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THE ILC BEAM DELIVERY SYSTEM – CONCEPTUAL DESIGN AND R&D PLANS [*]

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Abstract

The Beam Delivery System of the ILC has many stringent and sometimes conflicting requirements. To produce luminosity, the beams must be focused to nanometer size. To provide acceptable detector backgrounds, particles far from the beam core must be collimated. Unique beam diagnostics and instrumentation are required to monitor parameters of the colliding beams such as the energy spectrum and polarization. The detector and beamline components must be protected against errant beams. After collision, the beams must also be transported to the beam dumps safely and with acceptable losses. An international team is actively working on the design of the ILC Beam Delivery System in close collaboration. Details of the design, recent progress and remaining challenges will be summarized in this paper.

INTRODUCTION

The present document describes the goals and status of the International Linear Collider (ILC) Beam Delivery System (BDS), designed internationally with participation of many laboratories and institutions around the world. It also outlines a roadmap for arriving at a baseline ILC configuration by the end of 2005 and for producing a Conceptual Design Report with cost evaluation by the end of 2006.

Design of the ILC Beam Delivery System has to satisfy many stringent and sometimes conflicting requirements. To produce luminosity, the beams must be focused at the Interaction Point (IP) to a size of about 500 by 5 nm. To provide acceptable detector backgrounds, particles far from the beam core must be collimated. Unique beam diagnostics and instrumentation are required to monitor parameters of the colliding beams such as the luminosity spectrum and polarization. Ideally, there should be energy and polarization diagnostics both upstream and downstream of the IP. The incoming beam properties must be measured in the BDS diagnostics sections to facilitate tuning of the machine. Fast intra-train and slow inter-train feedbacks are needed to keep the beams in collision and maintain the small beam sizes. The detector and beamline components must be protected against errant beams. After collision, the beams must be transported to the beam dumps safely and with acceptable losses. The Interaction Region (IR) design must be compatible with the detector size, the solenoid field, the configuration of the vertex detector, and other parameters of the various detector concepts. The issues of constructability and cost minimization are important and require close collaboration with the Conventional Facilities group.

The BDS design for the linear collider is quite mature. The Final Focus (FF) optics evolved from the SLC design with chromaticity correction by interleaved sextupoles, to a design with non-interleaved (for horizontal and vertical planes) sextupole pairs, which was verified experimentally at the Final Focus Test Beam (FFTB) and the KEK B-Factory. The lessons learned at these facilities resulted in the recently proposed FF with local chromaticity correction [1]. Designs for the IR, BDS instrumentation and beam dumps follow the lessons learned at SLC and at other colliders.

The earlier LC proposals, NLC/GLC and TESLA, adopted different approaches to the BDS design, primarily because of the format of the beam pulse trains, and also partly because of the IR configuration. The NLC/GLC bunch spacing was only a few nanoseconds so a crossing angle was required to avoid parasitic beam collisions. The TESLA bunch spacing was several hundred nanoseconds, allowing head-on collisions, in principle, so the main IR had zero crossing angle (the second optional IR had a crossing angle of 34 mrad suitable for gamma-gamma) and the linacs pointed to the head-on IR.

The TESLA head-on IR design used electrostatic separators overlapped with a magnetic field to bend the disrupted beam while compensating for the kick on the incoming beam. The head-on approach required that the Final Doublet and near-IR photon collimation masks would be shared by the incoming and outgoing disrupted beam and that collimation requirements would be set by both the incoming and outgoing beams. The need to provide a large bend to extract the disrupted beam (which has significant energy spread) just after the IP, and the coupled design constraint for the incoming and outgoing beamlines present challenges for the head-on scheme. The Technical Review Committee evaluation stressed the problems with the head-on IR design, such as large beam losses in the extraction line, beamstrahlung photon losses on the septum, reliability problems of the electrostatic separators, and difficulty to extend the design beyond 500 GeV CM [2].

