Next Linear Collider
Beam Position Monitors

Steve Smith
SLAC
October 23, 2002
What’s novel, extreme, or challenging?

- Push resolution frontier
  - Novel cavity BPM design for high resolution, stability
  - Push well beyond NLC requirements
- Push bandwidth frontier
  - Stripline BPM with very high bandwidth and resolution
- Pickup-less BPM
  - HOM-Damped RF structures as position monitors
- Low propagation delay BPM
  - Feedback within bunch-train crossing time (250 ns)
NLC Linac BPMs

• “Quad” BPM (QBPM)
  – In every quadrupole (Quantity ~3000)
  – Function: align quads to straight line
  – Measures average position of bunch train
  – Resolution required: 300 nm rms in a single shot

• Structure Position Monitor (SPM)
  – Measure phase and amplitude of HOMs in accelerating cavities
  – Minimize transverse wakefields
  – Align each RF structure to the beam
  – 22 k devices in two linacs

• “Multi-Bunch” BPM (MBBPM)
  – Measure bunch-to-bunch transverse displacement
  – Compensate residual wakefields
  – Measure every bunch, 1.4 ns apart
  – Requires high bandwidth (300 MHz), high resolution (300 nm)
  – Line up entire bunch train by steering, compensating kickers
Other NLC BPMs

• Damping Ring
  – Button pickups
  – Rather conventional, like 3rd generation light sources
  – But higher readout rate (~MHz)

• Interaction Point Intra-Train Deflection Feedback
  – Correct beam-beam mis-steering within time of train crossing
  – Low propagation delay!
NLC “QBPM”

- Mainstream workhorse BPM
- In every quadrupole +
- Requires high resolution 300 nm
- Stability
- Single bunch to 180 bunches
- Stripline vs. cavity pickup?
- Cavity with novel coupler
# QBPM Requirements

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resolution</td>
<td>300 nm rms</td>
<td>@ $10^{10}$ e$^-$ single bunch</td>
</tr>
<tr>
<td>Position Stability</td>
<td>1 $\mu$m</td>
<td>over 24 hours (!)</td>
</tr>
<tr>
<td>Position Accuracy</td>
<td>200 $\mu$m</td>
<td>With respect to the quad magnetic center</td>
</tr>
<tr>
<td>Position Dynamic Range</td>
<td>$\pm$2 mm</td>
<td></td>
</tr>
<tr>
<td>Charge Dynamic Range</td>
<td>$5 \times 10^8$ to $1.5 \times 10^{10}$ e$^-$ per bunch</td>
<td></td>
</tr>
<tr>
<td>Number of bunches</td>
<td>1 - 190</td>
<td>Singlebunch - multibunch</td>
</tr>
<tr>
<td>Bunch spacing</td>
<td>1.4 ns</td>
<td></td>
</tr>
</tbody>
</table>
Use Striplines for Q BPM?

- Electronics in tunnel enclosure
- Signal amplitudes in a ~30 MHz band around 714 MHz are demodulated and digitized
- Critical elements:
  - Front-end hybrid
  - Calibration signals
  - Sampler / digitizer choices:
    - Direct analog sampling chip + slow, high resolution ADC?
    - IF downconversion + fast, high resolution ADC?
  - Digital receiver algorithms for amplitude reconstruction
    - bandpass filter
    - digital downconversion
    - low pass filter
  - Position proportional to ratio of amplitude difference/sum
Can we achieve 300 nm resolution?

• Example: Final Focus Test Beam Position Monitor
  – Achieves single bunch resolution of \( \sim 1.2 \, \mu \text{m} \, \text{rms} @ 9 \times 10^9 \, \text{e}^- \)
  – Algorithm: low pass filter, sample, digitize
  – Bandwidth \( \sim 30 \, \text{MHz} \)
  – Micron resolution is a few dB above thermal noise floor

• NLC Q-BPM
  – Beam pipe radius is factor of two smaller
  – Process signal where it is big, i.e. 714 MHz instead of 32 MHz
  – Noise floor is not an issue
  – Must control systematics
What’s wrong with striplines?

