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Beam Instrumentation Challenges at the International Linear Collider[1]

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Abstract. The International Linear Collider (ILC) is a proposed facility for the study of high energy physics through electron-positron collisions at center-of-mass energies up to 500 GeV and luminosities up to 2 x 10^{34} cm-^{2} sec^{-1}. Meeting the ILC's goals will require an extremely sophisticated suite of beam instruments for the preservation of beam emittance, the diagnosis of optical errors and mismatches, the determination of beam properties required for particle physics purposes, and machine protection. The instrumentation foreseen for the ILC is qualitatively similar to equipment in use at other accelerator facilities in the world, but in many cases the precision, accuracy, stability, or dynamic range required by the ILC exceed what is typically available in today's accelerators. In this paper we survey the beam instrumentation requirements of the ILC and describe the system components which are expected to meet those requirements.

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INTRODUCTION

The International Linear Collider (ILC) is a proposed experimental facility for the study of Terascale particle physics via electron-positron collisions at center-of-mass energies of up to 500 GeV, with possible future extensions to 1 TeV or higher. Figure 1 shows a schematic view of the ILC. The key operating parameters of the ILC are summarized in Table 1.

Table 1. Key operating Parameters of the ILC.

Parameter	Value
Train Repetition Rate	5 Hz
Bunches per Train	2820
Bunch Spacing	307 nsec
Train Length	~900 μsec
Particles per Bunch	2 x 10^{10}
Energy at Damping Ring	5 GeV
$\gamma\varepsilon_{x,y}$ at Damping Ring	8 μm x 20 nm
σ_z at Damping Ring	6 mm
Energy at IP	250 GeV
$\gamma\varepsilon_{x,y}$ at IP	10 μm x 40 nm
$\sigma_{x,y}$ at IP	650 nm x 5.7 nm
σ_z at IP	300 μm
Power per beam at IP	11.2 MW

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From the parameters in Table 1, the key operational challenges of the ILC are immediately apparent: Generation and preservation of extremely low transverse emittances; bunch length compression by a factor of 20; maintaining collisions in high-intensity beams with vertical sizes in the nanometer regime; machine protection in the presence of multi-megawatt beams with extremely small vertical dimensions and a facility duty cycle of 0.5%.

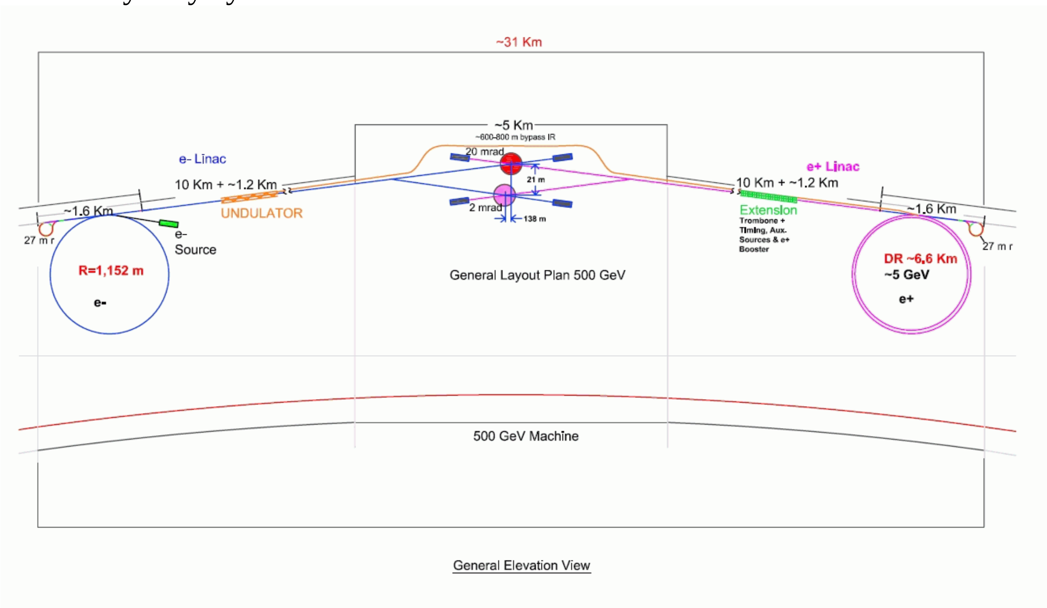

FIGURE 1. Schematic of the International Linear Collider.

