam parameter optimization. The design and performance of the instrumentation directly enters the process of system wide tolerance and performance estimation.

Linear colliders are not the only kind of particle accelerator where instrumentation has a greatly increased role. A primary thrust for the development of third generation synchrotron radiation (SR) sources has been long term stabilization of the optical beamlines to an extent close to that required for an LC. The difference between 3rd generation storage ring light source instrumentation and LC instrumentation is the reliance of phase space monitors to ensure the best possible emittance propagation. Just as, a decade ago, improved BPM performance was pivotal in the understanding of SR machines, the LC of the coming decade must rely on precise, reliable, transverse and longitudinal beam size monitors.

The defining role for the device, well beyond that of a general purpose diagnostic, is the specific set of procedures into which it will be integrated. These include correction of optical aberrations, collective effects (such as linac wakes), RF phase errors in addition to first order orbit distortion and optics errors[7,8]. The BPM system and the profile monitor system are the most affected by the high degree of integration. In the following section we present examples of self contained optimization procedures vital to the performance of an LC.

### Linac Procedures

Emittance preservation in long linacs is perhaps the best studied LC performance issue[9]. Several processes have been implemented to address it including: 1) beam based structure and quad alignment using BPM's and movers, 2) sets of diagnostic pulses that sample the fields at large offsets and 3) brute force global optimization using beam profile monitors and local closed bumps.

The NLC X-band main linac which takes the beam from 6 to 250 GeV consists of about a half a million disk loaded waveguide irises. The short $\sigma_z$ =100 μm bunches are effectively deflected by the iris if their trajectory is offset from the nominal centerline. Kicks comparable to the distribution of angles ($\sigma_{y'}$ ~ 0.5μrad) in the beam result from few micron offsets of the irises within the structure assembly. Since the best accuracy one can expect of external survey transit based alignment is around 50 to 100μm, a beam-based alignment procedure must be used resulting in an improvement of the positioning precision by more than 10 times. Remote positioners are required.

Because of the energy spread in the beam, kicks from quadrupole offsets also cause emittance dilution. Figure 1 shows the quadrupole positioning error that causes a 25% single bunch vertical emittance growth for nominal linac beam parameters. Assuming the BPM and quadrupole centers stay within a few microns of each other over a reasonable 'stable' time period, and that the quadrupole center does not move as the quad strength is varied a bit, a simple magnet shunting procedure can be used to calibrate the relative offset. It is important that the procedure be short, especially if the 'stable' time period is short, since there are many quadrupoles and the calibration process cannot be used during colliding beam operation.

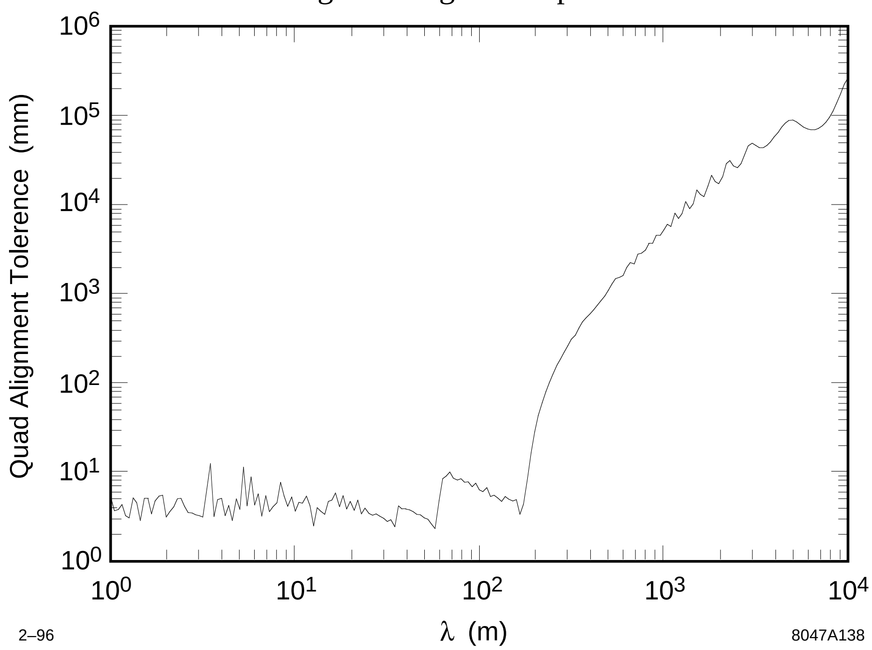


**FIGURE 1.** NLC Linac Quadrupole misalignment tolerance for 25% emittance growth as a function of the spatial wavelength of the misalignment [10]. An energy spread of 0.6% is assumed.