• Striplines are difficult to fit into limited quad ID
• Accuracy hard to establish
  – Works on small differences of large numbers
• Position accuracy / stability requires precision of many elements
  – Internal elements
    • Stripline position
    • Feedthroughs
    • Termination
  – External elements
    • Cables
    • Connections
    • Processor
QBPMs Should be Cavities!

- Cavity BPM features:
  - Signal is proportional to position
  - Less common-mode subtraction than for strips
  - Simpler geometry
  - Accuracy of center better, more stable
  - Pickup compact in Z dimension

- Cavity Drawbacks:
  - Higher processing frequency
  - Are wakefields tolerable?
Cavity BPM

- Pick a basic design and evaluate characteristics
- Pillbox cavity, for example
- Choose frequency, processing scheme
- Calculate
  - Dimensions
  - Sensitivity
  - Noise figure budget
  - Common-mode rejection
  - Wake fields
Operating Frequency

- Sensitivity increases with frequency
- Size decreases with frequency
- Cable loss increases
- Cost of electronics increases
- Should be multiple of 714 MHz bunch spacing
- Possible operating frequencies:
  - 2856 MHz (cavities are too big!)
  - 5712 MHz (inexpensive commercial parts)
  - 11.424 GHz (share phase cavity with LLRF)
  - 14.280 GHz (integrate position cavities with RF structure)

- Example: 11.424 GHz
# Cavity BPM Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dipole frequency</td>
<td>11.4 GHz</td>
<td></td>
</tr>
<tr>
<td>Monopole frequency</td>
<td>7.2 GHz</td>
<td></td>
</tr>
<tr>
<td>Cavity Radius</td>
<td>16 mm</td>
<td></td>
</tr>
<tr>
<td>Wall Q</td>
<td>~4000</td>
<td>Ignoring beam duct, etc</td>
</tr>
<tr>
<td>Cavity coupling</td>
<td>β = 3</td>
<td></td>
</tr>
<tr>
<td>Loaded Q</td>
<td>1000</td>
<td></td>
</tr>
<tr>
<td>Bandwidth</td>
<td>11 MHz</td>
<td></td>
</tr>
<tr>
<td>Beam aperture radius</td>
<td>6 mm</td>
<td></td>
</tr>
<tr>
<td>Sensitivity</td>
<td>7 mV/nC/µm</td>
<td>(too much signal!)</td>
</tr>
<tr>
<td>Bunch charge</td>
<td>0.7 x 10^{10} e⁻</td>
<td>Per bunch</td>
</tr>
<tr>
<td>Signal power @ 1µm</td>
<td>-29 dBm</td>
<td>Peak power</td>
</tr>
<tr>
<td>Decay time</td>
<td>28 ns</td>
<td></td>
</tr>
<tr>
<td>Required resolution</td>
<td>σ = 200 nm</td>
<td></td>
</tr>
<tr>
<td>Required Noise Figure</td>
<td>57 dB</td>
<td>For σ = 100 nm, thermal only</td>
</tr>
<tr>
<td>Wakefield Kick</td>
<td>0.3 volt/pC/mm</td>
<td>Long range</td>
</tr>
<tr>
<td>Structure wakefield kick</td>
<td>~2 volt/pC/mm</td>
<td>Per structure</td>
</tr>
<tr>
<td>Short-range wakefield</td>
<td>~1/200th of structure</td>
<td></td>
</tr>
</tbody>
</table>
How much does monopole mode leak into dipole mode frequency?
This creates an apparent beam centering offset.
But processor looks only at dipole-mode frequency
And uses odd-mode coupler to eliminate even-symmetry mode

<table>
<thead>
<tr>
<th>Comparison</th>
<th>Voltage</th>
<th>Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ratio of monopole mode voltage to dipole mode voltage due to 1 mm beam offset, measured at outer radius of pillbox</td>
<td>4200</td>
<td>72 dB</td>
</tr>
<tr>
<td>Tail of monopole mode at dipole-mode frequency</td>
<td>3.5</td>
<td>11 dB</td>
</tr>
<tr>
<td>Coupler rejection of monopole mode (-30dB)</td>
<td>0.1</td>
<td>-19 dB</td>
</tr>
</tbody>
</table>