BEAM POSITION MONITORS

The most ubiquitous of all the beam instrumentation in the ILC, as in most accelerators, is its suite of Beam Position Monitors (BPMs). In the low-emittance transport (LET) of the ILC, between the electron and positron damping rings, the number of BPMs will be on the order of 1,000. Each of the 3 damping rings is expected to have approximately 500 BPMs, and the high-emittance injectors will require additional BPMs.

BPM Resolution

The resolution requirement of the ILC BPMs is set by two missions: emittance tuning and beam jitter analysis. In the case of jitter analysis, it is clear that the BPM resolution has to be comparable to the level of beam jitter which is of interest, which in the case of the ILC is at the level of a fraction of the RMS transverse beam size. Figure 2 shows the RMS vertical beam size in the transfer line from the damping ring to the main linac. The typical beam sizes are between 1 and 20 μm, which implies that a single-shot resolution of 1 μm or smaller should be satisfactory.

Determination of the resolution requirements for emittance tuning is somewhat more complicated. Since BPMs do not generally return useful information on beam sizes or emittances, and since semi-local correction of emittance dilution is essential in order to maintain the extremely small vertical emittances of the ILC, it is necessary to use one of a number of indirect approaches for inferring aberrations and errors from the beam trajectory, and determining an orbit which will minimize emittance growth from those aberrations. Figure 3 shows a simulated example of one such indirect approach: Dispersion Free Steering (DFS), in which the change in the beam orbit as a function of the linac energy gain is used to measure the dispersion at each BPM and thus to deduce a set of orbit corrections which minimizes the dispersion in a semi-local manner [1]. The emittance growth after convergence is shown as a function of BPM resolution. Figure 3 shows that (a) the residual emittance growth is a strong function of BPM resolution, but (b) the performance improvement appears to saturate for BPM resolution which is better than 1 μm. While there are a number of different algorithms which have been used to tune the ILC orbit to minimize emittance growth, none has yet shown dramatic improvement for BPM resolution which is better than 1 μm. Based on both emittance tuning and jitter diagnostics, therefore, a BPM resolution in the range of 1 μm single-shot, single-bunch appearse to be acceptable.

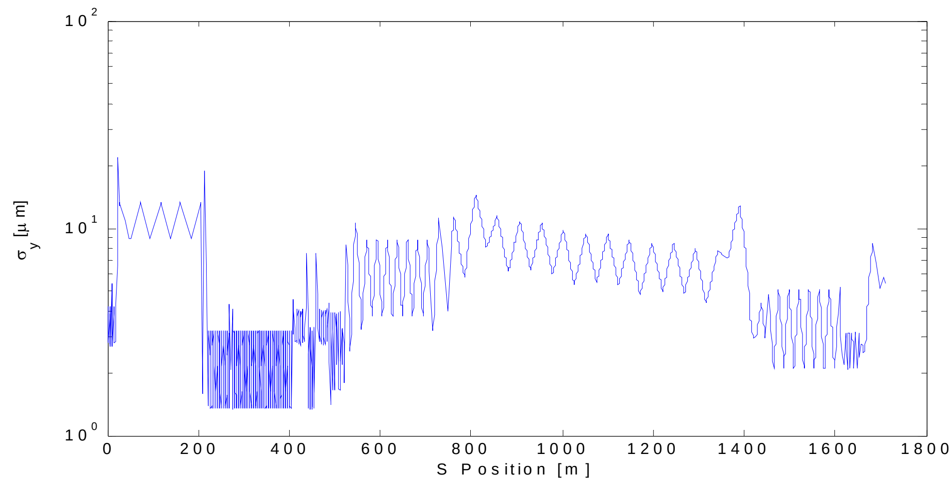

Figure 2. RMS vertical beam size in the ILC Ring to Main Linac transfer line.

