

BEAM DELIVERY SYSTEM IN ILC*

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Abstract

The challenges of the International Linear Collider (ILC) Beam Delivery System (BDS) are reviewed and compared with the achievements in SLC and FFTB. An overview is provided of the necessary R&D for the BDS design, beam simulations and benchmarking in test facilities, especially the ATF2 facility under construction at KEK. The major issues are explored both from the beam dynamics and the technological point of view, as well as the plans foreseen and the schedule to address them.

INTRODUCTION

The BDS is a key sub-system of the ILC that takes the beam emerging from the LINAC and then collimates, chromatically corrects, performs beam diagnostics, and then focuses the beam down to nanometer scales within the detector, before dumping the beams in specialised beam dumps. The worldwide community is currently optimising the BDS design within the ILC Global Design Effort (GDE), which has produced a baseline conceptual design [1] that defines the status of the BDS and provides a very full set of references for more detailed study. An outline of the BDS conceptual design is given in Fig. 1, which shows two BDS sections and two interaction regions (IRs).

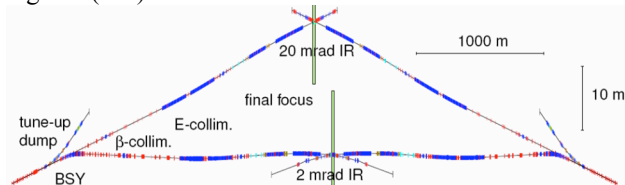


Figure 1: layout of the two IRs and associated BDS sections in the ILC baseline conceptual design.

HISTORICAL OVERVIEW

A proof of principle for the ILC has been provided by the Stanford Linear Collider (SLC) and an important experiment was performed at the Final Focus Test Beam (FFTB), also at SLAC, aiming at 60 nm beam spot sizes; the results of these facilities are presented here as an introduction to the key BDS performance parameters needed for the ILC. The next phase of test facility, the ATF2 at KEK, will be described later.

SLC

The SLC machine was the first of its kind, utilising a linac to accelerate electrons and positrons to 45 GeV and

colliding them head-on after rotating their trajectories in arcs at the end of the linac. The first luminosity was delivered in 1992 and, by the end of the SLC programme in 1998, the luminosity was sufficient to produce 300 Z^0 's per hour, with electron beam polarisation of nearly 80%.

The history and final performance figures of the SLC have been well documented [2]; a selection of the key performance parameters is presented in Table 1, including the horizontal and vertical emittances ϵ_x , ϵ_y achieved at the final focus (FF) and the spot sizes σ_x , σ_y at the detector interaction point (IP).

	Design	Achieved	Units
Beam Charge	7.2×10^{10}	4.2×10^{10}	e^\pm/bunch
Rep Rate	180	120	Hz
FF ϵ_x	4.2×10^{-5}	5.2×10^{-5}	m rad
FF ϵ_y	4.2×10^{-5}	1.0×10^{-5}	m rad
IP σ_x	1.65	1.4	μm
IP σ_y	1.65	0.7	μm
Pinch factor	220%	220%	H_d
Luminosity	6×10^{30}	3×10^{30}	$\text{cm}^{-2}\text{s}^{-1}$

Table 1: Typical finally-achieved SLC operating parameters compared to the design values.

Many lessons relevant to the ILC were learnt by the end of the SLC; those particularly relevant to the BDS include:

- Precision, non-invasive diagnostics will be essential to characterise and monitor the beams; *e.g.* more than 60 wire scanners were eventually installed throughout the SLC. Automated procedures will be needed to provide long term history and to allow correlation with other events.
- Feedback will be essential to combat the inherent instabilities of a linear collider. Several generations of development were required to produce both slow and also pulse-to-pulse feedback systems at the SLC. More than 50 feedback systems were finally employed there to control over 250 beam parameters.
- A variety of innovative optical tuning techniques, developed initially at SLC, will be needed at the ILC; these include precision beam-based alignment and betatron and dispersion matching.
- Care must be taken to minimise synchrotron radiation (SR) in the BDS. Early on at the SLC about 30% luminosity dilution in the FF was due to SR in the bends of the chromatic correction section (discussed further below). This has implications for the BDS layout and upgrades to very high-energies.