An IR design with a sufficiently large crossing angle ($\sim$20 mrad) to allow independent incoming and outgoing beamlines avoids these difficulties. However, it requires development of a crab-cavity and compact final focusing quadrupoles and may have somewhat less detector hermeticity. More recently, several conceptual ideas were proposed to effectively preserve the physics advantages of head-on collisions while avoiding the most sig-

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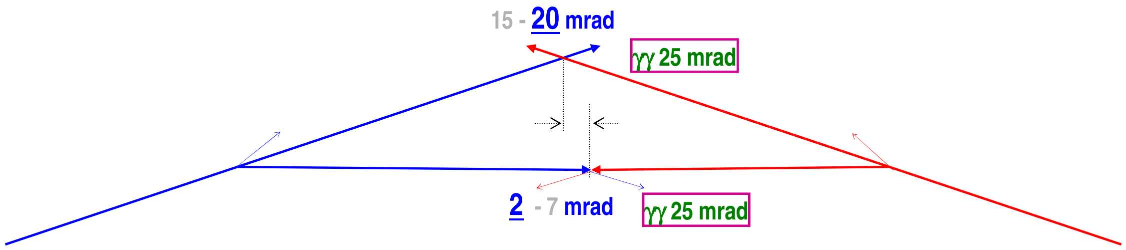

Figure 1: Tentative, not frozen configuration, working hypotheses, "strawman", recommended by the Working Group 4 at the first ILC workshop [4].

nificant problems. A scheme with small vertical crossing angle (0.3 mrad) was suggested by R. Brinkmann and a scheme with small horizontal crossing angle was suggested by O. Napoly originally in 1997 for CLIC and discussed in application for ILC in [3].

At the 1st ILC workshop at KEK in November 2004, the major undetermined parameter of the BDS design was the crossing angle and the choices ranged from head-on, to very small vertical or small horizontal crossing angle, to the large horizontal crossing angle (7-20 mrad) developed for NLC/GLC.

TENTATIVE BDS BASELINE

The ILC Beam Delivery System is being designed by an active international group, with overall more than a hundred people involved. Good communication helped the BDS group to start discussion of the baseline configuration before the first ILC workshop, and to come up with a tentative baseline configuration at the workshop [4]. This tentative baseline, described below in detail, has remained the focus of subsequent design efforts without major changes.

Several critical assumptions, which are beyond the scope of the BDS group, have been adopted for this baseline design. First, following the recommendation of the particle physics community, we assume that ILC will have two interaction regions, which could possibly focus on different physics programs, and allow for different approaches to the search for new physics. Second, to provide a complementary physics program at the two IRs, one of the IRs has a rather large crossing angle, providing optimized performance for e+e- and allowing the possibility of gamma-gamma collisions, while the other IR has a very small crossing angle, providing maximum detector hermeticity, which may be important for studies of certain SUSY scenarios. It is however recognized that the design of an IR with a small crossing angle is more difficult and has larger performance risk, especially at higher energies. Finally, we assume that multi-TeV collisions, provided either with CLIC technology or with some other now still exotic technique such as plasma acceleration, should not be precluded in the future by the choice of BDS configuration. Since CLIC requires a crossing angle, extraction of multi-TeV beam is much easier with crossing angle, and since bending must be minimized at high energy, the linacs should point towards the large crossing angle IR. This also facilitates lengthening the BDS if required for multi-TeV.

For the large crossing angle IR, the impact on e+e- luminosity has been evaluated for different choices of crossing angle, particularly between the ~35 mrad suitable for gamma-gamma and the NLC/GLC angle of 7-20 mrad. Several effects make the 35 mrad less favorable for e+e- collision: tighter phase stability requirements for the crab cavities; larger emittance growth due to synchrotron radiation (SR) in the detector field which scales as $\theta_c^{5/2}$; wider pairs distribution; modest loss of efficiency for dark matter/SUSY candidates and poorer rejection of background (loss of tagging electrons close to beam). Overall, there was clearly decreased performance at 35 mrad with respect to the optimal 7-20 mrad. The group concluded that at the present time, the IR and detector should be optimized for e+e-, i.e. crossing angle of at most 20 mrad. Later the detector and IR could be modified for gamma-gamma running when needed. This also took into account that most of the hardware needed for gamma-gamma is still in a conceptual stage and requires significant R&D, prototyping and demonstration before a run decision (e.g. the IR design which accommodates disrupted beam with large angles, large aperture extraction line, optical cavity to reduce the laser power by a factor of a hundred, etc.).