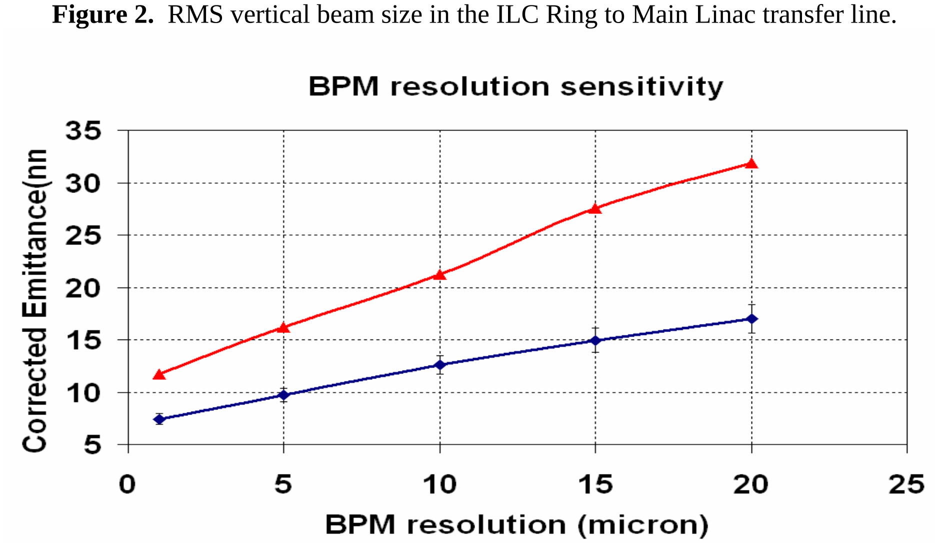

Figure 3. Convergence of simulations of Dispersion Free Steering (DFS) as a function of BPM resolution in the ILC main linac. The mean (blue) and 90% CL (red) from 100 simulations are shown.

BPM Stability and Coupling

The limits on tolerable BPM coupling can be deduced from the typical ratio of the beam transverse sizes. The emittance ratio at the exit of the damping ring is 400:1, implying that the typical ratio in the beam sizes is the square root of this ratio, or 20:1. If we make the reasonable assumption that the beam motion in the *xz* and *yz* planes will be comparable to the *x* and *y* beam sizes, respectively, then it is clear that the cross-plane coupling in the BPMs should be small compared to this ratio so that random motion in the (larger) horizontal plane does not create spurious measurements of motion in the (smaller) vertical plane. For a typical beam size ratio of 20:1, a coupling of 0.1% should be acceptable from this perspective.

The stability requirement of the BPMs can be derived from emittance requirements: once the emittance is tuned, the main technique for preserving a small emittance is preserving the "gold orbit" which corresponds to the small emittance. This can only be accomplished to the degree that the BPM offsets remain stable with respect to the rest of the accelerator. Figure 4 shows a simulation of the effect of random changes in the BPM centers on the emittance, assuming that the orbit is steered to slavishly preserve the "gold orbit" determined at some previous time. From Figure 4 it is clear that the stability of the BPM centers should be at a level of a few μm.

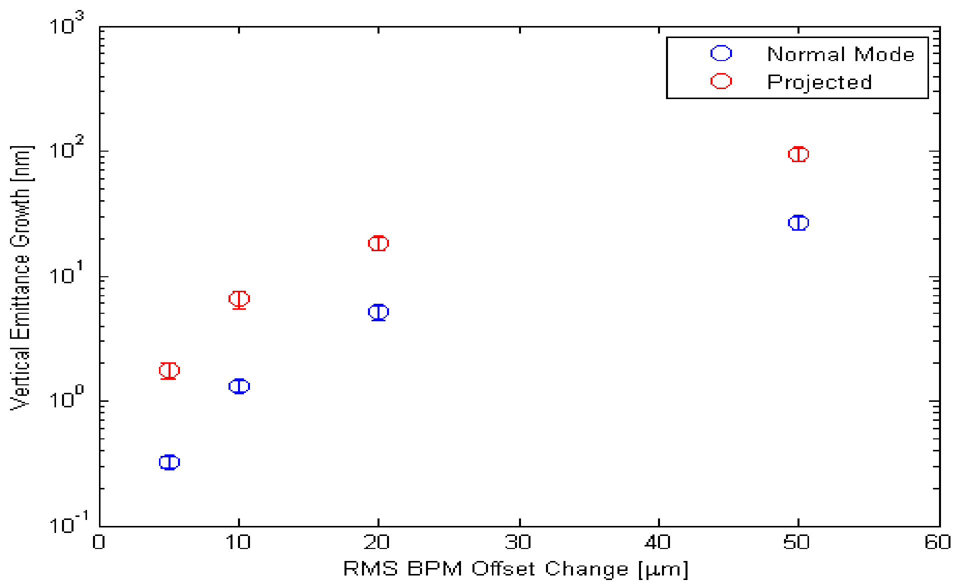

Figure 4. Simulated emittance growth in the ILC as a function of RMS orbit variation from changes in the offsets of the BPMs. Both the projected emittance (blue) and the normal-mode emittance (red) are shown.

