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Machine-Detector Interface Issues for the ILC Polarimeters*

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This note examines several Machine-Detector Interface (MDI) issues for the Compton polarimeters in the Beam Delivery System of the International Linear Collider (ILC), including i) alignment tolerances, ii) impact of crossing angle and IR magnets on spin alignment, iii) Z-pole operation, and iv) costs and conventional facilities.

1. Introduction

Four Compton polarimeters are included in the Beam Delivery System (BDS) for the ILC.[2,3] There are two polarimeters, one upstream and one downstream of the collider IP, for each of the electron and positron beams. A layout of the BDS showing the polarimeter locations is shown in Figure 1. The upstream polarimeters are 1800 meters upstream of the collider IP with a horizontal offset of 1.5 meters, while the downstream polarimeter is 170 meters downstream of the IP with no offset.

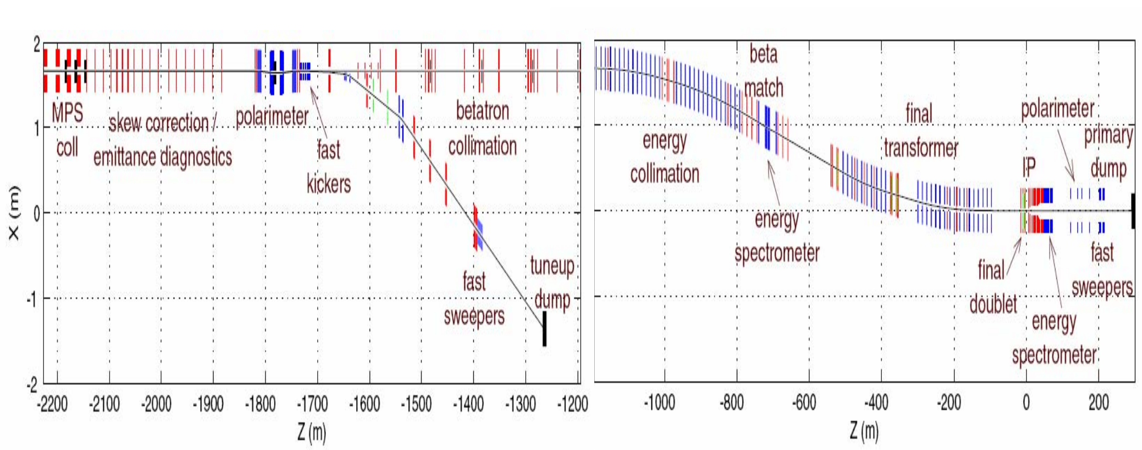

Figure 1: Schematic of the Beam Delivery System.

The polarimeters employ magnetic chicanes with parameters shown in Table 1. In the ILC Reference Design Report (RDR)[2] the upstream polarimeter chicane is designed to accommodate a laserwire detector and a machine-protection energy collimator. The inclusion of these additional functions compromises the polarimeter performance, and work is ongoing to address this.[4] The downstream polarimeter chicane successfully accommodates a detector for the downstream energy spectrometer and provides magnetic elements for the GAMCAL system.[5]

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Table 1: Magnetic chicane parameters for the BDS Compton polarimeters.

Spectrometer Parameters	**Upstream Polarimeter**	**Downstream Polarimeter**
Spectrometer Length (m)	76.9	72.0
# magnets	12	6
Magnetic Field (T)	0.0982	0.4170 (1, 2) 0.6254 (3, 4) 0.4170 (5,6)
Magnet Length (m)	2.4	2.0
Magnet ½-gap (cm)	1.25	11.7 (1-3) 13.2 (4) 14.7 (5,6)
Magnet pole face width (cm)	10.0 (1-3) 20.0 (4-9) 30.0 (10-12)	40.0 (1-3) 54.0 (4) 40.0 (5-6)
Dispersion at mid-chicane, for E_{beam} = 250 GeV	20mm	20mm

The polarization measured by the polarimeters can differ from the luminosity-weighted polarization relevant for physics analyses due to spin alignment and beam transport effects between the polarimeter Compton IP and the collider IP. Beam-beam collision effects can also contribute to this difference and are described in Reference [6]. Section 2 of this paper discusses alignment tolerances for the beam transport elements, while Section 3 discusses the impact of the crossing angle and IR magnets on spin alignment.