*Work supported by PPARC, the Royal Society, and by the Commission of European Communities under the 6th Framework Programme Structuring the European Research Area, contract number RIDS-011899

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- Careful design of the FF region was required to reduce higher-order aberrations. For the BDS, a new optics design is now proposed (discussed below).
- The most difficult problems were almost always those that were not expected.

FFTB

The FFTB [3], which started up in 1993 at SLAC, aimed at focussing an electron beam (from the end of the SLC Linac) to sizes comparable to those required for the ILC, as indicated in Table 2:

	SLC	FFTB	ATF2	ILC
E_{beam} (GeV)	45.6	46.6	1.3	250
σ_E/E (%)	0.25	0.25	0.1	0.1
N_{e^-} ($\times 10^{10}$)	4.2	1	1-2	2
σ_y (nm)	800	60	37	5.7
$\gamma\epsilon_v$ (m-rad)	1×10^{-5}	3×10^{-6}	3×10^{-8}	4×10^{-8}
Asp. ratio x/y	2.5	16	13	115
σ_z (mm)	~ 1	~ 1	~ 5	0.3

Table 2: Parameters of previous (SLC, FFTB), and planned (ATF2 [4]), prototype FF parameters compared to those of the “nominal” ILC [1].

The electron spot-size finally obtained was $1.7\mu\text{m}$ (σ_x) \times 75nm (σ_y), an achievement that required significant advances in beam line optics, control and instrumentation:

- The high chromaticity introduced by the strong focussing doublet, was corrected with a two-family set of non-interleaved sextupoles. For the BDS, this “traditional” FF optics has been replaced, as discussed below.
- The pole-faces of the final quadrupoles were fabricated to a precision of $\pm 2\mu\text{m}$ and the magnet strength stability for critical elements was 10^{-5} .
- A cavity BPM with nm pulse-to-pulse resolution was commissioned at the IP.
- A novel spot-size monitor, the “Shintake monitor” [5], was developed to measure the modulation of the Compton-scattering rate across an interference fringe pattern of two laser beams at the IP. This allowed three different measurement ranges: $0.8\mu\text{m} < \sigma_x < 4\mu\text{m}$, $150\text{nm} < \sigma_y < 750\text{nm}$, and $40\text{nm} < \sigma_z < 200\text{nm}$.
- An ion-scattering beam size monitor [6] was used to measure σ_x and both the aspect ratio and tilt angle of the beam-spot at the IP.
- Beam-based alignment was performed at the beginning of each FFTB run.
- The measurement and matching of the incoming phase space to the FFTB was performed in a section containing five quadrupoles and two skew quadrupoles, while measuring the electron spot-size with wire scanners. In the ILC BDS a similar technique is planned, but using laser-wires [7] as discussed below.

In May 1994 a vertical spot-size of $70 \pm 7\text{nm}$ was obtained at the FFTB [3], as measured by the Shintake monitor. This result is close to the design spot-size of

60nm; the remaining discrepancy might be attributed to vibration of the final quadrupoles. The lessons learnt at the FFTB have been important inputs to the ILC BDS design and, importantly, the project was an excellent training ground for a generation of accelerator physicists. The ATF2 project aims to build on these achievements.

