Beam Delivery System in the ILC

Grahame A. Blair
EPAC06
Edinburgh
28th June 2006

- Introduction
- SLC
- GDE Baseline concept
- Some key sub-systems
- ESA/FFTB/ATF2
- Outlook + Summary
ILC Layout
ILC parameters

<table>
<thead>
<tr>
<th></th>
<th>min</th>
<th>nominal</th>
<th>max</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bunch charge $N$</td>
<td>1</td>
<td>2</td>
<td>$2 \times 10^{10}$</td>
</tr>
<tr>
<td>Number of bunches $n_b$</td>
<td>1330</td>
<td>2820</td>
<td>5640</td>
</tr>
<tr>
<td>Linac bunch interval $t_b$</td>
<td>154</td>
<td>308</td>
<td>461 ns</td>
</tr>
<tr>
<td>Bunch length $\sigma_z$</td>
<td>150</td>
<td>300</td>
<td>500 $\mu$m</td>
</tr>
<tr>
<td>Vert. emit. $\gamma e_y^*$</td>
<td>0.03</td>
<td>0.04</td>
<td>0.08 mm$\cdot$mm$\cdot$rad</td>
</tr>
<tr>
<td>IP beta (500GeV) $\beta_z^*$</td>
<td>10</td>
<td>21</td>
<td>21 mm</td>
</tr>
<tr>
<td></td>
<td>$\beta_y^*$</td>
<td>0.2</td>
<td>0.4 mm</td>
</tr>
<tr>
<td>IP beta (1TeV) $\beta_z^*$</td>
<td>10</td>
<td>30</td>
<td>30 mm</td>
</tr>
<tr>
<td></td>
<td>$\beta_y^*$</td>
<td>0.2</td>
<td>0.6 mm</td>
</tr>
</tbody>
</table>

BDS must:
- Focus the beam to size of about 500 (x) $\times$ 5 (y) nm at IP
- Collimate beam halo
- Monitor the luminosity spectrum and polarization
- Measure incoming beam properties to allow tuning of the machine
- Protect detector and beamline components against errant beams
- Extract disrupted beams and safely transport to beam dumps
Detailed BDS

- Skew correction
- Energy diag. chicane & MPS energy collimator
- MPS betatron collimators
- 4-wire 2D $\varepsilon$ diagnostics
- Kicker, septum
- Polarimeter chicane
- Betatron collimation
- Tune-up dump

To IR2
To IR1

Sigma (m) in tune-up extraction line
Stanford Linear Collider (SLC)

<table>
<thead>
<tr>
<th></th>
<th>Design</th>
<th>Achieved</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam charge</td>
<td>$7.2 \times 10^{10}$</td>
<td>$4.2 \times 10^{10}$</td>
<td>e$\pm$/bunch</td>
</tr>
<tr>
<td>Rep Rate</td>
<td>180</td>
<td>120</td>
<td>Hz</td>
</tr>
<tr>
<td>FF $\varepsilon_x$</td>
<td>$4.2 \times 10^{-5}$</td>
<td>$5.2 \times 10^{-5}$</td>
<td>m rad</td>
</tr>
<tr>
<td>FF $\varepsilon_y$</td>
<td>$4.2 \times 10^{-5}$</td>
<td>$1.0 \times 10^{-5}$</td>
<td>m rad</td>
</tr>
<tr>
<td>IP $\sigma_x$</td>
<td>1.65</td>
<td>1.4</td>
<td>$\mu$m</td>
</tr>
<tr>
<td>IP $\sigma_y$</td>
<td>1.65</td>
<td>0.7</td>
<td>$\mu$m</td>
</tr>
<tr>
<td>Pinch Factor</td>
<td>220%</td>
<td>220%</td>
<td>Hd</td>
</tr>
<tr>
<td>Luminosity</td>
<td>$6 \times 10^{30}$</td>
<td>$3 \times 10^{30}$</td>
<td>cm$^{-2}$s$^{-1}$</td>
</tr>
</tbody>
</table>

- first LC
- 45 GeV beams
- 300 Z$^0$'s per hour
- e$^-$ polarisation of 80%

- Many of today's ILC experts were involved in getting SLC to work
- Many important LC lessons learnt:
## BDS: Lessons from the SLC