The baseline ILC described in the RDR[2] provides collider physics with beam energies in the range 100-250 GeV. Precise polarimetry is required for this full energy range. The RDR also provides for detector calibration at the Z-pole with 45.6 GeV beam energies. However, the RDR does not require accurate polarimetry or energy spectrometer measurements at the Z-pole. A proposal to modify the baseline ILC to require precise polarimetry and energy measurements at Z-pole energies is being put forth,[7] and Section 4 of this paper describes some of the reasons for this. The downstream polarimeter described in the RDR is expected to perform well at the Z-pole, while the upstream polarimeter performance is degraded due to inclusion of the laserwire detector and the energy collimator in the system design.

The ILC is a very expensive machine, which is resulting in significant time delays and increased efforts on alternative accelerator designs. Careful cost evaluation and cost optimization is a major priority for the project. One cost cutting measure being considered is to eliminate either the upstream or downstream diagnostics for polarimetry and precise energy measurements, which would reduce the number of polarimeters from four to two and similarly for the energy spectrometers. An overview of the polarimeter costs is presented in Section 5, along with a discussion of the merits for having both upstream and downstream diagnostics.

2. Alignment

Misalignments between the beam trajectory at the polarimeter Compton IP and the collider IP will result in a pointing error for electron or positron spin vectors. Spin precession due to any net bend angle between these locations is described by the BMT equation,

$$\theta_{spin} = \gamma \frac{g-2}{2} \cdot \theta_{bend} = \frac{E(GeV)}{0.44065} \cdot \theta_{bend}$$

At E=250 GeV, the net spin rotation and polarization projection as a function of net bend angle is given in Table 2 for bend angles of 50 and 100 μrad.

Table 2: Spin rotation and resulting polarization projection for bend angles of 50 and 100 μrad.

θ_{bend}	θ_{spin}	$\cos(\theta_{spin})$
50 μrad	28.3 mrad	0.9996
100 μrad	56.7 mrad	0.9984

The goal for beam trajectory alignment is to keep any net bend angle between the collider IP and the Compton IP, for either the upstream or downstream polarimeters, to be less than 50 μrad. This will keep differences in the longitudinal polarization at these locations below 0.1%. Accelerator component alignment tolerances are described in Reference [2] and are summarized in Table 3. As can be seen from this table one expects to achieve component alignments of 1 μrad over distances up to 200 meters. One should be able to extrapolate this to achieve alignments of 10 μrad over distances up to 2000 meters, thereby achieving the alignment goals for both upstream and downstream polarimeters. There will be a complication for the upstream polarimeter which has a net horizontal offset of 1.5 meters from the collider IP. The alignment goal should still be achievable, but the procedure for this needs to be fleshed out.

An important check of the spin alignment will be comparing optimized spin rotator settings for the upstream and downstream polarimeters. Ideally, these settings should be identical. Quantifying any deviations will be important for determining and checking systematic effects for spin alignment, as well as for developing correction procedures. Additionally, it will be important to monitor correlations of polarimeter measurements with local BPM trajectories, and the downstream polarimeter will need to monitor correlations with IP BPM trajectories. As discussed in Reference [8], if the spin is misaligned between the collider IP and the downstream polarimeter Compton IP there will be a significant dependence of the measured polarization on the beam-beam collision horizontal offset. This will cause an error in determining the luminosity-weighted polarization if not corrected for. It also provides an excellent opportunity for checking and determining any spin misalignment between the collider IP and the Compton IP. The measured polarization should have a symmetric dependence on the beam-beam offset. An asymmetric result can be used to determine systematic errors in the spin alignment, and possibly to develop a procedure for correcting this as well.

Table 3: Accelerator component alignment tolerances (taken from Table 4.7-1 in Reference [2]).

Area	Type	Tolerance
Sources, Damping Rings and RTML	Offset	150 μm (horizontal and vertical), over a distance of 100 m.
	Roll	100 μrad
Main Linac (cryomodules)	Offset	200 μm (horizontal and vertical), over a distance of 200 m.
	Pitch	20 μrad
	Roll	
BDS	Offset	150 μm (horizontal and vertical), over a distance of 150 m around the IR.

3. Crossing Angle and IR Magnets

A crossing angle between the colliding beams means that the beam trajectory and the detector solenoid axis will be misaligned. This causes a vertical deflection of the beam and also impacts the trajectory of low energy pairs produced in the collision as discussed in Reference [9]. A detector-integrated dipole (DID) can be included in the solenoid to compensate either for the beam trajectory at the IP or the trajectory of low energy pairs as they leave the IR. For background reasons it is preferable to align the trajectory of low energy pairs with the extraction beamline (anti-DID solution), but this results in a significant vertical beam angle at the IP. An example of this is shown for the SiD in Figure 2.