So the common-mode leakage is negligible.
(Even if the offset were tens of microns, its just a fixed offset)
BPM Cavity with TM$_{110}$ Couplers

- Dipole frequency: 11.424 GHz
- Dipole mode: TM$_{11}$
- Coupling to waveguide: magnetic
- Beam x-offset couple to “y” port

- Sensitivity: 1.6mV/nC/µm
  (1.6×10$^9$V/C/mm)

- Couple to dipole (TM$_{11}$) only
- Does not couple to TM$_{01}$
  - May need to damp TM$_{01}$
  - OR, use stainless steel to lower Q

- Compact
- Low wakefield

Zenghai Li
TM_{110} Mode Coupler

Waveguide

Beam pipe

“Magnetic” coupling

Port to coax

Zenghai Li
COM-Free BPM

TM010 mode does not couple out to pickup antenna.

will be used for C-band Accelerator Alignment
Waveguide Signal With Beam Excitation

Y Waveguide Voltage

Y Waveguide Voltage Spectrum

Impedance Spectrum

Zenghai Li
Cavity Dimensions

Cavity sensitivity (?)
- \( \frac{dF}{db} : -0.78 \ \text{MHz/\mu m} \)
- \( \frac{dF}{da} : +0.022 \ \text{MHz/\mu m} \)
- \( \frac{dF}{dL} : +0.042 \ \text{MHz/\mu m} \)

<table>
<thead>
<tr>
<th>sharp iris</th>
<th>MAFIA</th>
<th>Omega2</th>
<th>Omega2 prediction</th>
</tr>
</thead>
<tbody>
<tr>
<td>( r_{\text{cav}} ) (mm)</td>
<td>14.2</td>
<td>14.2</td>
<td>14.695</td>
</tr>
<tr>
<td>( F_1 ) (with guide)</td>
<td>12.17413</td>
<td>11.424</td>
<td></td>
</tr>
<tr>
<td>( F_1 ) (no guide)</td>
<td>12.30448</td>
<td>11.96617</td>
<td>11.55435</td>
</tr>
<tr>
<td>( \Delta F_1 )</td>
<td>0.13035</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Zenghai Li
Azimuthal Misalignment

• Monopole modes sensitivity to displaced coupler:
  – $dx'/dx \sim 2$ in power ratio
  – $<0.01$ monopole mode measured at dipole mode frequency
• We do get X-Y coupling
Radial Misalignment

• Small x-y coupling
• Little fundamental mode

Y WAVEGUIDE VOLTAGE SPECTRUM

X WAVEGUIDE VOLTAGE SPECTRUM

Zenghai Li

Steve Smith   October 2002
Excellent Performance (in simulation)

- Relatively easy to fabricate
- Tolerant of errors
- Strong signal
- Good centering
- Small wakefields

⇒ Build prototypes
Develop Cavity BPM Prototype

- Team:
  - Ron Johnson, Zenghai Li, Takashi Naito, Jeff Rifkin, S. Smith
- Frequency: 11.424 GHz
- Axially symmetric X-Y cavity
- TM$_{110}$ mode couplers designed by Z. Li
- Two couplers per mode for prototype cavity
- Integrate fundamental mode phase reference cavity in same block.
- Measure on bench
- In beam
Cavity Antenna Test

Dipole Mode Amplitude vs. Antenna Position

BPM Response Magnitude

Antenna Position (microns)

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Antenna Test – Phasor Response

Polar Plot of Dipole Mode Response

Re(A)  x 10^3

Im(A)  x 10^3
Antenna Position

BPM Measurement vs. Antenna Position

Resolution = 0.23 microns rms
Antenna Test – Residual Plot

Position Error vs. Antenna Position

Measurement error (microns) vs. Antenna Position (microns)

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Prototype Cavity Conclusions

- Excellent position response.
- Linear across null.
- Resolution is 230 nm rms.
- Resolution may be dominated by micrometer stage
Cavity Q-BPM Conclusions