<table>
<thead>
<tr>
<th>BDS</th>
<th>SLC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Precision diagnostics essential</td>
<td>&gt; 60 wire scanners were needed</td>
</tr>
<tr>
<td>Automated diagnostics</td>
<td>long term history + correlations</td>
</tr>
<tr>
<td>Feedback system essential</td>
<td>&gt; 50 needed for &gt; 250 beam parameters.</td>
</tr>
<tr>
<td>Innovative tuning procedures</td>
<td>beam-based alignment, $\beta$-match…</td>
</tr>
<tr>
<td>SR must be minimised; implications for high E.</td>
<td>~30% luminosity dilution in the FF was due to SR in the CCS bends.</td>
</tr>
<tr>
<td>New FF design</td>
<td>FF optimised to reduce higher order aberrations</td>
</tr>
<tr>
<td>The most difficult problems will almost always be unexpected</td>
<td>They were…</td>
</tr>
</tbody>
</table>
BDS Collimation + Diagnostics

LINAC

skew correction

MPS betatron collimators

4-wire 2D \( \epsilon \) diagnostics

Energy diag. chicane & MPS energy collimator

kicker, septum

polarimeter chicane

betatron collimation

tune-up dump
BDS Collimation

Halo at ~10^{-3} of bunch charge is assumed
Spoilers ~ 1 X_0 followed by downstream absorbers
Issues: - Survivability of spoilers
- Wake-fields
Smallest collimator gaps are ±0.6mm with tail folding octupoles and ±0.2mm without them.
BDS Full Simulations

Beam aperture
SR
halo

BDSIM
WEPCH124
Agapov et al.

Dynamic heat load

MARS+STRUCT
Mokhov et al.

Jackson et al.
Amirikas et al.

MOPL082
MOPLS074
MOPLS062
Dealing with muons in BDS

Assuming 0.001 of the beam is collimated, two tunnel-filling spoilers are needed to keep the number of muon/pulse train hitting detector below 10.

9 and 18m Toroid spoilers
Long magnetized steel walls

Keller et al.

\[ \mu^\pm \text{tracks that reach IR} \]
Spoiler R&D

Spoiler should either:
• be able to survive at least 2 direct-hits from ILC bunch
• or be “consumable”

Both ideas have been considered:

“permanent”

“consumable” Frisch et al.

Picture from beam damage experiment at FFTB. The beam was 30GeV, 3-20x10^9 e-, 1mm bunch length, s~45-200um^2. Test sample is Cu, 1.4mm thick. Damage was observed for densities > 7x10^{14}e^-/cm^2. Picture is for 6x10^{15}e^-/cm^2
 Spoiler Wakefield Studies

Currently ongoing at SLAC-ESA

- Geometric wake-fields
- Resistive-wall wake-fields
- Benchmarking against simulation codes

Deflection angle
Measured downstream with BPMs to give measure of Wake-field kick

Studies of thermal shock
Survivability

MOPLS070,071

Watson et al.
## End Station A

<table>
<thead>
<tr>
<th>Parameter</th>
<th>SLAC ESA</th>
<th>ILC-500</th>
</tr>
</thead>
<tbody>
<tr>
<td>Repetition Rate</td>
<td>10 (up to 30) Hz</td>
<td>5 Hz</td>
</tr>
<tr>
<td>Energy</td>
<td>28.5 GeV</td>
<td>250 GeV</td>
</tr>
<tr>
<td>e⁻ Polarization</td>
<td>(85%)</td>
<td>&gt;80%</td>
</tr>
<tr>
<td>Train Length</td>
<td>Single bunch; (up to 400 ns possible)</td>
<td>1 ms</td>
</tr>
<tr>
<td>Microbunch spacing</td>
<td>20-400 ns</td>
<td>337 ns</td>
</tr>
<tr>
<td>Bunches per train</td>
<td>1 (or 2)</td>
<td>2820</td>
</tr>
<tr>
<td>Bunch Charge</td>
<td>(2.0 \times 10^{10})</td>
<td>(2.0 \times 10^{10})</td>
</tr>
<tr>
<td>Energy Spread</td>
<td>0.15%</td>
<td>0.1%</td>
</tr>
</tbody>
</table>
End Station A

- Wakefield box Collimator
- Wire scanner
- E158 magnet support blocks
- E158 target stand
- BPM’s
- SPEAR concrete girders
- Collimator, BPM’s
- Wire scanner, BPM’s
- E158 magnet support blocks
Other Beam Tests in ESA

1. BPM test stations
   • Linac BPMs, nano-BPMs

2. IP BPMs/kickers (necessary for fast inter-train and intra-train feedbacks)
   • Sensitivity to backgrounds, rf pickup

3. EMI impact on beam instrumentation or Detector electronics?
   • Plans to characterize EMI along ESA beamline in progress using antennas and fast scopes

4. Bunch length and longitudinal profile measurements
   • electro-optic, Smith-Purcell, coherent transition radiation

5. Spray beam or fixed target to mimic pairs, beamsstrahlung, disrupted beam
   • for testing synchrotron stripe energy spectrometer, IP BPMs, BEAMCAL

Woods et al. MOPLS067
White et al. THPCH089
Beam Physics Measurements

Precision beam measurements are needed for ILC physics.