ILC BASELINE BDS DESIGN

The ILC Baseline Conceptual Design [1] will now be outlined, with an emphasis on recent developments and ongoing R&D. The key sub-sections are discussed in order, starting at the exit of the linac and ending after the IP at the beam dumps. Immediately after the Linac, the main elements are shown in Figure 2:

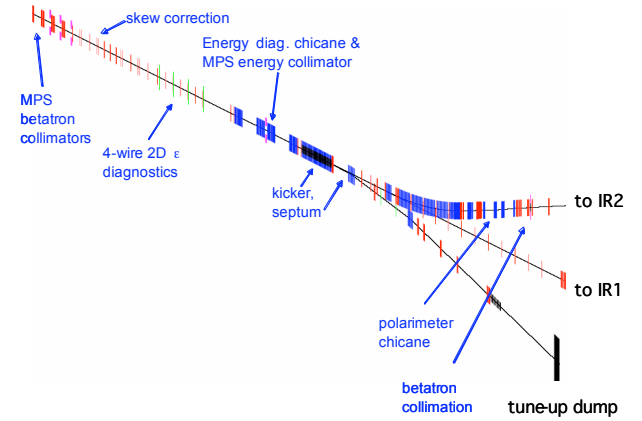


Figure 2: layout of the section of the BDS immediately after the Linac and before the FF region.

Collimation + Machine Protection

A beam halo will accompany the core beam and must be collimated to ensure that no particles in outer regions of phase space can enter the final focus system. This is because the SR generated by their wide trajectories in the final focus quadrupoles would produce unacceptable backgrounds in the detector. Present studies [1] assume a conservative 0.1% beam halo. In addition to transverse phase space (betatron) collimation, protection must be provided against off-energy particles, which is performed by the energy collimators located downstream of the betatron collimators. The performance of the collimation system is currently under detailed study [8].

Each collimator consists of a thin spoiler (0.5 -1 radiation length) followed downstream by thick (~ 30 radiation length) absorbers. The role of the spoiler is to disrupt any bunch that impinges on it such that the bunch has spread out by the time it hits the absorber. The spoiler must be able to survive direct hits from at least 2 bunches, by which time the rest of the train from the linac can be re-directed to a dump before entering the BDS. An alternative is to use consumable spoilers [9].

The spoilers need to collimate very close to the beam and so will generate wake-fields that may disrupt the following bunches. An important R&D programme is

ongoing [10] to measure these wake-field effects and to optimise the design of the collimators.

Skew Correction and Emittance Measurement

The skew correction section (Figure 2) contains four skew quadrupoles separated by appropriate betatron phase advances. It is needed to minimise any coupling between the horizontal and vertical beam phase space so that the small vertical emittance delivered by the damping rings is maintained at the IP. The skew correction method involves modifying the strength of each skew quadrupole while measuring the corresponding beam profile using downstream laser-wire scanners. The current scheme [11] employs four laser-wire scanning systems, each scanning the horizontal and vertical bunch sizes.

The laser-wires in the BDS will require very finely focussed laser-beams with laser waists of order $\sim 1 \mu\text{m}$, fast scanning systems to enable intra-train scans, and high power pulsed lasers with excellent pointing stability, located not too far from the measurement points. A vigorous programme of R&D is currently underway [12] to meet these technical challenges. The laser-wire signal consists of high energy (close to the beam energy) Compton-scattered photons together with off-energy scattered electrons. The current scheme [1] is to extract cleanly the high energy photon signal (totalling up to about 113 TeV per bunch) in a calorimeter located in the downstream energy diagnostics chicane, the location of which is indicated in Figure 2, with details shown in Figure 3:

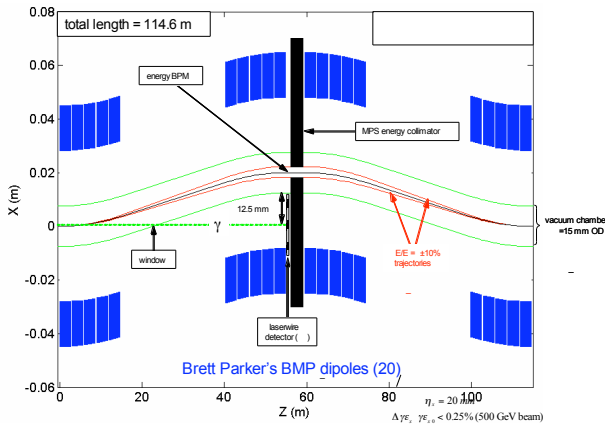


Figure 3: Energy diagnostics chicane, including possible location of the laser-wire photon detector.