The stability requirement is made more complicated by the fact that the stability of the BPMs is only one factor out of many which causes the emittance to grow over a period of time, and thus there would be some degradation of the performance of the accelerator over time even if the BPMs were perfectly stable. In addition, global tuning of the emittance is performed quasi-continuously. In general, it is accepted that an emittance growth on the order of 10 nm over a period of many hours is tolerable, since such small growths can be corrected globally and global corrections can be applied in a time which is short compared to several hours; but that emittance growth at the level of approximately 100 nm, which is at the limit of the global correction range, must not develop over time scales of less than 1 week, preferably longer. This obviously implies tolerances on many systems other than the BPMs, but a full discussion of stability tolerances in the ILC is beyond the scope of this paper.

Maintaining Collisions

As shown in Table 1, the vertical RMS size of the beams at the IP is 5.7 nm. Ensuring that such small beams actually collide with one another is a non-trivial exercise, which is made more difficult by the fact that, for the ILC parameters, the luminosity loss as a function of "miss distance" is much larger than for rigid beams due to the single-bunch kink instability [2]. Furthermore, the combination of natural ground motion, cultural noise, and technical noise which is imported to the ILC site will certainly drive the beams out of collision in a matter of seconds at best; at worst, these sources of beam motion will be sufficient to push the beams far out of collision on every accelerator cycle [3]. At this time there is no BPM technology available which can achieve a resolution of 0.5 nm, and even if there were such a technology it would not be possible to place it at the collision point since all the desirable real estate in the vicinity is claimed by the particle physics detectors.

Fortunately, the same strong beam-beam interaction which drives the rapid luminosity loss for small offsets results in enormous beam-beam centroid deflections. Figure 5 shows a typical relation between the beam-beam offsets and deflections: deflections at the level of 10 μrad are achieved for 5 nm offsets, which implies that BPMs which measure the beam-beam deflection can be used to preserve collisions. Since the orbit of each train is expected to be different from that of the preceding train, it will be necessary to use a feedback operating on intra-train timescales to preserve collisions, by using the deflection signal of early bunches to apply a correction to later bunches. This implies that the collision feedback BPMs require bunch-by-bunch measurements of the beam position, and that the process of measuring the beam deflections and computing a correction must in general have a latency which is sufficiently small to allow the feedback to operate efficiently.

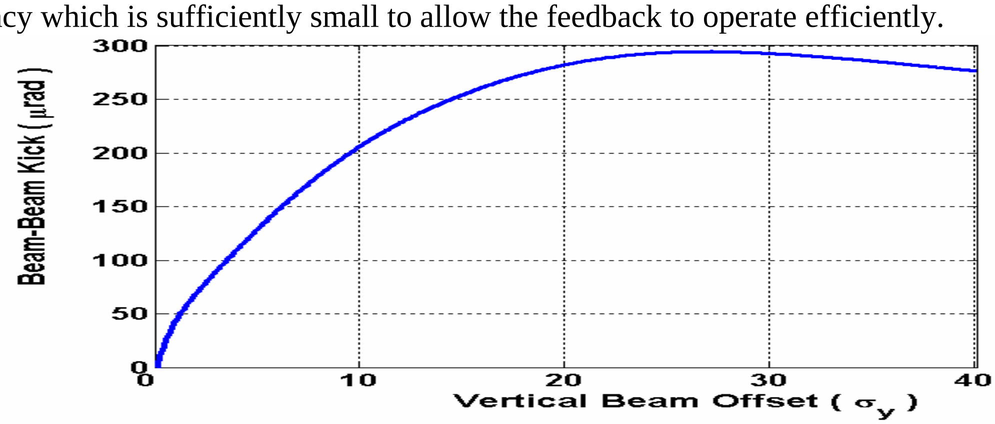

Figure 5: Beam-beam deflection at the ILC collision point as a function of miss distance. The deflection signal is extremely strong, yielding deflections of microradians for nanometer-scale offsets between the beams. The large deflection signal allows conventional BPMs to be used to maintain collisions via feedback.