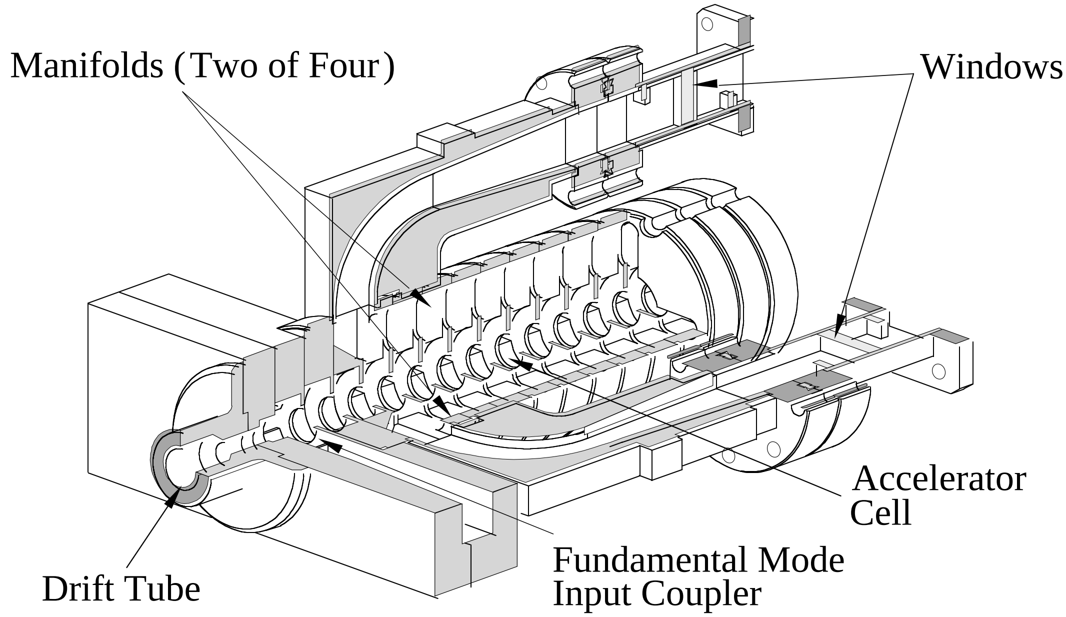

**FIGURE 2.** NLC Linac X-band accelerator structure showing the beginning dozen cells with 2 of their 4 damping / HOM manifolds.

Structure irises cannot be ‘shunted’ or adjusted in a simple way so another technique must be used to align them. The NLC linac structure uses damping slots both to extract the higher order modes (HOM) and to deliver them as a signal for a structure beam position monitor (SBPM) processing system. Figure 2 shows the input end of the 1.8 m X-band copper accelerating structure. In each cell, the worst higher order dipole mode has a different frequency [11] in order to force the decoherence of the long range wakefields. This chirp is used to identify beam offset signals within a given cell (or group cells) in the 208 cell structure.

RF based beam position monitors are not new[12,13] and are attractive for LC because of their monolithic structure. However, instrumented damping guides integrated with a chirped dipole HOM accelerating structure are new. A structure test facility, ASSET, has been installed in the SLAC linac for the purpose of developing the structure design and technology[14]. Structures are tested using a ‘pump – probe’ technique where bunches of opposite charge are launched through the structure and the relative timing between them is adjusted. Using the test facility it is possible to compare the response of the structure dipole HOM signals and the BPM signal processing system with absolute trajectory offsets since the probe bunch is kicked by the residual dipole HOM. Figure 3a shows the response as the absolute offset of the pump beam is varied. It shows the characteristic behavior of RF type BPM’s, namely that the direction of the error is not known without a measure of the phase with respect to a nominal signal, in this case provided by a stripline. The second part of the figure, shows the detected offset for a nominally centered beam as a function of position along the structure length. In this test, the receiver frequency is tuned to the HOM associated with a given cell or group of cells so that, as the receiver tuning is changed, the offset dependence on $z$ can be determined. The data are overplotted with the external cell offsets as measured by a coordinate measuring machine prior to the structure installation into the test facility. The excellent agreement (few microns) indicates the precision of the structure fabrication and the signal resolution of the SBPM.

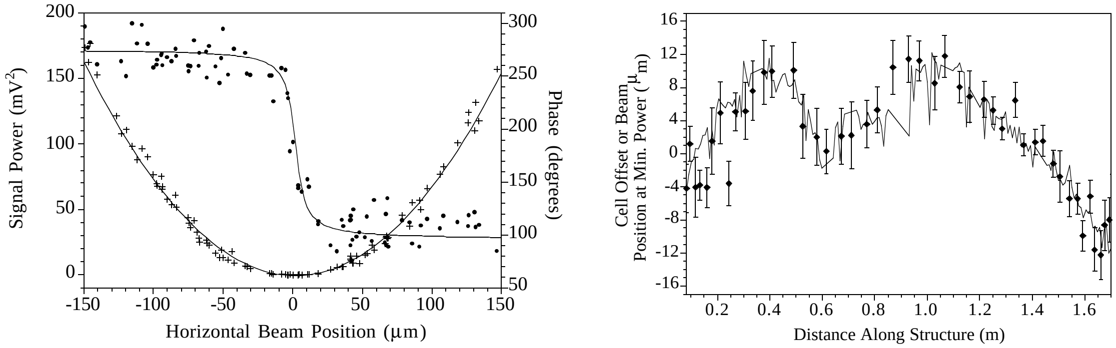


**FIGURE 3.** Results from structure testing using the pump-probe technique. The left hand part (a) of the figure shows the position response of the SBPM (phase and amplitude) and the right hand side (b) shows the detected centroid position for a straight line beam trajectory in the center of the structure compared with the measurements from the outside of the structure made with a coordinate measuring machine.