- It is easy to get signal
- Resolution can be much better than required
- Signal is proportional to displacement
- Accurate centering is much easier than for striplines
- Common-mode is not a problem
- Wake fields are OK
- Requires microwave processing
Limits of Cavity BPM

• How far can you push cavity BPM technology?
• Way beyond NLC machine requirements!
  – QBPM designed for low Q, low coupling
• Signal to thermal noise limit for resolution-optimized cavity
  – $\sigma = 0.1$ nm for 11 GHz pillbox cavity and $10^{10}$ e\textsuperscript{-} in a single bunch.
• Is a nanometer resolution BPM useful?
• Ground isn’t stable at this level
• Active stabilization needed.
  – But is available, and demands beam tests!
    • Passive isolation
    • Geophone feedback
    • Optical anchor (interferometer)
Nanometer Resolution BPMs

- Push cavity BPM technology to its limits
- Push existing C-band cavities to 1nm at ATF (KEK)
- Harder at 5.7 GHz than 11.4 GHz!
• NLC alignment tolerances and diagnostic requirements derive from wakefield emittance dilution.
• Transverse wakefields cause head-tail displacement
• Can we measure this directly, rather than by position of the mean charge of the bunch?
• Observation at ASSET:
  – BPM Cavity power vs. beam position has minimum which depends on bunch tilt
  – Tilt signal is in quadrature with position signal
Response of BPM to Tilted Bunch Centered in Cavity

Treat as pair of macroparticles:

\[ V(t) = \frac{a}{2} \left( \frac{q}{2} \delta \sin(\omega(t - \frac{\sigma_t}{2})) - \frac{q}{2} \delta \sin(\omega(t + \frac{\sigma_t}{2})) \right) = \frac{a \delta q}{2} \cos \omega t \sin \frac{\omega \sigma_t}{2} \]
Tilted bunch

- Point charge offset by $\delta$
- Centered, extended bunch tilted at slope $\delta/\sigma_t$
- Tilt signal is in *quadrature* to displacement
- The amplitude due to a tilt of $\delta/\sigma$ is down by a factor of:
  
  $V_t/V_y = \frac{\omega \sigma_t}{4} = \frac{\pi \sigma_t}{2T}$

\[ V_y(t) = a q \delta \sin(\omega t) \]

\[ V_i(t) = \frac{a \delta q}{2} \cos \omega t \sin \frac{\omega \sigma_t}{2} \]
Example

- Bunch length \( \sigma_t = 200 \mu m/c = 0.67 \) ps
- Tilt tolerance \( d = 200 \) nm
- Cavity Frequency \( F = 11.424 \) GHz
- Ratio of tilt to position sensitivity \( \frac{1}{2} \pi f \sigma_t = 0.012 \)
- A bunch tilt of 200 nm / 200 \( \mu m \) yields as much signal as a beam offset of 0.012 * 200 nm = 2.4 nm
- Need BPM resolution of ~ 2 nm to measure this tilt
- Challenging!
  - Getting resolution
  - Separating tilt from position
- Use higher cavity frequency?
Position-Tilt Discrimination

- Phase-sensitive detection
- Position jitter or dithering measures phase of position signal
- Quadrature part of signal is tilt + background
  - One phase of residual common mode
  - RF interference/leakage
- The higher the frequency the better!
- Tiltmeter also sensitive to beam tilt / cavity tilt
Tiltmeter R&D Plans

- Test with C-Band cavity BPMs at ATF (KEK)
  - First test done, cavity tilt dominates
  - Put more cavities on goniometers
NLC RF Structure

- Use dipole modes in accelerating cavities to measure beam position.
- Align each RF structure to the beam
- Minimize transverse wakefields
Transverse Modes in Structure

Transverse modes contain position information
Modes associated with z position along structure.
Tunable receiver can measure position along structure.