Considering the choices between head-on and very small crossing angle solutions, the advantages and disadvantages of each scheme have been reviewed. In the TESLA head-on scheme, large losses were predicted in the extraction line, especially at 1 TeV. The design is also not compatible with post-IP energy and polarization diagnostics. The electrostatic separator requires a field of 50 kV/cm at 500 GeV CM and 100 kV/cm at 1 TeV CM (while the value typically used in LEP operation was 30 kV/cm, and 50 kV/cm was used in conditioning). This raises feasibility questions in a high SR environment and MPS issues. The photon losses at (or near) the septum were estimated to be 5-15 kW, which would cause irradiation, background, and concerns about survivability. With the reduced bunch spacing at 1 TeV CM, a parasitic collision would occur at 26.5 m from IP. The SR masking is overconstrained because of shared incoming and outgoing apertures.

The small vertical ($\theta_c \sim 0.3$ mrad) crossing angle solution preserves the physics advantages of the head-on scheme and eliminates the losses at the septum (modulo discussion whether the margin is sufficient). However, the electrostatic separator would still be needed, and there are

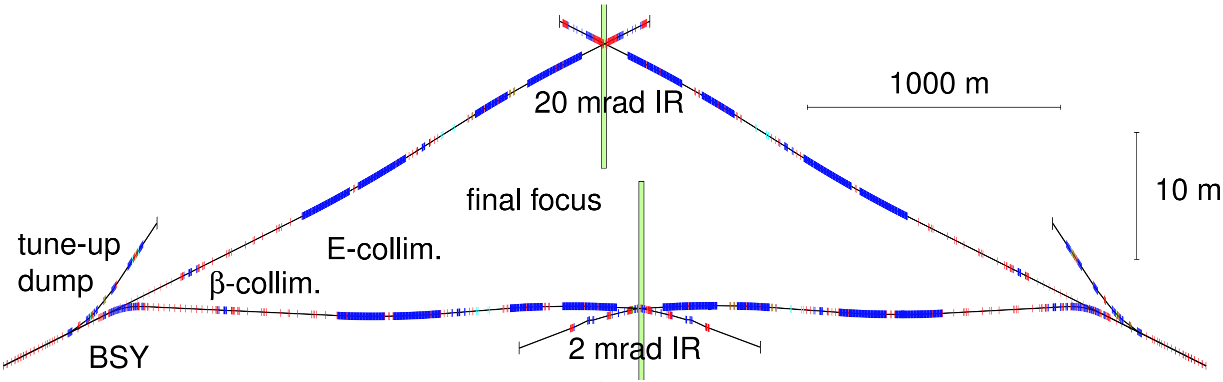

Figure 2: Layout of the present ILC BDS.

new issues: the vertical crab-crossing has rather tight phase stability, and the Final Doublet may need to become a quadruplet to reduce overfocusing of the disrupted beam.

On the other hand, the concept of a small horizontal crossing angle (1.5-2 mrad) is attractive, as it has the major advantages of head-on (in terms of detector hermeticity for SUSY coverage), requires only very minor crab-crossing, avoids septum, electrostatic separator and parasitic crossing, and might allow for post-IP diagnostics.

During the first ILC workshop at KEK, these considerations together with the desire for diverse physics with minimum performance risk, led the BDS group to concentrate on a strawman configuration shown schematically in Fig. 1. There are two IRs, one with 20 mrad crossing angle (with a possible range for studies of 15-20 mrad), and the other with a 2 mrad crossing angle (with a possible range for studies of 2-7 mrad). The possibility of gamma-gamma collisions with 25 mrad crossing angle (given recent developments with compact SC quads that could allow a gamma-gamma crossing angle as small as $\sim$25 mrad) was to be evaluated for either IR (which may require moving beamlines and additional tunnels). Given the shallow angle between the two BDS tunnels, the two interaction halls were offset longitudinally by about a hundred meters to provide sufficient transverse separation. The linacs point toward the 20 mrad IR, with minimal bending.

In this concept, the impact of crossing angle on physics and machine risk performance is minimized, there are separate extraction lines with pre- & post-IP diagnostics in both IRs, the layout is optimized for e+e-, while the civil engineering modification needed to create 25 mrad at either IR for $\gamma\gamma$ is yet to be studied. The longitudinal separation between IRs guarantees access to one detector while the other is in operation.