The second example requirement, the generation of sets of diagnostic pulses, illustrates the level of integration needed for the BPM system. As used at the SLC, diagnostic pulses were generated using small pulsed magnets near the entrance to the linac[15]. A sequence of $e^+$ and $e^-$ pulses with substantial, several $\sigma_{xy}$, betatron oscillation amplitudes are launched and recorded in quick succession at regular intervals. At its simplest and most naïve level, the data serve a function similar to that of a tune monitor in a storage ring, showing the oscillation wavelengths and indicating energy and magnetic errors. Without exciting an oscillation that probes both the quadrupole fields as a function of energy and the collective effects associated with the transverse wakefield, such errors are difficult to detect.

Application control software is used to sequence both the generation of the pulses and the data acquisition, analysis and recording. It is important that no time be wasted in the process because the kicked pulses must be dumped and cannot be used for collisions.

## Damping Ring

In many ways, LC damping rings[16], are very similar to 3rd generation SR sources, such as the Swiss Light Source[17]. However, the vertical emittance is much smaller in a damping ring ($\gamma\varepsilon_x \sim 3\text{x}10^{-6}$ m-rad; $\varepsilon_x \sim 0.8$ nm at 2 GeV) than it is in a SR source where lifetime considerations are very different. The beam lifetime in a damping ring need only be a few minutes because the train of bunches is stored only long enough for it to damp close to equilibrium, about 50ms, after which it is extracted from the ring and injected into the main linac.

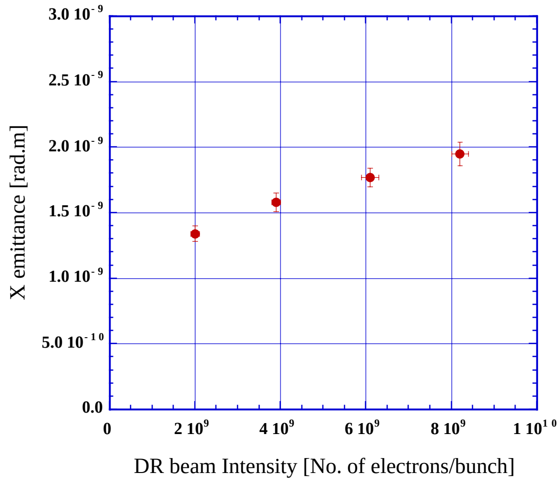


**FIGURE 4.** Emittance (*x* on the left and *y* on the right) results from the KEK ATF damping ring. The plots show the emittance dependence on intensity, mostly due to multiple intra-beam scattering. At 2 x $10^9$ e-/pulse, $\sigma_y \sim 8\mu$m.

While the minimum horizontal emittance is given by the properties of the ring lattice, the achievable vertical emittance is determined by errors. It can therefore be quite small; limited primarily by the detection and correction scheme precision. The primary errors are skew coupling, introduced by strong sextupoles, and residual vertical dispersion. Typical designs target emittance coupling ratios of between 0.1% and 1% and residual vertical dispersion peaks of a few mm corresponding to trajectory differences of 20μm at the extremes of the energy aperture.

Dispersion and coupling correction schemes rely on the ring and extraction line position monitors. Achromatic skew bumps are used to perturb the coupling without changing dispersion. The profile monitor system both in and out of the ring is used as a check for small offsets in the minimization procedures and the stability of the resulting machine configuration. Typical stability time constants are determined by the thermal behavior of the ring enclosure.

Stability specifications developed for 3$^{rd}$ generation light sources, such as SOLEIL[18], require stability of 1 μm over 10 m in a 1 hour interval, and 10 μm over 10 m per day. Records at APS[19] show 2.5 to 20 μm movement in the 1 minute to two week interval range. Their record also shows that, since the BPM system itself is drifting, feedback does not help. In order to compensate for BPM offset drift in NLC, in all systems from the DR downstream, periodic application of a quad shunting procedure is required. Just as in the case of the linac system, each quad strength is adjusted in turn and the downstream disturbance observed. The sensitivity of the procedure should allow correction of errors comparable to the resolution of the monitor. A key parameter is how long it takes to acquire the offset data with respect to the alignment degradation time mentioned above.

## Beam Delivery

The beam delivery layout is dominated by the collimation system, the final demagnification system and its aberration correction systems. The tolerances on the dispersion, chromatic and skew corrections are quite tight and the beam delivery instrumentation must provide for their continuous optimization. One of the most successful tools used for optimization is 'dither' feedback which supplanted a more simple-minded 'scan-parabola' optimization at SLC during the last year of its operation[20]. In the dither system, small +/- excitations are made in the optical corrector systems and luminosity data is collected and correlated with the sign magnitude of the excitation. If the perturbation is small enough and the sensitivity of the luminosity monitor is good enough, colliding beam operation can continue during the dither with minimal impact.