RDDS1 dipole mode frequency distributions: $dn/df$ is the mode density and $kdn/df$ is the density weighted by the mode kick factors ($k$).
• Damped, Detuned RF structures (DDS)
  – Damped: 4 HOM manifolds conduct transverse modes to load
  – Detuned: HOM mode frequency depends on z-position in structure
  – Two of the manifolds, have coax couplers which sample a fraction of the HOM power
• BPM measures amplitude and phase of transverse modes at load.
• Tune over 14 – 16 GHz to see position from one end to the other.
• Use to align structures to beam.
SPM Receiver

- Tunable across dipole band
  - Frequency selects z-coordinate of position measurement
- Receiver is phase-sensitive:
  - Reduces noise
  - Provides sign of offset.
- Beam phase reference provided by nearby cavity BPM
  - Needs phase accuracy of only $\pm 90^\circ$ in order to extract the sign of the beam direction.
  - Noise performance improves slightly with better phase reference
  - Low-level RF system requires beam phase accuracy of a few degrees, which will be from the same source.
## SPM Requirements

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Requirement</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quantity</td>
<td>~22,000 X,Y BPM’s</td>
<td>in X-band linacs</td>
</tr>
<tr>
<td></td>
<td>~ 700 X,Y BPM’s</td>
<td>in S-band linacs</td>
</tr>
<tr>
<td>Resolution</td>
<td>rms = 5 $\mu$m or 10% of beam position, whichever is greater</td>
<td>single bunch of $3 \times 10^9$ e$, for at least one mode near each end</td>
</tr>
<tr>
<td>Position Dynamic Range</td>
<td>$R &lt; 3$ mm</td>
<td>single bunch or low current multibunch</td>
</tr>
<tr>
<td></td>
<td>$R &lt; 0.5$ mm</td>
<td>full current, multibunch</td>
</tr>
<tr>
<td>Stability of Center</td>
<td>&lt;1 $\mu$m over 30 minutes</td>
<td></td>
</tr>
<tr>
<td>Survival</td>
<td>90 bunches @ $1.5 \times 10^{10}$ at 3 mm radius</td>
<td>Must not damage receiver</td>
</tr>
</tbody>
</table>
Comparison of rf structure relative cell positions measured by dipole-mode BPM (points) and Coordinate Measuring Machine (line). Dashed lines show NLC rms structure alignment tolerance.
Structure Position Monitor

- Looks promising
- Have not developed even prototype electronics
- R&D needed on integrated RF module
- Large system, it must be:
  - high performance
  - reliable
  - cheap
Multi-Bunch BPMs

- Bandwidth frontier (300 MHz bandwidth)
- Stripline pickups
- Report position of every bunch in bunch train
- Used to program broadband kickers to straighten out bunch train

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Conditions &amp; Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resolution</td>
<td>300 nm rms</td>
<td>for bunch-bunch displacement frequencies below 300 MHz</td>
</tr>
<tr>
<td></td>
<td>At $0.6 \times 10^{10}$ e$^-$ / bunch</td>
<td></td>
</tr>
<tr>
<td>Position Range</td>
<td>$\pm 2$ mm</td>
<td></td>
</tr>
<tr>
<td>Bunch spacing</td>
<td>2.8 ns or 1.4 ns</td>
<td></td>
</tr>
<tr>
<td>Number of Bunches</td>
<td>1 - 190</td>
<td>@ 1.4 ns</td>
</tr>
<tr>
<td>Beam current dynamic range</td>
<td>$1 \times 10^9$ to $1.4 \times 10^{10}$</td>
<td>Particles / bunch</td>
</tr>
<tr>
<td>Number of BPMs</td>
<td>278</td>
<td></td>
</tr>
</tbody>
</table>
Multi-Bunch BPM Electronics

• Model
  – Preprocess using matched filters, sum-difference hybrids
  – Digitize waveform from stripline using either
    • fast ADC’s
    • Sampling chip followed by slow ADC
  – Deconvolute bunch-bunch response from multibunch using impulse response measured with single bunch

• R&D
  – Demonstrate concept
  – Develop switched capacitor analog memory chip
    • Save
      – cost
      – space
      – power
• Sampling Chip development
  – In house
  – Ohio State

• Proofs of Principle
  – Measuring bunchtrains at KEK-ATF
  – Digital receiver algorithm for Q-BPM, DR-BPM
    • test in linac, PEP-II