In addition to providing a beam energy measurement, this chicane is part of the machine protection system (MPS) because it will enable any off-energy beam to be detected and extracted cleanly to the dumps via the downstream kicker system plus high-bandwidth extraction line.

Final Focus

The main task of the ILC FF system is to focus the beams to the nm sizes required at the IP, which requires strong final doublet (FD) quadrupoles. The corresponding chromaticity of these quadrupoles

combined with the ILC energy spread (Table 2) would, in the absence of chromatic correction, lead to a severely diluted beam size. Chromatic correction is one of the primary drivers of FF optics design. Traditionally (e.g. at FFTB) the chromatic correction was performed in a dedicated section, making the system relatively simple for design and analysis; however a disadvantage was that the chromaticity of the FD was not locally compensated, so the compensation would depend on any energy losses due to wake-fields or SR along the beam-line.

The new approach [13] adopted for the ILC:

- corrects chromaticity as locally as possible,
- minimises the number of bends,
- maximises the dynamic aperture,
- minimises the number of elements,
- reduces the length of the BDS significantly,
- increases the energy bandwidth of the FF system,
- eases the scaling of the system to higher energies.

This was achieved by interleaving two sextupoles with the two FD quadrupoles and a bend upstream to generate dispersion across the FD to cancel locally the chromaticity. The geometric aberrations introduced by the sextupoles are cancelled by two more sextupoles upstream of the bend. In addition, four more quadrupoles are needed at the front, to match the incoming beam [13].

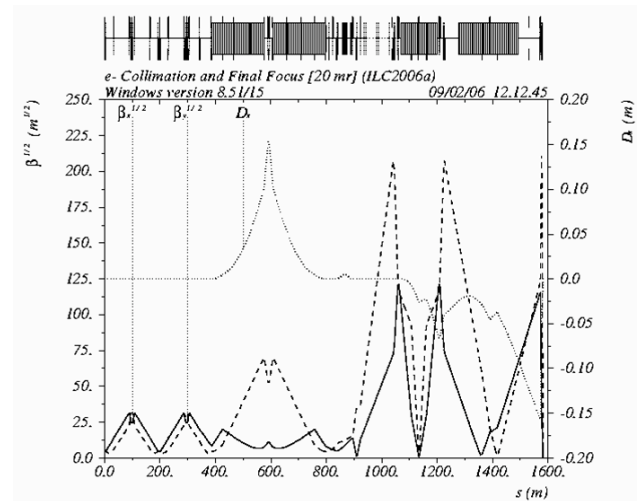


Figure 4: The optics of the collimation and FF system of the ILC BDS.

Interaction Region Issues

The ILC baseline has two IRs, one with a crossing angle of about 20 mrad and one of about 2 mrad. Other schemes are also under study, including one of 14 mrad [14] and a head-on scheme [15]. A detailed discussion of the pros and cons of each scheme can be found in [1].

The larger crossing angle solutions separate the incoming beam from the spent beam, with no shared FF magnets as illustrated in Figure 5 for a design with a 14 mrad crossing angle. This separation makes it easier to find a beam optics solution for the spent beam extraction line, at the expense of some detector hermeticity in the forward region. In addition the larger crossing angles are

more reliant on a “crab cavity”, which rotates the bunches about their centre, so as to maximise their overlap at the IP; otherwise they would pass through each other at the crossing angle with subsequent loss of luminosity. A major R&D programme is underway to develop suitable crab crossing systems [16].