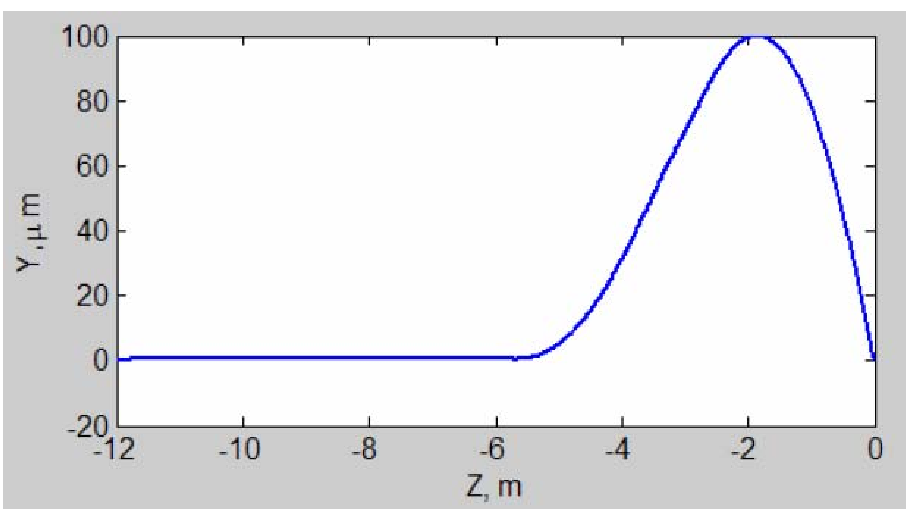

Figure 2: Vertical trajectory of the beam in SiD with anti-DID and 14-mrad crossing angle. Collider IP is at Z = 0 meters. (Taken from Figure 9 in Reference [9].)

With the anti-DID solution, additional orbit compensation is needed to achieve the goal of less than 50 μrad misalignments between the beam trajectory at the collider IP and the polarimeter Compton IPs. This compensation is energy-dependent and is not easily done by compensating the orbit at the upstream polarimeter with correctors due to tolerances on emittance growth. Corrector compensation is more easily done for the downstream polarimeter. For the upstream polarimeter, it is highly desirable to implement local orbit compensation near the IR to align the incoming vertical beam trajectory with the trajectory at the collider IP. Such a scheme looks feasible, but has not yet been fully described.[9] For the downstream polarimeter, the following procedure can be used to set the extraction line corrector magnets:

i. Obtain an extraction line reference orbit with the solenoid, anti-DID and correctors off.
ii. Then use correctors to reproduce the reference orbit as the solenoid and anti-DID are ramped to nominal settings (can compare calculated and actual corrector settings).
iii. Then use additional correctors to match beam angle at the Compton IP with the collider IP angle (if non-zero).

4. Z-pole Operation

The baseline ILC described in the RDR includes Z-pole operation for detector calibration, but not for physics data. However, there are good arguments to use a modest (pre-GigaZ) Z-pole data sample, including calibration data, for

i. Polarimeter calibration. Z-pole data can be used to check the luminosity-weighted polarization extrapolated from polarimeter data with a physics-based measurement using the Blondel scheme from an A_{LR} measurement. (It will also be possible to check the A_{LR} result obtained against the SLD measurement.)
ii. Energy spectrometer calibration. A Z-pole mass determination from an energy scan can be used to check the energy spectrometer calibration
iii. Physics measurements. ILC luminosity at the Z-pole should be $\sim 8 \cdot 10^{32} cm^{-2} s^{-1}$, which is 40 times larger than at LEP and 400 times larger than at SLC. Z-pole calibration data could thus be used to improve on SLD's A_{LR} measurement and many other Z-pole measurements. If this is successful, then a dedicated Z-pole run of at least a week will be desirable. Such physics running will be good preparation to evaluate capability for a Giga-Z program. Excellent polarimetry, energy and luminosity measurements will be needed for such a program.

Currently, there is much effort on cost reduction for the ILC and this may result in some loss of scope for ILC physics. Modifying the baseline ILC physics program to provide (pre-GigaZ) Z-pole physics data taking would add significantly to the ILC physics program at relatively small cost.