One impact of the longitudinal IR separation on the overall design is that the bunch spacing must be an exact multiple of a given number, for example, 2*176 ns at 500 GeV and 176 ns @ 1 TeV. (The TDR specified a bunch spacing of 337 ns @ 500 GeV and 176 ns @ 1 TeV, which are not exact multiples, but were allowed by the zero longitudinal separation between IRs.) One could separate the IR halls transversely by substantially lengthening the site, but this would be too costly.

The tentative configuration selected by WG4 at the ILC workshop still required significant effort to develop into a complete design. This included completing the optics design for both IRs with all diagnostics and extraction, evaluating the physics impact of the strawman configuration, analyzing the impact of detector concepts on optimization of IR parameters, developing civil engineering plans including provision for $\gamma\gamma$ option, etc. The next section describes recent progress in developing this baseline.

PROGRESS TOWARD THE BASELINE

Since the 1st ILC workshop, the BDS design has progressed significantly. The design of the 20 mrad crossing angle IR, optics and magnets have been refined. The concept of the 2 mrad crossing angle has been developed in sufficient detail in terms of the optics, magnet design and layout, so that modeling of backgrounds, beam losses in the beamline with nominal and high luminosity parameters, and a conventional facilities design can be evaluated and compared with the performance of the 20 mrad IR. There is an ongoing effort to design the IR and magnets for the gamma-gamma option to fit the 20 mrad IR. The work will continue and a fully detailed baseline configuration prepared by the Snowmass Workshop in August, 2005.

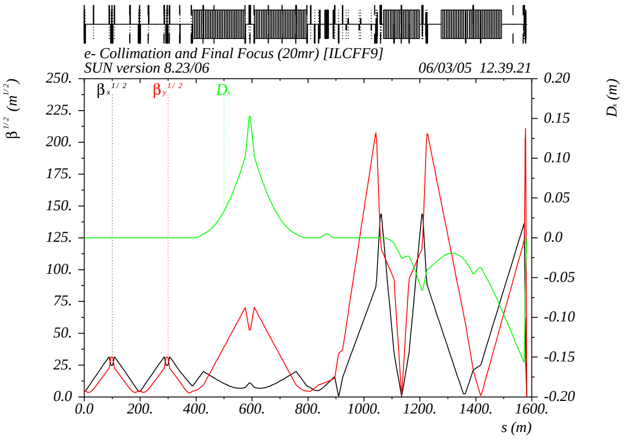

Figure 3: Optics of incoming BDS beamline optimized for 20 mrad IR (ILC-FF9).

The BDS optics for the 20 mrad IR is shown in Fig. 3 (version ILC-FF9). It is based on the NLC design with the following modifications: the beam size at the betatron collimation spoilers is increased in area by a factor of 10 to allow passive survival if impacted by one or two bunches; an energy spectrometer chicane is inserted between the energy collimation and final focus proper; a polarimeter chicane is inserted upstream of the betatron collimation (see [5], notes on March 8, 2005).

Recent achievements at BNL with direct winding technology (see B.Parker et al. in [6]) have further improved the design of the compact superconducting magnets for a 20 mrad IR. The feasibility of automatic winding of seven-strand SC cable with a tight bend radius has been demonstrated. This allows the first SC final quad QD0 to be even more compact, and the first extraction quad to start at the same distance from the IP, as schematically shown on the left in Fig. 5, which greatly improves extraction performance. Moreover, these advances in compact SC quad design make it possible to design a $\gamma\gamma$ IR with a crossing angle much smaller than the $\sim$35 mrad considered earlier – 25 mrad or possibly even 20 mrad. If the latter is possible, one of the IRs would be directly upgradable for $\gamma\gamma$ without the need to move the beamlines.

Design of the extraction line for 20 mrad IR was refined in several iterations to use the advantages of the latest compact SC quad combined with the extraction quad, to optimize the extraction performance and reduce particle losses, and to optimize the performance of the energy and polarization diagnostics in the extraction line (see Y.Nosochkov et al. in [6]).