- Very accurate energy spectrometry is required ($\sim 10^{-4}$)
- cavity BPM system at the SLAC End Station A

- Polarized beams important for ILC physics
  - $P(e^-) \sim 90\%$ and $P(e^+) \sim 60\%$
- strong programme of R&D is underway on the spin tracking issues.
- Measurement of the polarisation will be made both upstream and downstream of IP using Compton polarimeters
  
  K. Moffeit et al. SLAC-PUB-11322, N. Meyners presentation at LCWS05:
BDS Diagnostics section

Skew Correction
Emittance measurement

Φ = 50, 30, 12 mm
Φ = 4 mm

MPS β-collimators
skew correction
2D emittance measurement
MPS E-collimator

Woodlev
Skew Correction

4-skew quads to minimise Horizontal-vertical coupling

4-laser-wire IPs, each measuring Vertical and horizontal spot-size quads to minimise
Minimum vertical spot-size ~ 1 µm

LINAC →

Jenner et al.  TUPCH048
BDS Laser-wire

2-d scans at PETRA

μm scale R&D at ATF Ext

BDS-LW R&D

TUPCH049,050

MOPLS080,81

HIGH POWER LASER
BEAM SPLITTER
DEFLECTOR
MIRROR
ELECTRON BUNCH
LASERBEAM
COMPTON SCATTERED GAMMAS
BENDING MAGNET
ELECTRON BEAM TRAJECTORY
SCATTERED ELECTRONS
GAMMA-RAY DETECTOR

a) IN ELECTRON BEAM DIRECTION

LASER BEAM
ELECTRON BEAM

b) IN LASER BEAM DIRECTION

Laser Beam
ELECTRON BEAM

σ_x

σ_y

σ_z

x

y

z
BDS Laser-wire Issues

- Electron spot-sizes can (eventually) approach ~1µm in 1 TeV machine
  - laser waist should be smaller than this for emittance measurement
  - R&D programme on-going at ATF to address this
- 4 Vertical and Horizontal (ie 2-d) LW stations required
  - R&D programme at PETRA to address this
- Other machine errors may dominate emittance measurement
  - beam jitter, residual dispersion, beta-function error, ….
- Intra-train scanning will require ultra-fast laser scanning techniques
- Extraction of signal – best to use photons:

Energy deposit (GeV/m) from LW Compton-scattered electrons

Carter et al

TUPCH048
BDS Diagnostics section

- MPS β-collimators
- Skew correction
- 2D emittance measurement
- MPS E-collimator

Diagnostics chicane
Spectrometry + fast extraction of off-momentum beam
Diagnostic Chicane

- **Vacuum Chamber**: \( \Phi = 15 \text{ mm OD} \)
- **Window**: \( \eta_x = 20 \text{ mm} \)
- **Energy BPM**: \( \Delta \gamma \epsilon, / \epsilon_{\gamma_0} < 0.25\% \) (500 GeV beam)
- **MPS Energy Collimator**: \( \Delta E / E = \pm 10\% \) trajectories
- **Laserwire Detector (\( \epsilon \))**: up to \( \sim 113 \text{ TeV of energy per bunch in LW photon detector} \)
- **Total Length**: 114.6 m
Summary of first of BDS:

Next comes the IR regions, which may have different characteristics:
Stability – Tolerance to FD motion

Ground motion

IP offset leads to angular deflection after interaction
ILC intratrain simulation

ILC intratrain feedback (IP position and angle optimization), simulated with realistic errors in the linac and “banana” bunches, show Lumi $\sim 2 \times 10^{34}$ (2/3 of design). Studies continue.

Luminosity through bunch train showing effects of position/angle scans (small). Noisy for first $\sim 100$ bunches (HOM’s).

Injection Error (RMS/$s_y$): 0.2, 0.5, 1.0

MOPLS122,3 Burrows et al.
A Straightness Monitor Made from Distance Meters

- Setup planned at KEK
- Red lines: Distance meter.
- Multilateration measure 6D coord. of A with respect to B.

Typical spectra: Single channel - Repeated scans

Single line distance meter results from Oxford; few microns precision
IP Stabilisation + BDS alignment

Parking clamp stabilises car during measurement

FSI reference interferometer

Vacuum tube connecting the measurement units in each measuring car

Drive unit (blue) with gear box (green) and motor controller (lilac). Each service car is individually propelled and the motors are synchronised to each other and controlled

First of the three measurement cars carrying the launch of the LSM. All measurement cars provide 6 DOF motion for their measurement units, allowing them to home onto the LSM beam and to aim their interferometers at the reflectors in the next car.