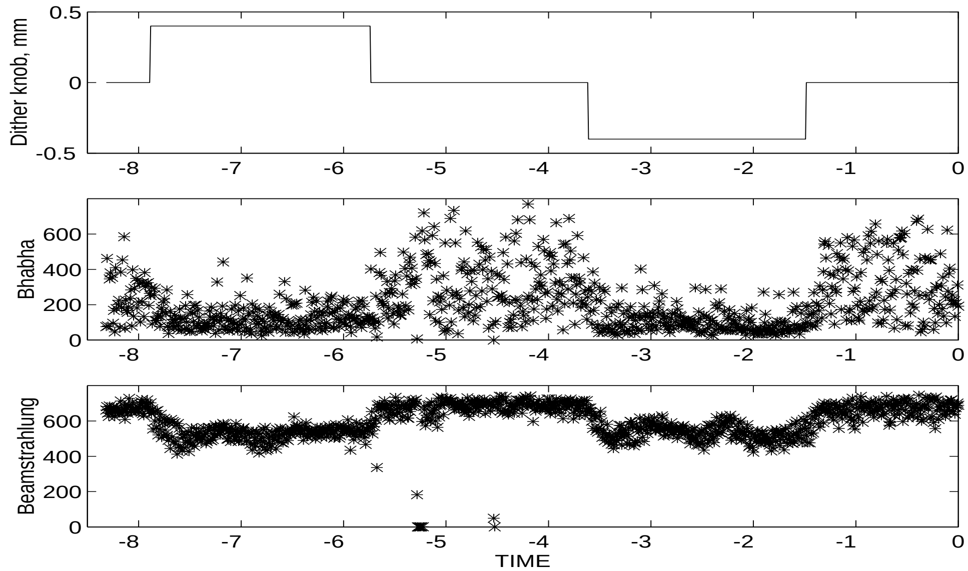


**FIGURE 5.** SLC results from luminosity 'dither' optimization feedback. The top part of the figure shows the control, in this case the corrector for an optical aberration, moving up and down as a function of time. The middle plot shows the response of the radiative bha-bha luminosity monitor, a relatively unstable signal, and the bottom plot shows the response of the beam-strahlung signal, showing the radiation from incoming particles as they are scattered in the collective field of the opposing beam.

## BEAMLINE INSTRUMENTATION - POSITION MONITORS

There are four basic types of position monitors to be used in the NLC: 1) Quadrupole positioning devices to be used for magnet centering (QBPM), 2) Structure BPM's mentioned above for structure alignment and single bunch wake minimization, 3) damping ring BPM's with multi-turn capability and 4) BPM's with the capability of detecting single bunches within the train (FFBPM).

**Table 2:** BPM performance requirements for NLC (top part) in comparison with the FFTB cavity BPM test and older BPM systems from SLC.

| | Resolution (μm) | Resolution/position dynamic range |
|---|---|---|
| QBPM (cavity or strip) | 0.3 | $1.5 \times 10^{-4}$ |
| FFBPM strip | 0.100 / spatial mode | $5 \times 10^{-5}$ |
| DR BPM (8 mm button) | 2 | $4 \times 10^{-4}$ |
| SBPM | 2 | $1 \times 10^{-4}$ |
| Cavity BPM – FFTB test | 0.025 | $4 \times 10^{-7}$ |
| SLC arc BPM (1985) 50 mm strip[21] | 20 | $3 \times 10^{-3}$ |
| SLC Linac BPM (1983) 120 mm strip | 30 | $3 \times 10^{-3}$ |

The NLC will use about 3500 BPM's of the first 3 types; each structure will have an SBPM connection. The BPM system is roughly equal in cost to the beam size monitor system. The number of BPM's is about twice that of SLC.

The most difficult performance requirement, described in figure 1, is control of the offsets at the micron level. If the BPM offsets were stable with respect to the focus magnet center to within a micron for a period of years, then the constant quad shunting procedure would not be needed. Several stripline calibration systems have been studied, typically using local signal splitters and reverse feedthroughs to generate a simulated balanced beam signal. None of these were appealing enough.

Cavity BPM's, on the other hand, may have adequate offset stability because of their mechanical simplicity and rigidity. Such a system is under analysis for NLC.

BPM signal processing has improved in the 15 years since the SLC was constructed by about a factor of 50 in resolution when compared to the monitor size. This is due in large part to the inclusion of narrow band techniques.

## Profile Monitors

Profile monitors can be grouped into two different types: imagers using optics and video electronics and scanners using multiple pulse device or beam scanning of some sort. We will discuss both types.

Since LC $\sigma_y \sim 1$ to 5 μm, only a few wavelengths of light, options for imagers are limited. In this paper we will describe the application of interferometer techniques that provide resolution beyond simple microscopic optics[22]. Most optical systems use fluorescent material, transition radiators or synchrotron radiation. X-ray pinholes will be useful for LC damping rings by extending the wavelength well beyond optical.