5. Costs and Conventional Facilities

With the need for ILC to reduce its costs, it is important to examine the need for implementing both upstream and downstream instrumentation for polarimeters and energy spectrometers. Before examining these instrumentation costs, it is important to note that the primary reason for wanting this upstream and downstream instrumentation is very similar to the motivation for wanting two physics detectors! Independent measurements can be critical for precision measurements and demonstrating confidence in new physics results. It is notable that such independent measurements were very important at SLC and LEP-II for both polarization and energy measurements:

i. SLD polarimeter: there were three independent measurements from 1 electron detector and 2 gamma detectors (laser systematic of 0.1% was common to all three).
ii. SLD energy: a Z-pole scan was used to check calibration of the energy spectrometer using the known Z-mass from LEP-I; this resulted in a small correction to the energy measurements.
iii. LEP-II energy: the primary measurement used resonant depolarization (RDP) and NMR measurements. The result was checked with additional measurements: comparing NMR and flux loop magnetic field measurements; and using other techniques provided by the synchrotron tune and a BPM spectrometer. (At the ILC, RDP and synchrotron tune techniques cannot be used.)

The main cost categories for the polarimeters are i) tunnel and beamline length, ii) magnets, vacuum chambers and support stands, iii) laser buildings and penetration shafts, and iv) laser & optics sytems, detectors and DAQ.

The length of the upstream polarimeter chicane adds to the length of the BDS and also to the RTML beamline and the service tunnel by moving the RTML turnaround further away (see Figure 3). The extraction line length is currently set by the distance from the collider IP to the beam dump, so the extraction line polarimeter does not increase the extraction line length. The downstream polarimeter magnets and corresponding support stands, however, are much larger than those for the upstream polarimeter. Each polarimeter has a laser building on the surface with a 130-meter penetration shaft to the beam tunnel. A configuration proposed for the extraction line polarimeter is shown in Figure 4.

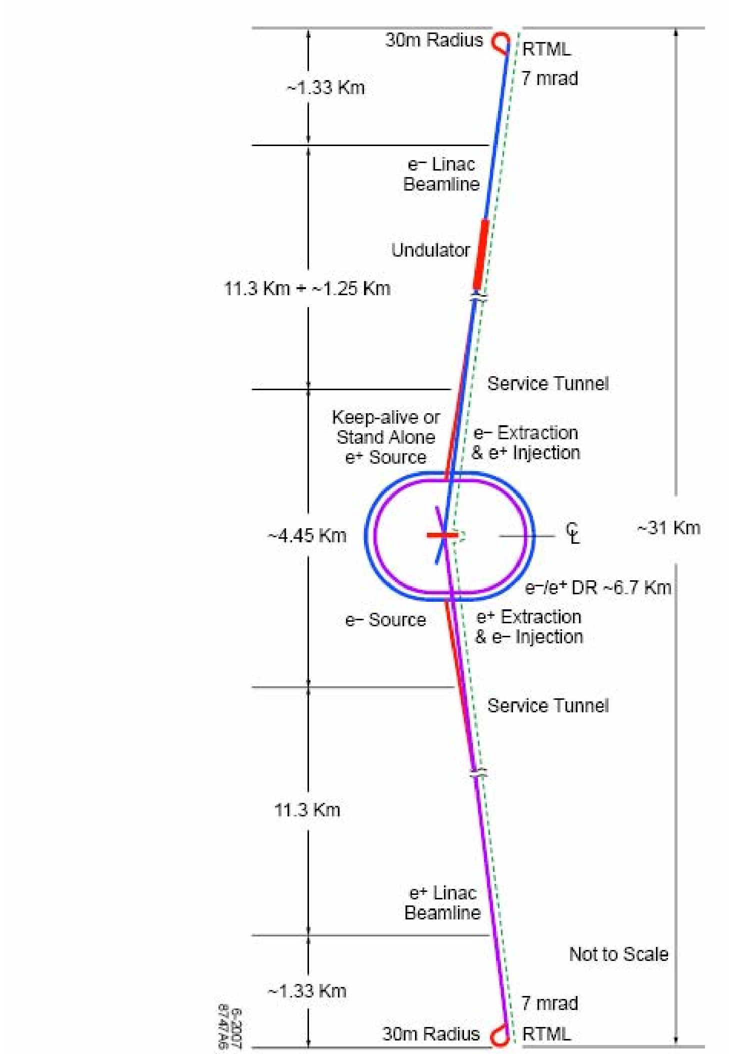

Figure 3: ILC layout shows the beamlines and service tunnels (taken from Figure 1.1.3 in Reference [2]).