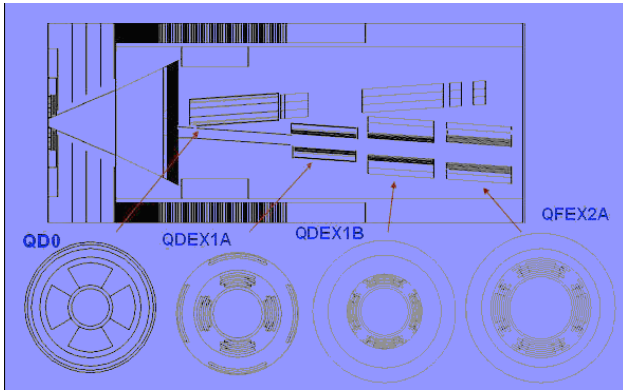


Figure 5: 14 mrad crossing angle IR [14]. The incoming beam is separated from the outgoing one.

The small crossing angle IRs are generally favoured from the viewpoint of detector hermeticity and are less reliant on the crab crossing system. However the fact that the incoming and outgoing beams must share the inner most magnets reduces significantly the design flexibility. Work is ongoing [17] to optimise the 2mrad design to reduce the backgrounds and to minimise energy losses in the critical elements.

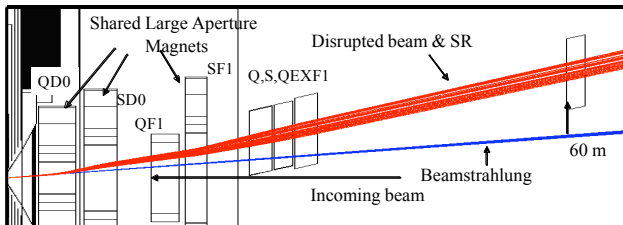


Figure 6: 2mrad solution, where incoming and outgoing beams must share the magnets closest to the IP.

The IR must also house the intra-train feedback systems, which are needed to ensure that the electron and positron bunches meet at the IP, even though the FD quadrupoles will be moving relative to each other due to ground motion and other cultural noise present in the IR. When the electron bunches are sufficiently close to experience the electromagnetic fields of the incoming positrons, the resultant bunch deflections are measured downstream using dedicated beam position monitors (BPMs). Since deflection is function of IP bunch separation, the BPM readings provide a measure to kick the incoming bunches such that they collide at the IP. A vigorous R&D programme [17] is ongoing to address the detailed technical issues. In addition a major simulation effort is underway to understand how the feedback may work in practice [18]. An example of the output from such simulations is shown in Figure 7, where it is shown

that the beams are brought rapidly into collision so that the full luminosity is achieved within a small fraction of the 2820-bunches of an ILC train.

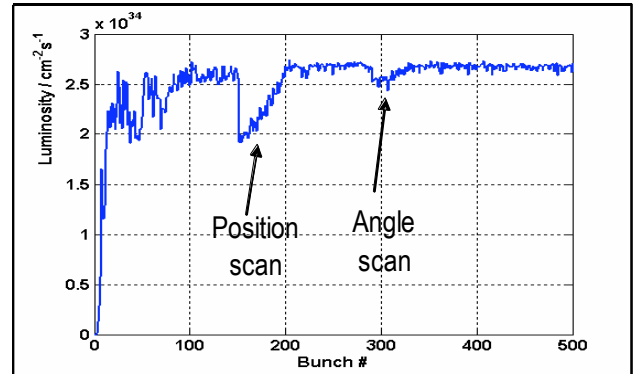


Figure 7: Simulations of how the intra-train feedback system may work in practice.

Because of the nm IP beam sizes at the ILC, the IR component position stability requirements will be as small as a few nm. An intensive programme of R&D has been carried out at the KEK Accelerator Test Facility (ATF) to test RF cavity BPMs, which could in principle provide resolutions of less than one nm and thereby form the basis of the desired beam-based stability measurement. These BPMs will be particularly important at ATF2, where there is no beam-beam effect to utilise for nm sensitivity. To date, they have been able to demonstrate a resolution of ~ 20 nm over a dynamic range of ± 20 μm [20].