• Test promising parts on eval boards

• Prototype
Multi-Bunch BPM

Block Diagram

BPM

Front End Box

Front End Box

Tek 3054
ATF Bunch Current

Bunch Current Mod Revolution Frequency

Time (ns)

October 2002
Damping Ring BPMs

- Button pickups in rings
- Cables to holes in tunnel wall
- Quantity 486 total in three rings
  - Two main damping rings & e\(^+\) Pre-damping ring
- Process signals in digital receiver
  - Measure amplitude in \(\sim 10\) MHz bandwidth about 714 MHz
- Differences from PEP BPM:
  - Slightly higher resolution
    - smaller signal
    - smaller beam duct
  - High peak readout rate (once per turn \(\sim\)MHz)
# DR-BPM Requirements

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Requirement</th>
<th>Conditions &amp; Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Duct radius</td>
<td>17.5 mm in arcs, up to 31 mm in straights</td>
<td>PEP-II is 33 mm in arcs, 45 mm in straights</td>
</tr>
<tr>
<td>Button Diameter</td>
<td>8 mm</td>
<td>PEP-II is 15 mm</td>
</tr>
<tr>
<td>Button Transfer Impedance</td>
<td>~ 0.2 Ohm</td>
<td>@ 714 MHz</td>
</tr>
<tr>
<td>Time resolution</td>
<td>Average over 20 bunches</td>
<td>Can we average over train?</td>
</tr>
<tr>
<td>Measurement Rate</td>
<td>Read every turn, (1.4 MHz in preDR)</td>
<td>PEP-II ADC runs at 136 kHz</td>
</tr>
<tr>
<td>Onboard processing</td>
<td>Multi-turn logging, Multi-turn averaging, Sine fit to turn-by-turn data</td>
<td>Several 14-bit ADCs @ 65 MHz</td>
</tr>
<tr>
<td>Resolution for train of &gt; 20 bunches</td>
<td>$\sigma \leq 1 \mu m \cdot \sqrt{1 + \left( \frac{500mA}{I_{train}} \right)^2}$</td>
<td></td>
</tr>
<tr>
<td>Resolution for single bunch</td>
<td>$\sigma_{\text{Single}} \leq 5 \cdot \mu m$</td>
<td>For $Q_s &gt; 10^{10}$ electrons</td>
</tr>
<tr>
<td>Initial accuracy</td>
<td>TBD</td>
<td>Before beam-based-alignment</td>
</tr>
<tr>
<td>Stability wrt time</td>
<td>1$\mu m$, 10$\mu m$</td>
<td>over a few hours, over 24 hours</td>
</tr>
<tr>
<td>Stability wrt fill pattern</td>
<td>&lt;10$\mu m$ shift, single bunch to full train</td>
<td></td>
</tr>
</tbody>
</table>
Intra-pulse Feedback