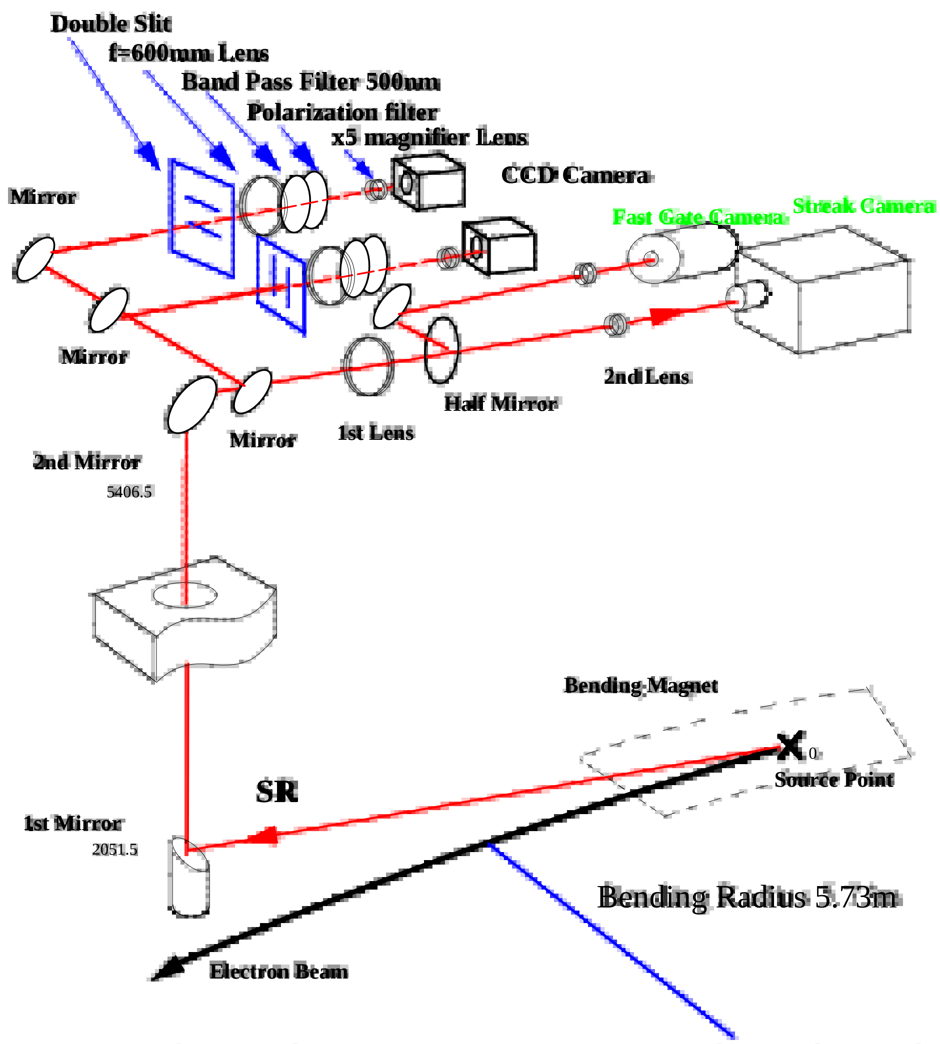


**FIGURE 6.** Synchrotron radiation monitor system at KEK-ATF, showing the optical interferometer system.

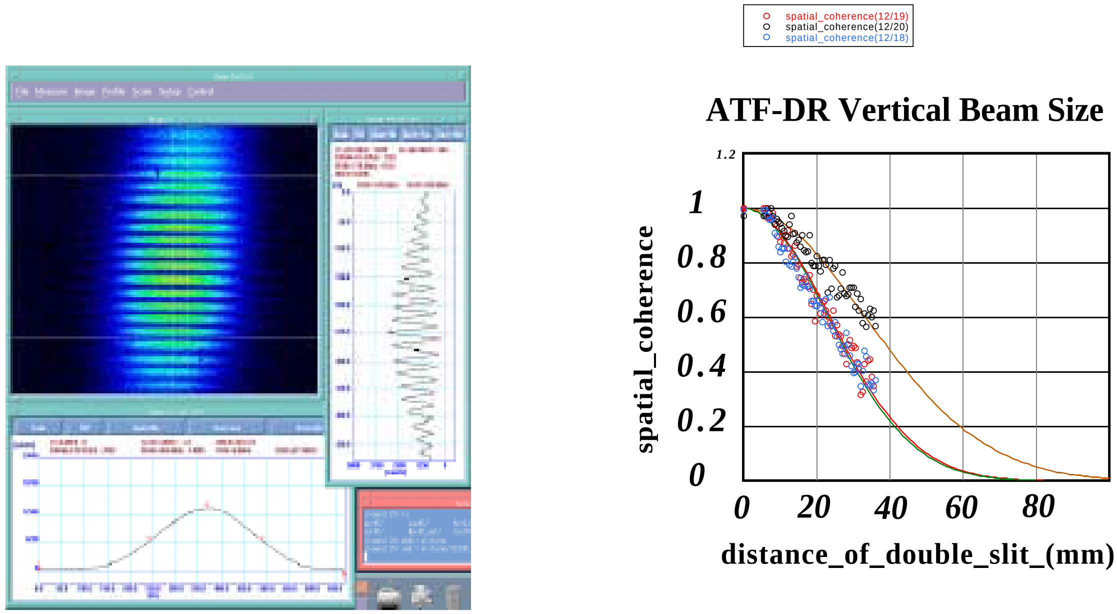


**FIGURE 7.** Results from the interferometer at KEK-ATF. The right hand part of the figure shows the video image from the interferometer and the left hand part of the figure shows the results of a scan of the slit spacing. The beam size of the upper curve in the figure is 14 µm. The data only extend to a slit spacing of 37 mm because of the natural opening angle of the light.