BDS Beam Instrumentation

In addition to the BDS machine-specific instrumentation, additional precision beam measurements are needed for the ILC physics programme. Very accurate energy spectrometry is required ($\sim 10^{-4}$) in order, for instance, to measure the top-quark mass to the required precision. A BPM spectrometer is being investigated to do this, using cavity BPMs at the SLAC End Station A [20], aiming at a system for measurement upstream of the IP at the ILC.

Polarized beams will play a key role in the physics programme at the ILC. It is expected that the electron and positron sources will be able to produce beams with polarizations of about 90% and (possibly) 60% respectively. A precise knowledge of the polarisation at the IP is necessary and a strong programme of R&D is ongoing to understand the spin tracking issues [22]. Measurement of the polarisation will be made both upstream and downstream of the IP using Compton polarimeters [23].

Beam Dumps

The ILC baseline [1] has two beam dumps per IR, each rated to 18MW, together with additional beam dumps for tuning and machine protection. Nearer the IP, beamstrahlung dumps are required, rated up to 3MW each. The current proposed technology is a pressurised

water dump, similar to that used at the SLC. An alternative based on a long (~1 km) column of argon gas has also been proposed. Further details are reviewed in [24].

ATF2

The ATF2 project [4] will be located at an extension of the current ATF facility at KEK, as shown in Figure 8, so as to use the very small emittance beams from the ATF damping ring in order to build a prototype BDS. The parameters of the ATF2 beam are listed in Table 2.

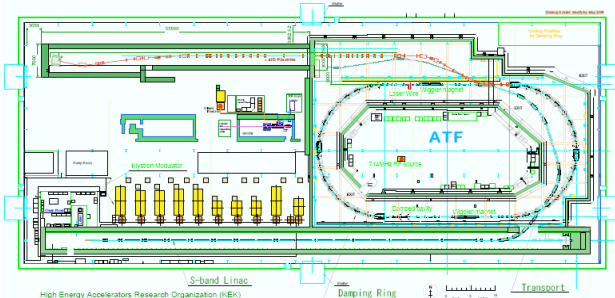


Figure 8: Planned layout of the ATF2 project

The ATF2 project is structured as two phases. In phase A the aims are to:

- demonstrate the compact final focus system based on local chromaticity correction,
- achieve a spot-size of 37 nm,
- maintain the small spot-size over extended periods.

The aims of phase B are to:

- demonstrate beam orbit stabilisation with nm precision at the IP,
- establish control of beam jitter at the nm level, with an ILC-like beam.

Many of the key technologies, described above as requirements for the BDS, will be developed and tested at ATF2; these include fast feedback systems, fast kickers, nano-BPMs, laser-wires and an upgraded Shintake monitor (originally used at FFTB). Most importantly, the ATF2 project will provide the appropriate training to young scientists and engineers, who will eventually build the ILC BDS.

The civil engineering required to extend the current ATF facility for ATF2 will start in summer 2007 and first commissioning of the new beam-line is planned to start in 2008.

ENERGY UPGRADE

The ILC BDS is designed so that both IRs can operate at up to a centre-of-mass energy of 1 TeV without significant loss of luminosity. If multi-TeV energies are to be considered then the main constraints affecting the BDS are [1]:

- a crossing angle of about 20 mrad is required
- any horizontal bend between the high energy end of the linac and the BDS should be less than 2 mrad. There should be zero vertical bend.

- The final stages of the linac should be laser-straight; this will enable extension of the BDS into the linac tunnel, in case it proves necessary.

SUMMARY

The ILC BDS baseline designs are well advanced, however there is still a lot of R&D to do before all the demands can be met. A new generation of physicists are meeting these challenges head-on at international test facilities; an exciting time lies ahead.

ACKNOWLEDGEMENTS

The author is grateful to the large number of people who have contributed to the ILC BDS baseline design, from which much of the material presented here was extracted. Special thanks are due to A. Seryi, M. Woodley for providing additional information.

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