Ground Motion at NLC IP

- Differential ground motion between opposing final lenses may be comparable to the beam sizes
- Several solutions possible:
  - Optical anchor stabilization
  - Inertial stabilization (geophone feedback)
  - Pulse-to-pulse beam-beam alignment feedback
- Can we use beam-beam deflection within the crossing time a single bunch train?
## NLC Interaction Point Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Stage 1</th>
<th>Stage 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>CMS Energy (GeV)</td>
<td>490</td>
<td>888</td>
</tr>
<tr>
<td><strong>Luminosity</strong> ( \times 10^{33} )</td>
<td><strong>22</strong></td>
<td><strong>34</strong></td>
</tr>
<tr>
<td>Repetition Rate (Hz)</td>
<td>120</td>
<td>120</td>
</tr>
<tr>
<td><strong>Bunch Charge</strong> ( \times 10^{10} )</td>
<td><strong>0.75</strong></td>
<td><strong>0.75</strong></td>
</tr>
<tr>
<td>Bunches/RF Pulse</td>
<td>190</td>
<td>190</td>
</tr>
<tr>
<td>Bunch Separation (ns)</td>
<td>1.4</td>
<td>1.4</td>
</tr>
<tr>
<td><strong>Eff. Gradient</strong> ( \text{MV/m} )</td>
<td><strong>50.2</strong></td>
<td><strong>50.2</strong></td>
</tr>
<tr>
<td>Injected ( \gamma \varepsilon_x / \gamma \varepsilon_y ) ( \times 10^{-8} )</td>
<td>300 / 2</td>
<td>300 / 2</td>
</tr>
<tr>
<td>( \gamma \varepsilon_x ) at IP ( \times 10^{-8} ) m-rad</td>
<td>360</td>
<td>360</td>
</tr>
<tr>
<td>( \gamma \varepsilon_y ) at IP ( \times 10^{-8} ) m-rad</td>
<td><strong>3.5</strong></td>
<td><strong>3.5</strong></td>
</tr>
<tr>
<td>( \beta_x / \beta_y ) at IP (mm)</td>
<td>8 / 0.10</td>
<td>10 / 0.12</td>
</tr>
<tr>
<td>( \sigma_x / \sigma_y ) at IP (nm)</td>
<td><strong>245 / 2.7</strong></td>
<td><strong>200 / 2.2</strong></td>
</tr>
<tr>
<td>( \sigma_z ) at IP (um)</td>
<td>110</td>
<td>110</td>
</tr>
<tr>
<td>( \gamma \text{ave} )</td>
<td>0.11</td>
<td>0.26</td>
</tr>
<tr>
<td>Pinch Enhancement</td>
<td>1.43</td>
<td>1.49</td>
</tr>
<tr>
<td>Beamstrahlung ( \delta B ) (%)</td>
<td>4.6</td>
<td>8.8</td>
</tr>
<tr>
<td>Photons per e+/e-</td>
<td>1.17</td>
<td>1.33</td>
</tr>
<tr>
<td>Two Linac Length (km)</td>
<td>5.4</td>
<td>9.9</td>
</tr>
</tbody>
</table>
## Beam-Beam Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma_y$</td>
<td>2.65 nm</td>
<td>(!)</td>
</tr>
<tr>
<td>$\sigma_x$</td>
<td>245 nm</td>
<td></td>
</tr>
<tr>
<td>$\sigma_z$</td>
<td>110 (\mu)m</td>
<td></td>
</tr>
<tr>
<td>Disruption Parameter</td>
<td>14</td>
<td></td>
</tr>
<tr>
<td>Deflection slope</td>
<td>25 (\mu)radian / nm</td>
<td>At origin</td>
</tr>
<tr>
<td>Displacement slope</td>
<td>100 (\mu)m/nm</td>
<td>At BPM</td>
</tr>
</tbody>
</table>
Intra-pulse Feedback

• Fix interaction point jitter within the crossing time of a single bunch train (266 ns)

• BPM measures beam-beam deflection on outgoing beam
  – Fast (few ns rise time)
  – Precise (≈micron resolution ⇒ ≪ 1nm beam offset resolution)
  – Close (∼4 meters from IP)

• Kicker steers incoming beam
  – Close to IP (∼4 meters)
  – Close to BPM (minimal cable delay)
  – Fast rise-time amplifier

• Feedback algorithm is complicated by:
  – round-trip propagation delay to interaction point in the feedback loop.
  – transfer function non-linearity
Intra-Pulse Feedback

Next Linear Collider

IP

Kicker

Amp

Round Trip Delay

BPM Processor

BPM
Beam Position Monitor

- **Stripline BPM**
  - 50 Ohm
  - 6 mm radius
  - 10 cm long
  - 7% angular coverage
  - 4 m from IP
  - Process at 714 MHz
    - Downconvert to baseband
    - need to phase BPM
    - Wideband: 200 MHz at baseband
    - Analog response with < 3ns propagation delay (plus cable lengths)
Fast BPM Processor

**Fast BPM Processor Block Diagram**

- **Top Stripline**
  - RF Hybrid
- **Bottom Stripline**
  - RF Hybrid
- **Timing System**
  - 714 MHz Phase Reference
- **Bandpass filter**
  - Bessel 4-pole 714 MHz 360 MHz BW
- **MIXER**
- **Lowpass filter**
  - Bessel 3-pole 200 MHz
- **Programable Attenuator**
  - MPS Network
  - Normalize BPM to Bunch Charge
  - (Bunch Charge)
- **Kicker Drive**