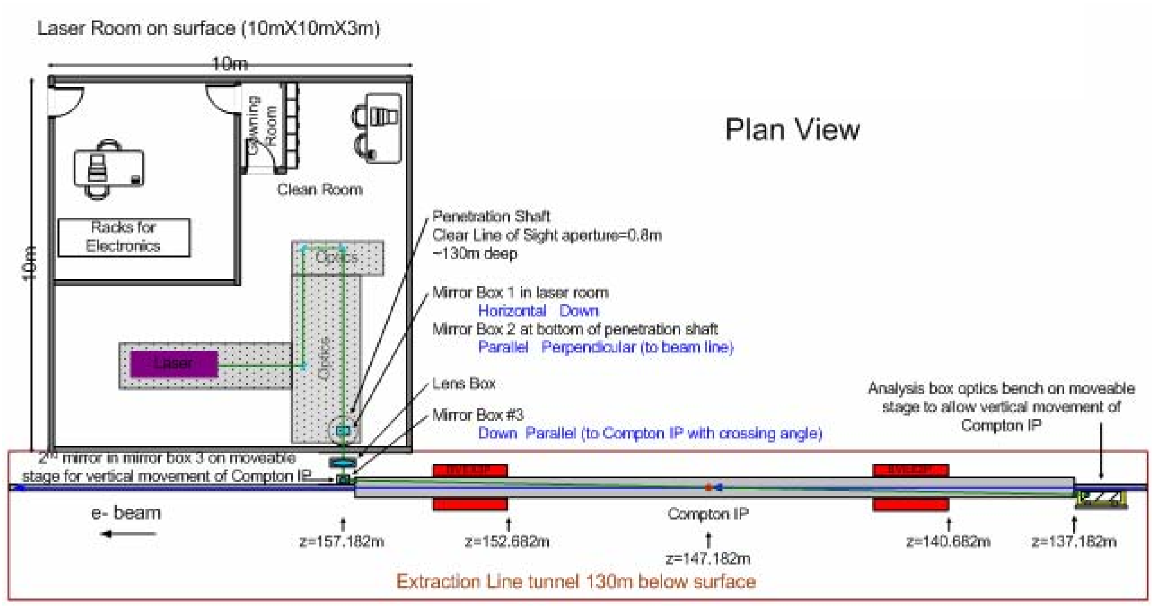

Figure 4: Proposed configuration of laser room, penetration shaft and extraction line layout for the downstream Compton polarimeter.

A summary of the costs for one upstream polarimeter and one downstream polarimeter is given in Table 4. The costs given are in 2007 dollars. Contingency and inflation are not included. Physicist salaries are also not included. These cost estimates are very preliminary, but have had input from conventional facility and magnet experts. One therefore can conclude that the cost of a single polarimeter is at the level of 5-7 million dollars. If one were to eliminate 2 upstream polarimeters or 2 downstream polarimeters, the ILC cost would be reduced by 10-14 million dollars which is approximately 0.2% of the ILC total project cost.

Table 4: Cost per polarimeter for RDR design

Cost Item	**1 Upstream Polarimeter ($M)**	**1 Downstream Polarimeter ($M)**
Tunnel lengths	0.8	0
Laser buildings & shafts	1.8	1.8
Magnets & stands	0.2	1.3
Vacuum chambers	0.1	0.2
Lasers & optics systems, Detectors & DAQ	1.5	1.0
Laser Safety Systems	0.1	0.1
Engineering & Design	0.5	0.5
TOTAL	**5.0**	**4.9**

6. Conclusions

i. BDS component and beam alignment:
   - need to achieve <50 μrad beam trajectory alignment at collision IP and polarimeter IPs. This looks feasible, but the procedure needs to be more fully fleshed out
   - checking for identical spin rotator optimization for the upstream and downstream polarimeters provides an important check for understanding and estimating systematics
   - it will be important to measure correlations with polarimeter measurements and local BPM orbits. Correlations of the downstream polarimeter measurements with the beam-beam offset measured by the IP BPMs can be used to determine spin misalignment between the collider IP and the Compton IP.

ii. Crossing angle and IR magnets:
   - cause misalignment of ~50-100 μrad of vertical beam angle at the IP with respect to the incoming beam trajectory; this needs to be compensated. It is best to do this locally near the IR. This looks feasible, but the procedure needs to be fully described.
   - Corrector magnets in the extraction line can be used to correct for this effect for the downstream polarimeter

iii. Z-pole operation:
   - The baseline ILC design described in the RDR baseline provides for detector calibration at the Z-pole, but polarization and energy measurements are not required.
   - Strong motivation exists, however, to use Z-pole calibration data for polarimeter and energy spectrometer calibration.
   - A modest (pre-GigaZ) Z-pole sample can be used for an excellent physics program. This requires excellent polarimetry, energy and luminosity measurements.

iv. Costs:
   - Eliminating upstream or downstream polarimetry would save ~$(10-15)M, which is ~0.2% of the ILC total project cost.
   - The physics benefit of having both polarimeter systems justifies this cost!

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