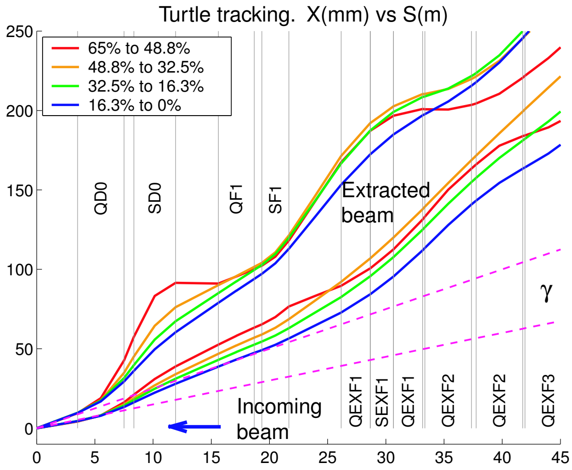

Figure 4: Tracking of extracted beam in 2 mrad IR.

Design of the 2 mrad IR has progressed from a concept to real optics. The first large bore SC quad QD0 is shared between incoming and outgoing beams. The next quad QF1 is a pocket-coil iron quad, with the disrupted beam going between the poles of QF1 in reduced field, resulting in a total kick that increases the separation from the incoming beam and helps extraction. For the disrupted beam with large energy spread ($\sim$60% or more) the kick by QD0 would defocus and disperse the beam and would result in beam losses unless a fast-alternating defocusing-focusing optics could be arranged. The final focus with local chromaticity correction, with sextupoles in the final doublet, provides just what is needed. For a particular sign of the crossing angle, the first sextupole SD0 focuses the disrupted beam. In order to maximize the energy bandpass of the extraction optics, the FD has been optimized to simultaneously satisfy both the incoming FF and extraction optics requirements (see Y.Nosochkov at al. in [5], notes of February 22, 2005).

Tracking of the extracted beam with 65% energy spread is shown in Fig. 4. The beamstrahlung photons initially follow the beam, but are then separated and directed to the dedicated photon dump. Special magnets with large aperture for disrupted beam and photons and with zero-field region for the incoming beam are needed to make this extraction design possible. Two designs for such challenging magnets have been considered – the Super Septum quad and Panofsky-style warm septum quad (see B.Parker and C.Spencer in [7] and B.Parker et al. in [6]). Using such specialized magnets, a first iteration of the 2 mrad design has been developed (see Y.Nosochkov et al. and R. Appleby et al. in [7] for the US-UK-France 2 mrad design task force). First evaluation of backgrounds in the 2 mrad IR indicated that the design performs rather well for the nominal ILC parameters, with no losses of beam or photons on beamline elements (see T.Maruyama in [7]). Design of the downstream energy and polarization diagnostics has been started (K.Moffeit in [5] notes on April 22, 2005) and will be further optimized.

The present optics of all BDS beamlines is shown in Fig. 2 (see [8]). Overall, counting the two interaction regions, there are almost eleven kilometers of diverse beamlines, instrumentation sections, beam dumps, detector systems and conventional facilities.

The BDS design will continue to be further optimized, in particular the 2 mrad beamlines. Design of subsystems, such as magnets, collimation (see N.Mokhov et al. in [6]), crab-cavities (see C.Adolphsen in [5], notes on March 1, 2005, and P.Goudket et al., in [9]), instrumentation, beam dumps, feedback and machine protection systems, etc. will continue.

Together with the present working baseline design, the BDS group is considering and evaluating several variations, in particular, alternative schemes for head-on or quasi-head-on collisions. A head-on scheme with an RF kicker based on a Finemet magnetic core has been suggested (see Y.Iwashita in [10], notes on February 16, 2005). MPS issues and significant losses of the disrupted beam (see L.Keller in [5], notes on March 8, 2005) makes this scheme problematic. Such ideas will continued to be explored in order to allow evaluation and comparison with the baseline.