The ATF at KEK group have developed a two slit interferometer[23] for imaging the vertical beam size well beyond the nominal diffraction limit for green light of around 50 µm. From a simplified point of view, this estimate uses the natural opening angle of the synchrotron light and discards the light in the exponentially decaying tails of the emission distribution. The tails, with a somewhat larger opening angle, contain light that can be used to achieve better resolution. By blocking the central portion of the synchrotron light and forming an interference pattern using the extremes the group have shown an effective resolution about 7 times smaller, about 7 µm. The limiting resolution of the device depend on the available light and on the aperture throughout the system. At ATF, as shown above in figure 4, the vertical beam size is below the resolution.

Figure 7 shows the interference pattern modulation depth plotted as a function of the slit spacing, basically a fourier transform of the beam spot. As the spot becomes smaller, the decrease in modulation depth is difficult to detect before the signal strength disappears.

At ATF we will test the resolution transition radiation and diffraction radiation interferometers, which are quite similar and have a somewhat wider predicted angular distribution. Fiorito and Rule[24] have shown that simple diffraction estimates are valid for OTR, and, at high energies, the distribution of OTR is broader than that of synchrotron light, providing the possibility of improved resolution. OTR has been used at FFTB for the imaging of ~50µm beams[25]. ATF provides one of the first opportunities for testing the technique with much smaller beams.

Scanning devices complement imagers for simple operational reasons. They are more easily calibrated, can be made more reliable and are more readily integrated in the machine control system. A scanner can easily be made non-destructive and non-invasive. Examples of scanners are traditional wire scanners, laser-based 'laserwires'[6] and laser interferometers[5]. The NLC design includes 100 laser – beam interaction chambers for profile monitoring downstream of the damping rings. An innovation considered for this system is a fast scanning system with a laser that mimics the train structure of the beam. With such a laser, the full scan takes only one full train machine pulse.

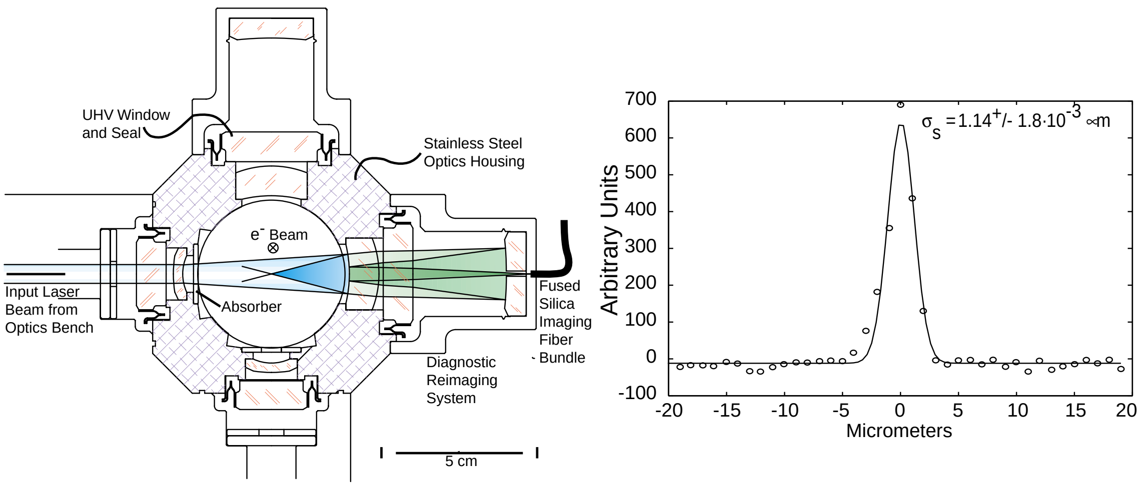


**FIGURE 8.** SLC Laserwire interaction point vacuum chamber. Reflective optics provided a spot size of 400 nm. Two directions could be illuminated using a nearby linear polarizer switch. The imaging fiber bundle served as a diagnostic for laser steering. The right hand side of the figure shows a beam scan made with the profile monitor.

An NLC laserwire installation consists of a sequence of 4 or 5 laser – electron beam interaction chambers (laser IP's), spaced by a substantial fraction of a betatron wavelength. In this way they are quite similar to the wire scanner sets used at SLC[26]. A single laser provides to each laser IP in sequence. An attractive feature of the laser based system that the laser power can be attenuated to the point where the signal is adequate yet the collinear scattered radiation is not enough to disturb downstream power-limited systems.

**Table 3.** LC Profile monitor expected performance.

| | Resolution (µm) | Maximum(µm) |
|---|---|---|
| Laserwire (scanner) | 0.5 | 20 |
| Laser interference pattern scanner (FFTB) | 0.05 | 2 |
| OTR interferometer (imager) | 8 | - |

Table 3 shows the expected performance of three proposed systems. The ranges of usefulness overlap. A special system will be needed near the IP, where the desired resolution exceeds that available from the laser interference pattern system.