Additional Requirements on the BPM System

There are a number of other requirements which are placed on part or all of the BPM system in the low-emittance portion of the ILC. For example:

- Difficult environments: many of the BPMs in the bunch compressor, the linac, and the IP are in cryogenic environments, and are often placed near superconducting RF cavities with strict vacuum cleanliness requirements. Other BPMs are in high-radiation environments such as the detector or the post-collision extraction lines.
- Much of the emittance tuning in the ILC cannot be performed at full power, but instead requires that only a single bunch be transported per accelerator cycle; however, the resulting "gold orbit" must remain valid for full trains, implying that a high degree of fill pattern transparency is required.
- On each accelerator cycle, a "pilot bunch" with a charge as low as 1×10^8 is accelerated 10 microseconds ahead of the first luminosity bunch, and similar pilot bunches are used for startup, commissioning, and recovery from outtages. The BPMs need to be able to respond to such low-charge bunches.
- In the case of the IR hall with a small (2 mrad) crossing angle, both the low-emittance incoming beam and the large-emittance spent beam pass through the IR BPMs, and the large-emittance beam has a much larger offset than the low-emittance one. The BPMs in this area must be capable of measuring the trajectory of the incoming beam with micrometer precision in the presence of an outgoing beam which is many millimeters off-axis.

Technology Choice for the ILC BPMs

In view of the requirements described above, dipole-mode RF cavities have been chosen as the technology of choice for the vast majority of the ILC BPMs. Cavities operating at approximately 6 GHz have achieved single-pusle resolutions as small as 20 nm [4] and center stability at the level of 50 nm for a period of many hours [5]. Cavities are more naturally amenable to the cleanliness demands of a superconducting accelerator than alternate technologies such as striplines, and recent cavity designs have shown excellent natural common-mode rejection [6]. The main drawback to cavity BPMs compared to striplines is ease of use: cavity BPM systems require much more care in the design, operation, and calibration of their processing systems, while stripline systems are more nearly "turn-key" installations. It is expected that a combination of experience, engineering, and relaxation of the specifications from the nanoscale back to the microscale will allow cavity BPM systems to become as robust as stripline systems are today.

In the case of the IR BPMs, it will most likely be necessary to use stripline technology due to the greater natural directionality of striplines: this directionality will permit the on-axis beam position to be measured in the presence of the off-axis beam propagating in the opposite direction. Stripline BPMs have demonstrated resolution at the micrometer scale and offset stability at the level of a few micrometers, which is more than adequate for the IR BPMs [7].

TRANSVERSE PROFILE MEASUREMENTS

The transverse size and shape of the beam will be measured in a number of locations throughout the low-emittance section of the ILC. Experience at the SLC has shaped the design of the ILC profile measurement system in several ways: most notably, the capability to perform non-invasive measurements of the transverse emittance on a routine basis was found to be crucial to preserving good performance of the SLC over time. The profile monitors in the ILC will therefore be deployed in multiplets which are positioned to optimize the rapid and non-invasive measurements of beam emittance, rather than singly.

The main technology for measurement of the transverse profile has to satisfy a number of criteria. First, as already mentioned, it must be as non-invasive as possible to normal luminosity operation. Second, it must be capable of measuring the emittance of beams with a relatively small vertical size (in the regime of micrometers or at most tens of micrometers) and a large xy aspect ratio (15 to 25 is typical). Third, the system must be operationally robust ("turnkey" in modern parlance). Ordinarily the optimum technology for a single-pass electron system would be wire scanners; in the ILC case, the charge density of the full bunch train is sufficiently high that there is considerable skepticism that any solid wire would be capable of surviving for an acceptable length of time. Experiments have been performed in which the solid material of the wire in a wire scanner is replaced with a liquid or gaseous target, but these experiments have not produced a fully satisfactory solution. The ILC has therefore chosen to use a renewable photon target, i.e., a laser wire.

Laser wires have been used as profile monitors for electron beams in facilities as diverse as the KEK-ATF ring at 1.28 GeV [8] and the SLAC SLC IP at 45.6 GeV [9]. The key challenges to adapting the laser wire for use at the ILC are as follows:

Wide range of beam energies. The beam energy in the ILC injector varies from a few tens of MeV to 5 GeV; in the area downstream of the damping ring it grows from 5 GeV to 250 GeV. Since the laser wire depends upon detecting the photons and/or degraded electrons from Compton scattering between the electron and laser beams, both the intensity and the qualitative properties of the signal (dominance of the photon vs the degraded electron signal) will be different at the various laser wire emittance stations throughout the ILC.