Master car carries main control computer, power distribution, vacuum control system, laser, EDFA and reference interferometer for FSI as well as laser for LSM.

Service car with two rotating cradles for the readout and control electronics racks of the measurement car’s sensors and motors.
IR Region layout

ILC2006b Beam Delivery Systems Layout

- 11 mrad NLC-style Big Bends
- 2 mrad (L* = 4.5 m) dump lines
- 20 mrad ILC FF9 (x 2)
- 2 mrad ILC FF (x 2)
- IP separation: 138.4 m (Z), 20.4 m (X)
- Path length difference (to IR2): 3 × 400 1.3 GHz periods = 276.7315 m
- 20 mrad (L* = 6 m) dump lines

Woodley
‘Large’ crossing angle (14 mrad)

Issues:
• Incoming and outgoing beams separate
• Strong dependence on crab-cavity
• Detector hermeticity at forward angles
‘Small’ crossing angle (~2 mrad)

Issues:
• Incoming and outgoing beams share magnets close to the IP; → less flexibility in design and minimisation of backgrounds
• Less dependence on crab-cavity
• Improved detector hermeticity at forward angles

A head-on scheme (zero crossing angle) is also currently being studied.

Appleby et al. MOPLS077
Payet et al. MOPLS060
Extraction line
Full Simulations

20 mrad

Optimisation ongoing
**Crab crossing**

\[ \sigma_{x, \text{projected}} \approx \sqrt{\sigma_x^2 + \phi_c^2 \sigma_z^2} \]

\[ \approx \phi_c \sigma_z \]

\[ = 20 \text{mrad} \times 100 \mu\text{m} \approx 2 \mu\text{m} \]

→ factor 10 reduction in Lumi

need one or two multi-cell cavities

\~15m from IP

<table>
<thead>
<tr>
<th>Crossing angle</th>
<th>1.3GHz</th>
<th>3.9GHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>2mrad</td>
<td>0.222</td>
<td>0.665</td>
</tr>
<tr>
<td>10mrad</td>
<td>0.044</td>
<td>0.133</td>
</tr>
<tr>
<td>20mrad</td>
<td>0.022</td>
<td>0.066</td>
</tr>
</tbody>
</table>

Burt et al. MOPCH163 MOPLS075
Beam dump for 18MW beam

- Water vortex
- Window, 1mm thin, ~30cm diameter hemisphere
- Raster beam with dipole coils to avoid water boiling
- Deal with H, O, catalytic recombination
- Gas dump also being studied
- 3MW beamstrahlung dumps near IR

Undisrupted or disrupted beam size does not destroy beam dump window without rastering.

Rastering to avoid boiling of water

20mr extraction optics

MOPLS079
FF with local chromatic correction

- Chromaticity is cancelled \textit{locally} by two sextupoles interleaved with FD, a bend upstream generates dispersion across FD
- Geometric aberrations of the FD sextupoles are cancelled by two more sextupoles placed in phase with them and upstream of the bend
- One third the length - many fewer components.
- Can operate with 2.5 TeV beams (for $3 \sim 5$ TeV cms)
- 4.3 meter L* (twice 1999 design)
- Improved bandwidth

Final Focus Test Beam

• Started operation at SLAC in 1993
• Aimed at 60 nm spot-sizes
• Eventually achieved:
  1.7µm (σₓ) × 75nm (σᵧ),
  Ground motion?

<table>
<thead>
<tr>
<th></th>
<th>SLC</th>
<th>FFTB</th>
<th>ILC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eₓ (GeV)</td>
<td>45.6</td>
<td>46.6</td>
<td>250</td>
</tr>
<tr>
<td>σₓ/E (%)</td>
<td>0.25</td>
<td>0.25</td>
<td>0.1</td>
</tr>
<tr>
<td>Nₑ⁻ (×10¹⁰)</td>
<td>4.2</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>σᵧ (nm)</td>
<td>800</td>
<td>60</td>
<td>5.7</td>
</tr>
<tr>
<td>γεᵧ (m-rad)</td>
<td>1×10⁻⁵</td>
<td>3×10⁻⁶</td>
<td>4×10⁻⁸</td>
</tr>
<tr>
<td>Asp. ratio x/y</td>
<td>2.5</td>
<td>16</td>
<td>115</td>
</tr>
<tr>
<td>σᵧ (mm)</td>
<td>~1</td>
<td>~1</td>
<td>0.3</td>
</tr>
</tbody>
</table>
Final Focus Test Beam