## Bunch length

In the main linac $\sigma_z \sim 100\mu m$, about 10 times shorter than $\sigma_z$ in the SLC. In that linac, the streak camera was useful as longitudinal diagnostic[27], but calibration and nonlinearity made it quite cumbersome to use and it was available only for use by experts. Because of the interplay between longitudinal and transverse in the LC linacs and bunch compressors, an accurate and readily available bunch length monitor is required.

In contrast to the transverse, the design longitudinal beam profiles are far from gaussian and can be asymmetric[28]. At $\sigma_z \sim 100\mu m$ (300 fs), coherent radiation diagnostics will be useful, but will have a limited role as a relative monitor in much the same way as broadband Ku band horn pickups have worked for SLC and ATF[29].

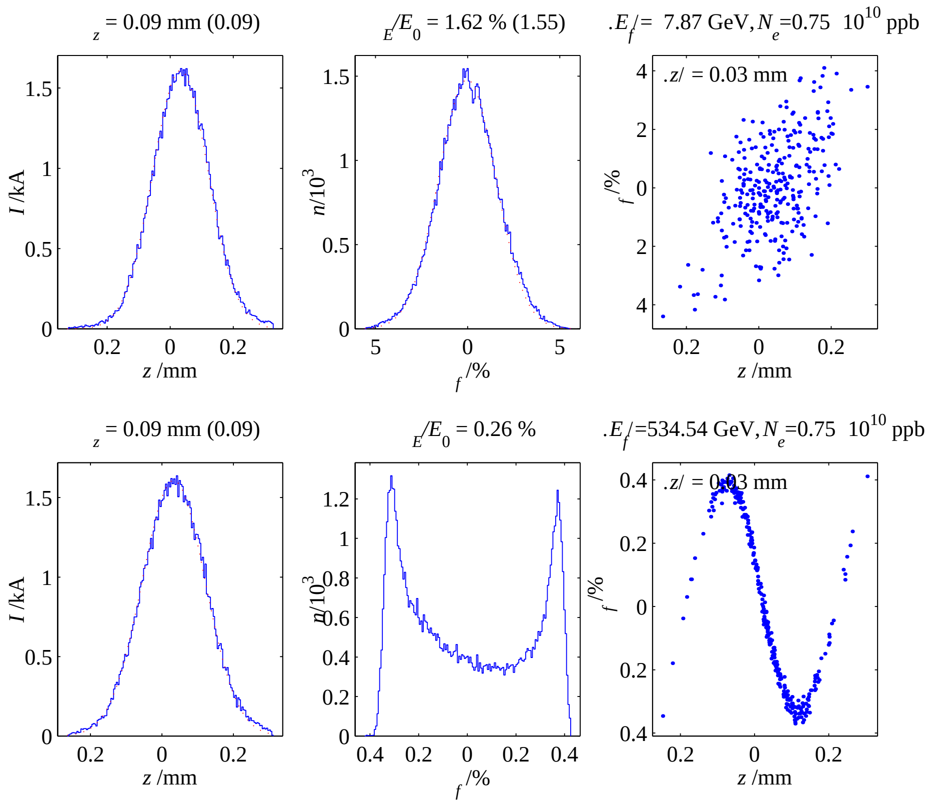


**FIGURE 9.** Tracking simulation results for longitudinal phase space transport in NLC. The figure shows the beam before and after the 500 GeV X-band linac.

The most direct proposal for a bunch length monitor, to be used both at NLC and the proposed 'Linac Coherent Light Source'[30], (LCLS) X-ray source, is actually quite an old idea of using transverse deflecting cavities[31]. Simple analysis shows that there is no dependence of the deflecting field on the transverse position of the beam in the structure, making the diagnostic free of aberrations. Figure shows how this will work at LCLS, where the design $\sigma_z \sim 30\mu m$. It is an ideal diagnostic given the availability of RF power and structures. In the example shown in the figure, the deflecting kick in the