Extraction of the Signal. Unlike other technologies in which the signal includes photons or particles which are scattered at large angles, the laser wire signal, with its $1/\gamma$ opening angle, has to be separated from the primary beam. This separation is usually accomplished with a chicane of bending magnets, which must be included in the design of the emittance measurement station.

Time Structure Matching. The peak power of the laser used in the laser wire must be made as high as possible to maximize the signal. In order to accomplish this while keeping the average power to a tolerably low level, the laser time structure must be in the form of short pulses separated by long gaps – the same, in other words, as the electron beam time structure.

Large Electron Beam Aspect Ratio. The metal fiber in a wire scanner has the same diameter over its entire length. A laser wire has a very small diameter at its focal point, but a larger diameter some distance away from the focal point due to its finite Rayleigh range. Since the electron beam is much larger in the horizontal than in the vertical, the divergence of the laser beam away from its focal point leads to a systematic overestimate of the electron beam height which is dependent on the electron beam width.

Limited Dynamic Range. The minimum beam size which can be measured in a laser wire is a function of the wavelength of light and the focusing optics, as well as the aforementioned systematic effect from the large horizontal electron beam size. At this time it does not appear to be practical to measure vertical RMS beam sizes which are smaller than 1 μm, and larger sizes will permit simpler and more robust designs for the laser wire system.

In addition to a large number of laser wire profile monitors, the ILC will include a smaller number of metal wire scanners. These devices will be exclusively for use at relatively low beam power, in locations where the natural beam size is relatively large, and in locations where the accelerator design cannot be readily adjusted to be compatible with a laser wire. For example, the initial tuning of the beam extracted from the damping ring will be performed with a metal wire: at this location the beam is large, the power can be lowered by using only 1 bunch per 200 msec accelerator cycle, and the area is not compatible with extraction of the relatively weak laser wire signal due to the nearby presence of collimators and an insertable stopper between the wire location and the nearest possible Compton detector.

The ILC will also utilize a small number of Optical Transition Radiation (OTR) profile monitors. OTR screens are even more susceptible to damage from high incident beam powers than are wire scanners, and so like the wire scanners OTRs will be limited to areas and circumstances under which high beam power density is not an issue. The relative ease of use of OTRs compared to laser wires or even metal wires, along with the wealth of information that OTRs can generate on a single-shot timescale, argues for their inclusion in a few locations and as a “diagnostic of last resort.”

BUNCH LENGTH MEASUREMENTS

The specifications for IP beam parameters of the ILC indicate that RMS bunch lengths in the regime of 150-300 μm (0.5-1.0 psec) are required, while the RMS bunch length in the damping ring will be 6-9 mm. Since the main linac and beam delivery system have almost no momentum compaction, it is therefore logical to place bunch length monitoring devices in the Ring to Main Linac transport, which is also where the two-stage bunch compressor is located.

The main bunch length measuring device for the ILC will be an adaptation of the technique used at the Sub-Picosecond Photon Source (SPPS) at SLAC and the VUV FEL at DESY, specifically: use of a high-frequency dipole-mode RF cavity at its zero crossing to produce a longitudinal “chirp” of the beam (essentially, using the RF cavity as a high voltage streak camera which streaks the beam itself); the beam which emerges from the cavity has a vertical or horizontal size which is proportional to its

RMS length, and measurement of this size with an OTR screen or wire scanner allows the bunch length to be computed [10].

The required cavity voltage is a function of the beam energy and the ratio of the bunch length to the angular divergence, since the cavity must produce a head-tail deflection which is large compared to the angular divergence in order to measurably enlarge the size of the "chirped" beam on a profile monitor relative to the "unchirped" size. In the ILC case the low vertical angular divergence permits the use of relatively modest voltages, which in turn permits the use of a relatively short dipole mode cavity with a conventional off-the-shelf power source – in this case, a 35 cm (10 cell) cavity operating at 2856 MHz driven by a SLAC 5045 klystron or its equivalent. At a total length of 35 cm, the fill time of the cavity will be approximately 150 nanoseconds, which is shorter than the inter-bunch period; thus, the cavity can act as a single-bunch device, allowing the operators to "chirp" a selected single bunch within the train for measurement. Since the lowest-band dipole mode of the cavity is also the one which is excited by the klystron, this also implies that there is little or no buildup of long-range wakefields over the length of the train, which eliminates the dipole mode cavities as sources of multibunch emittance growth. The short cavity length also reduces the single-bunch impact on beam emittance, which eases alignment tolerances of the cavities.