**Author Name**: Steve Smith  
**Date**: October 2002
Simulated BPM Processor Signals

BPM Pickup (blue)
Bandpass filter (green)
and BPM analog output (red)
• Position monitor processor looks like the simulation
Stripline Kicker

- **Baseband Kicker**
  - Parallel plate approximation $\Theta = 2eVL/pwc$
    - (half the kick comes from electric field, half from magnetic)
  - 2 strips
  - 75 cm long
  - 50 Ohm / strip
  - 6 mm half-gap
  - 4 m from IP
  - Deflection angle $\Theta = eVL/pwc = 1$ nr/volt
  - Displacement at IP $d = 4$ nm/volt
  - Voltage required to move beam 1 $\sigma$ (3 nm) 0.75 volts (10 mW)
  - 100 nm correction requires 12.5 Watts drive per strip
  - Drive amp needs bandwidth from 100 kHz to 100 MHz
Capture Transient

Capture transient from $2\sigma$ initial offset
Limits to Beam-Beam Feedback

• Must close loop fast
  – Propagation delays are painful
• Beam-Beam deflection response is non-linear
  – slope flattens within 1 \( \sigma \)
• Linear feedback converges too slowly beyond \( \sim 10 \sigma \) to recover most of lost luminosity.
• Should be able to fix misalignments of 100 nm with modest kicker amplifiers.
  – Amplifier power goes like square of misalignment.
Non-linear Response Challenges Feedback

• Beam-beam deflection non-linearity limits:
  – Limits useful (timely) range of convergence
  – Limits stability in collision
Non-linear Response Challenges Feedback

Optimize gain for small initial offset:

Then convergence is poor from far out:

Set gain for good convergence, then high gain at origin causes oscillation when near center:
Linearize Feedback

• Can we compensate non-linearity?
  – Fast?
    • Bandwidth
    • propagation delay
  – Accurately?

• Yes!

• Add compensation amplifier
  – Op-amp
  – Diodes to introduce desired non-linearity.
  – Bias adjust (knee or breakpoint)
Measured Transfer Function

Transfer Function

Output (Volts) vs. Input (Volts)
Large Signal Waveform

1 V step
Full BW

Settles to DC response in several ns
Simulink Model

Next Linear Collider

Simulink Model Diagram
Non-Linear Feedback Simulation

Full luminosity recovered in one round-trip time for 10 $\sigma$ initial offset.
Linearizer Conclusions

- Simple op-amp based non-linear amp is sufficient to improve:
  - Stability
  - Convergence speed \( \Leftrightarrow \) capture range
  - Programmable linearity compensation

- Low propagation delay: \( \sim 1 \text{ ns} \)
- High bandwidth > 200 MHz

- Sufficient to achieve:
  - Single round-trip convergence to \( < 1 \sigma \) from \( 10 \sigma \) initial offset.
  - Two-cycle convergence to \( < 0.1 \sigma \) from \( 10 \sigma \) initial offset.
    - Limited by dynamic range of present op-amp, not by accuracy of compensation
      - Fix with another amplifier or tune diode bias

- Breadboard prototype slightly peaky for small signals
  - Likely to be fixed with chip diodes in real layout
  - Ideally would make large signal response as peaky as small-signal response
  - (to compensate kicker fill time)

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Intra-Pulse Feedback
Intra-Pulse Feedback
(with Beam-Beam Scan & Diagnostics)

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Beam-Beam Scan

Beam bunches at IP: blue points
BPM analog response: green line
Conclusions

• **Q BPMs**
  – Need cavity BPMs
    • Accuracy
    • Stability
    • Compact

• **Damping Ring BPM**
  – Small evolution of current practice

• **Structure Position Monitors**
  – Electronically more like Direct Satellite TV receiver
  – New to us, but similar objects are commercially available

• **Multi-Bunch BPMs**
  – High resolution
  – High bandwidth
  – Beyond state of the art
  – Achievable based on reasonable extrapolation of technology
Extensions

- Beyond NLC machine requirements:
- Bunch tiltmeter
- Nanometer resolution BPM’s