A Prototype ILC Final Focus system:

- Used “conventional” FF chromatic correction.
- Pole-faces of the final quads were fabricated to ±2 µm and the magnet strength stability for critical elements was $10^{-5}$.
- A cavity BPM with nm pulse-to-pulse resolution at the IP.
- “Shintake-monitor” (now being upgraded for ATF2)
ATF/ATF2
Present Research Programmes at ATF

2. Laser wire R&D in Damping Ring (Kyoto University)
3. High quality electron beam generation by photo-cathode RF Gun (Waseda University)
4. X-SR Monitor R&D (University of Tokyo)
5. ODR R&D (Tomusk University)
6. Beam Based Alignment R&D
7. Nano-BPM project of SLAC, LLNL and LBNL
8. Nano-BPM project of KEK
9. FONT project (UK Institutes)
10. Laser Wire project at EXT (UK Institutes)
11. Fast Kicker Development project (DESY, SLAC, LLNL)
12. Fast Ion Instability Research
13. Multi-bunch Instability Study
### ATF2: The next step on the nm trail:

<table>
<thead>
<tr>
<th></th>
<th>SLC</th>
<th>FFTB</th>
<th>ATF2</th>
<th>ILC</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_{beam}$ (GeV)</td>
<td>45.6</td>
<td>46.6</td>
<td>1.3</td>
<td>250</td>
</tr>
<tr>
<td>$\sigma_{E/E}$ (%)</td>
<td>0.25</td>
<td>0.25</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>$N_{e-}$ ($\times 10^{10}$)</td>
<td>4.2</td>
<td>1</td>
<td>1-2</td>
<td>2</td>
</tr>
<tr>
<td>$\sigma_y$ (nm)</td>
<td>800</td>
<td>60</td>
<td>37</td>
<td>5.7</td>
</tr>
<tr>
<td>$\gamma\varepsilon_y$ (m-rad)</td>
<td>$1\times10^{-5}$</td>
<td>$3\times10^{-6}$</td>
<td>$3\times10^{-8}$</td>
<td>$4\times10^{-8}$</td>
</tr>
<tr>
<td>Asp. ratio $x/y$</td>
<td>2.5</td>
<td>16</td>
<td>13</td>
<td>115</td>
</tr>
<tr>
<td>$\sigma_z$ (mm)</td>
<td>$\sim1$</td>
<td>$\sim1$</td>
<td>$\sim5$</td>
<td>0.3</td>
</tr>
</tbody>
</table>

- Use new FF optics – verification of system
- Extract ILC-like train from DR using fast kickers
- Commission ILC-like diagnostics + feedback
- Train next generation of accelerator physicists + engineers
ATF2

(A) Small beam size
Obtain $\sigma_y \sim 35\text{nm}$
Maintain for long time

(B) Stabilization of beam center
Down to $< 2\text{nm}$ by nano-BPM
Bunch-to-bunch feedback of ILC-like train
Advanced beam instrumentation at ATF2

- BSM to confirm 35nm beam size
- nano-BPM at IP to see the nm stability
- Laser-wire to tune the beam
- Cavity BPMs to measure the orbit
- Movers, active stabilization, alignment system
- Intratrain feedback, kickers to produce ILC-like train

IP Beam-size monitor (BSM) (Tokyo U./KEK, SLAC, UK)

Laser-wire beam-size Monitor (UK group), low-f optics

Cavity BPMs with 2nm resolution, for use at the IP (KEK)

Cavity BPMs, for use with Q magnets with 100nm resolution (PAL, SLAC, KEK)
Higher Energy Issues

ILC BDS has been optimised for 0.5 - 1 TeV CMS. If need to extend to multi-TeV:

- 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.
Many thanks to:

• The ILC BDS team; especially A. Seryi, D. Angal-Kalinin, M. Woodley for input.
• PPARC/CCLRC LC-ABD collaboration.
• All collaborators at the ATF, ESA, …
• Everyone whose results I have used

Further background:

• ILC Baseline Conceptual Design: http://www.linearcollider.org/wiki/
• A. Seryi lecture at ILC summer school 2006.
SUMMARY

• ILC BDS is in good shape, with feasible designs for several crossing angles.
• Strong international R&D in many of the key issues for beam diagnostics, feedback, and control.
• We look forward to a vigorous collaboration at ATF2 to achieve 37nm spot-sizes for extended periods.
• Full simulations are now maturing and will give major input to the ILC TDR phase.
• Still lots to do…