In addition to providing raw bunch lengths, the dipole-mode cavities can be used to generate other diagnostic information. For example, a vertically "chriped" beam which is imaged in a region of horizontal dispersion provides information on the energy vs Z correlation within the bunch; similarly, a horizontally-chirped beam can provide information on any Y vs Z correlations. The ILC design includes hardware support for all these modes of operation. In most cases the "chirped" beam will be imaged via OTR, although in some cases a laser wire scanner may be preferred.

Although the dipole-cavity based bunch length measurement has many virtues, it is invasive to normal beam operation and, at least as designed for ILC, can only operate on a small number of bunches within the train. An additional diagnostic for the bunch length will be provided in the form of high-frequency RF detectors, which measure the power spectrum of the beam within certain bandwidths and thus allow the approximate bunch length to be inferred. These detectors can operate on every train and are completely non-invasive, but they require occasional calibration via another method of bunch length measurement in order to allow the absolute bunch length to be estimated. Because neither the dipole-cavity nor the RF detector method can satisfy all requirements, both will be provided in the ILC.

LUMINOSITY MEASUREMENT

We have already seen that the strong beam-beam interaction in the ILC implies that the beams must collide head-on to within a fraction of their RMS vertical size to provide acceptable luminosity, and that the beam-beam deflection signal gives useful information for the optimization of the relative trajectories of the colliding beams. In fact, there is a rather serious complication of this scheme, to wit: in the limit of strong beam-beam interactions, the shape of the bunch, particularly as seen in the yz plane, has an outsized impact on the luminosity generated in the collision. In fact, for reasonable degrees of "banana" or "S" mis-shapings in the yz plane, the maximum luminosity, zero centroid offset, and zero deflection all occur at different values of the beam-beam offset [11], and the offset which leads to optimum luminosity varies somewhat from train to train.

In this circumstance, the best method to maximize the luminosity is to first zero the beam-beam deflections in order to get close to the optimal solution, and to then directly maximize the luminosity as a function of beam-beam offset within the first few hundred bunches of each train. This implies that the ILC must have a luminosity monitor which is capable of measuring its nominal luminosity with a precision of a few percent in a single bunch crossing, and which has a latency which is sufficiently low to allow the measurement of luminosity to be used to adjust the orbit within the next 1-2 bunch crossings (about 300-600 nsec in the nominal parameters).

MACHINE PROTECTION

At normal incidence, the threshold for thermal damage to the surface of elemental niobium is approximately 5×10^{14} electrons per square cm; for copper at normal incidence the threshold is comparable if incrementally lower, and for titanium at normal incidence the threshold is about an order of magnitude larger [12]. The peak charge density in the ILC is around 1×10^{14} electrons per square cm at the exit of the damping ring, and about 40 times larger at the end of the linac. This indicates that serious damage can be done to the accelerator by even a single bunch out of a train which is mis-steered and encounters an accelerator iris, collimator, or vacuum chamber. The protection requirements for the detector, needless to say, will be even more stringent.

Initial operation of the ILC will therefore be accomplished with "pilot bunches" – single bunches with a low charge and/or large emittance which are incapable of damaging the accelerator. Pilot bunches with charges as low as 1×10^{8} are foreseen. In addition, the current design of the ILC calls for the use of a pilot bunch on each acceleration cycle of the facility: this bunch will be transported through the bunch compressor, main linac, and beam delivery areas approximately 10 microseconds prior to the first luminosity bunch. Any observed deviation of the pilot bunch orbit with respect to the "machine-safe" envelope or unacceptable loss of beam charge from the pilot bunch will trigger machine-protection beam abort systems which will safely remove the luminosity bunches from the beamline. The purpose of this system is to provide an additional layer of safety for some systems, including the particle physics detectors.

In order for the pilot bunch system to work, the ILC must include instrumentation which is designed solely to monitor the passage of the pilot bunch, including both its orbit and its transmission, and which is connected to the master MPS abort logic. This instrumentation must have extremely low latency, since the MPS abort system will already be pressed for time to function properly given the time-of-flight of the signals from the MPS instruments to the nearest upstream abort kickers. In addition, much of the standard suite of beam instruments must be capable of operating with pilot bunches during commissioning, although the exact parameters of their functionality in this mode (for example, resolution requirements for the standard BPMs at very low charge) have not yet been determined.

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