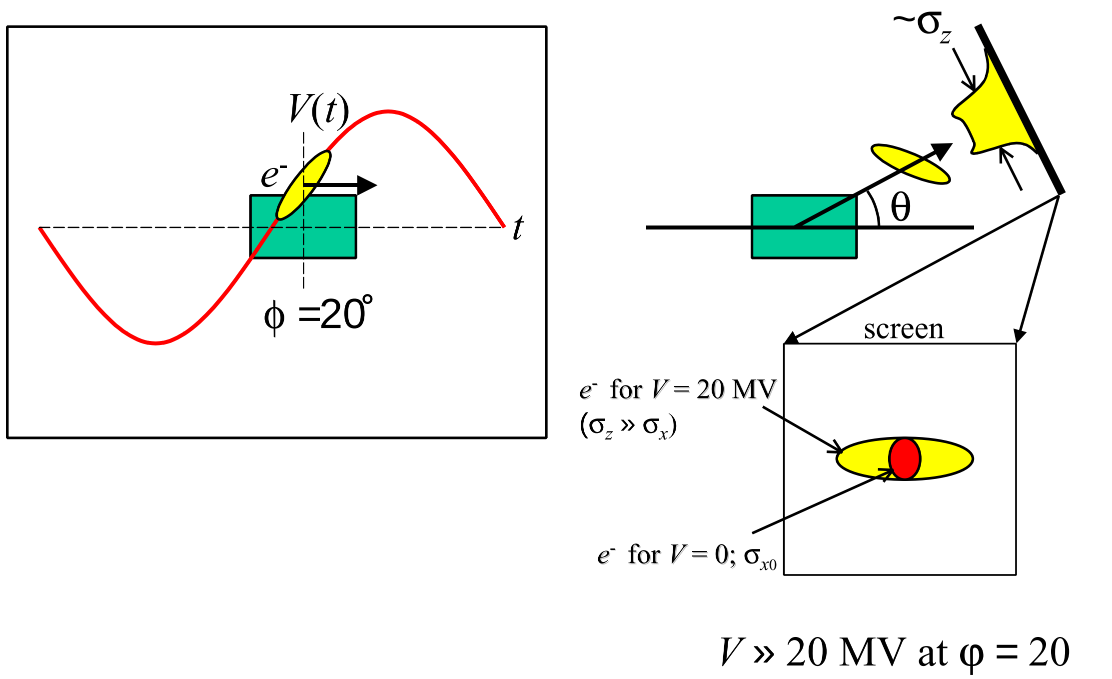


**FIGURE 10.** Bunch length monitor scheme using transverse deflecting structures. The 'crab' structure rotates bunch length into the transverse plane for use with a screen monitor. The 'un-crabbed' or crest deflected beam is used in order to de-convolute the geometric component of the measured beam size.

Another proposal uses the laserwire lasers to generate a beatwave at frequencies comparable to the inverse bunch length[32]. Although this is a scanning technique, its great advantage is that it is not destructive, as the laserwire above and it can use the same laserwire IP's, requiring only a change in the laser equipment.

## Loss Monitors

The charge density in the full intensity, fully accelerated beam, is such that a single errant pulse will damage any material. Of course, the interception of a small fraction of the full 8 MW beam will easily cause component damage in a relatively small number of pulses. Protection from single pulse and multi-pulse component damage require somewhat different approaches[33].

A comprehensive beam permit system will be implemented that ramps up the beam power density, starting with a benign, diffuse, low intensity single pulse pilot beam. Loss monitors are required to control the ramp by predicting and comparing the beam losses as $n_b$ is increased to the nominal 95. The NLC will use a modified version of the traditional gas filled coaxial line ion chamber for this.[34]

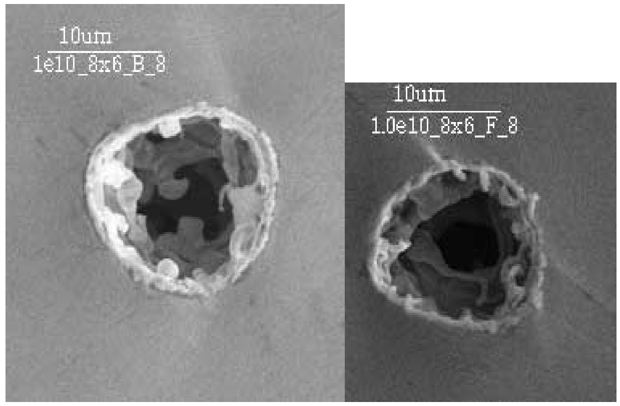


**FIGURE 11.** Single pulse damage results from a 1.4 mm thick copper coupon test in the SLAC FFTB. The photos show the front (right) and back sides of the coupon with the crater left by a 8 x 6 μm $\sigma_{x,y}$ beam of $10^{10}$ electrons.

# SUPPORTING INSTRUMENTATION

## Vibration

The micro-seismic disturbance and slow ground motion ('ATL') have been widely studied and are summarized in the Handbook[35]. The challenge is multiplied in the LC because the tolerances are in the nanometer range and the spatial range over which stability is required is much larger.

The data on ground motion with $f$ > 1/100 Hz show large site dependent components from 'cultural' noise, typically with $f$ ~ 10 to 100 Hz.

The problem can be broken into three basic parts: 1) characterization of the sources of vibration, 2) the mechanism of transmission from the source to the beamline and 3) the component support which may or may not include an active feedback system.

Several aspects of the problem are interesting. The power line-locked pulsed nature of the machine makes it possible to frequency and phase lock industrial support machinery such as pumps and fans greatly reducing the associated vibration.

In several cases, especially the demagnification system, simple suppression of sources must be augmented by some sort of stabilization system for frequencies small compared to the beam rate, the beam itself will be used but for frequencies close to and above the beam of ~100 Hz and external system must be used, based either on sets of inertial sensors or on an optical anchor . In the former case, small radiation hard sensors must be developed.

## Timing System

In the main linac, the beam is accelerated as much as 20 off-crest in order to provide the correct head/tail energy correlation. This results in strong phase sensitivity, a fraction of a degree X-band pulse to pulse stability. In contrast to a proton linac, the pulse is too short to close a phase feedback loop during the pulse. A stabilization system is required both for long term, long baseline distribution in the absence of beam to close the loop with beam phase signals[36]. The structure system provides the RF signal, as done at SLAC.

## ACKNOWLEDGMENTS

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