BDS RELATED TEST FACILITIES

Beam tests are crucial to mitigate risk for the ILC. Such tests have a long lead time and therefore need to be planned and started sufficiently early for them to have a positive impact on the final design of ILC. Below we briefly describe

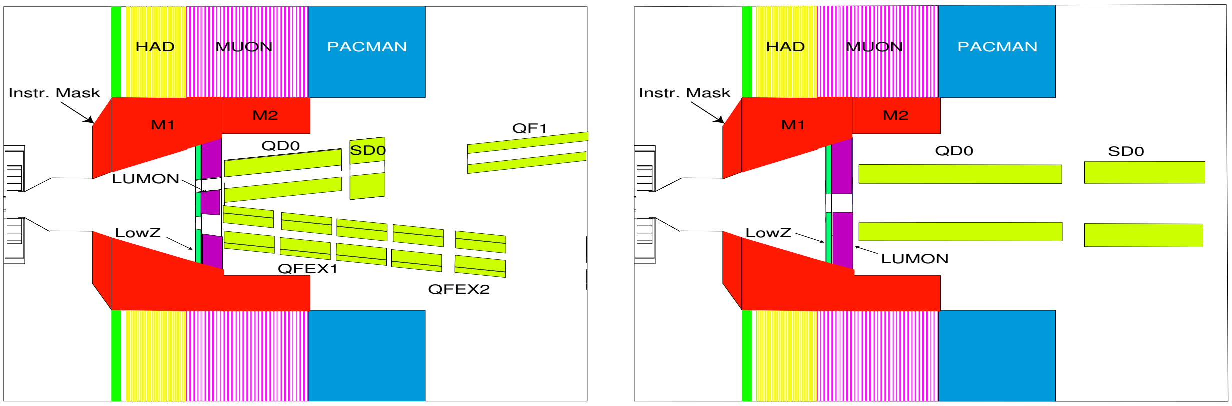

Figure 5: Schematics of 20 (left) and 2 mrad IRs with SiD detector. Geant models by T.Maruyama [7].

the beam tests and engineering developments relevant to BDS, which are current, planned or under discussion.

The BDS related beam tests are expected to be mostly conducted in two dedicated areas: End Station-A (ESA) beamline at SLAC (see M.Woods et al., in [6]) and ATF at KEK. For the latter, a BDS dedicated facility, ATF2, is being proposed, as described below.

A number of tests and developments relevant to BDS are ongoing at ATF, such as the laser wire, high resolution BPMs, optics correction techniques, fast intra-train feedback and various other techniques and instrumentation.

Among the tests proposed at ESA are investigations of the precision achievable in an energy spectrometer in real beam conditions, study of collimator wakefields, beam damage tests of prototype spoilers, study of electromagnetic interference effects with the SLD vertex detector, prototyping of the IR region, etc.

A special facility dedicated to ILC BDS studies is proposed at ATF, called ATF2 (see [11, 12] and S. Araki, et al. in [6]). The ATF damping ring, which is the only facility in the world producing the uniquely small ILC beam emittance, would be extended with a compact ILC-like final focus system capable of focusing the beam to 35 nm vertical beam size. The ATF2 will move beyond what was achieved at FFTB: it would not only achieve the small beam size, but also allow it to be maintained for a long time, with the eventual goal of demonstrating nanometer scale stability.

ATF2 would support studies of the properties of the final focus with local chromaticity correction, development of optics diagnostics and tuning techniques, and development of BDS instrumentation, while also providing a facility where young physicists can learn the techniques needed for design and operation of the ILC BDS. It is expected that ATF2 will provide valuable information for the ILC TDR, and would continue to serve during ILC construction and beyond.

DEVELOPING THE BDS CDR

The present stage “from concepts to optics & from boxes on the layout to GEANT models” will continue in 2005. The goal is to finish most of this before Snowmass. The next stage will focus on performance studies and further optimization of the design, DR to IP studies for the machine and machine-detector performance evaluation. An iteration of such studies should be done before the end of 2005. An evaluation of the impact of various parameter sets (nominal, high luminosity, etc.) on performance should be completed. The baseline configuration will then be finalized by the end of 2005. Ongoing engineering design and tests will continue and mature. The third stage will focus on an engineering design sufficiently detailed to develop a cost estimate. The beam tests and tests of detector components will continue. Civil construction studies will continue along with evaluation of the cost impact of parameters and options. This will be done during 2006 and result in a CDR with cost by December 2006.

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