NLC Damping rings generate low-\(e\) beams

- Emittances must be preserved through
  - bunch compressors
  - main linacs
  - beam delivery systems

In general smaller \(e_y\) implies problems in vertical 1-2 orders of magnitude harder than horizontal

<table>
<thead>
<tr>
<th>REGION</th>
<th>(e_x), mm.mrad</th>
<th>(e_y), mm.mrad</th>
</tr>
</thead>
<tbody>
<tr>
<td>From DR</td>
<td>3.0</td>
<td>0.02</td>
</tr>
<tr>
<td>Injector</td>
<td>0.2</td>
<td>0.002</td>
</tr>
<tr>
<td>Linac</td>
<td>0.1</td>
<td>0.008</td>
</tr>
<tr>
<td>BDS</td>
<td>0.3</td>
<td>0.005</td>
</tr>
<tr>
<td>Total</td>
<td>3.6</td>
<td>0.035</td>
</tr>
</tbody>
</table>
Main Linac Beam Dynamics

Most Severe Problem = Beam Break-Up (BBU)

- Wakefields resonantly drive tail of beam in $\beta$ oscillation
- Can cause exponential growth along linac
- Can be single-bunch (SLC) or multi-bunch (SLAC fixed-target)

Graph showing Beam Break-Up Emittance Growth as a function of distance $s$, in km.
**Curing Single-Bunch BBU**

- **Introduce correlated energy spread**
  - bunch head higher than bunch tail

- **⊥ WF kicks cancelled by quad chromaticity**

- **Used in SLC era and ever since**
• Design RF structure to have weak LR wake
• Two methods:
  – detuning (different HOM frequencies in each cell)
  – Damping (extract HOM power thru manifolds)
• Combination reduces LR wake 100x in 1.4 nsec inter-bunch period
• Understanding of low-wake structure design now excellent
Once BBU is eliminated, there are still the incoherent sources of emittance dilution:
- beam-to-quad offsets (misalignments)
- beam-to-RF-structure offsets (misalignments)
- RF structure pitch angles (misalignments)
- Quad roll errors
- Quad Strength

Fabrication errors in structures can reduce effectiveness of LR wake suppression
- Structure straightness errors
- HOM frequency errors
## Single-Bunch Dilutions: Tentative Tolerances

<table>
<thead>
<tr>
<th>Effect</th>
<th>Tolerance</th>
<th>$\Delta e_y$ Increase, mm.mrad</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam-to-Quad Misalignment</td>
<td>2.0 microns</td>
<td>0.0050</td>
</tr>
<tr>
<td>Beam-to-Structure Misalignment</td>
<td>5.0 microns</td>
<td>0.0014</td>
</tr>
<tr>
<td>Beam-to-Structure Pitch Angle</td>
<td>51 microradians</td>
<td>0.0008</td>
</tr>
<tr>
<td>Quadrupole Rotations</td>
<td>200 microradians</td>
<td>0.0008</td>
</tr>
<tr>
<td>Quadrupole Strength Errors</td>
<td>0.1%</td>
<td>0.0001</td>
</tr>
</tbody>
</table>
Alignment tolerances cannot be met by ab initio installation

Quads and RF structures need to be aligned with beam-based measurements
- some degree of local correction of e dilution is essential

The set of all such techniques ≡ “beam-based alignment” (BBA)
- Many people use “BBA” to mean a particular technique (varying quads and measuring change in deflection), we use it more generally
Quad with BPM: 0.3 µm x/y resolution

RF structures, each with 2 BPMs (1 each end), 5 µm x/y resolution

Quad with BPM: 0.3 µm x/y resolution

Remote-controlled girder translation stage, x/y degrees of freedom each end

Remote-controlled magnet translation stage, x/y degrees of freedom, 50 nm step size
RF Structure Alignment

- Use HOM signal as BPM
  - unambiguous: no HOM = structure aligned to beam
  - S/N resolution < 5 µm
- 12 per girder
  - effective resolution < 2 µm
- Girder arrangement changes nature of tolerances
  - 1st order: need only align average of 6 structures
  - next order: wakes on girder don’t exactly cancel
  - Relevant tolerance becomes RMS alignment of structures to girder!
Quad Alignment

- Each quad has a captured BPM
  - probably cavity-style
  - resolution ~ 0.3 µm

- Main problem: BPM Electrical Center ≠ Quad Magnetic Center
  - RMS difference ~ 100 µm
  - Can’t just “steer BPMs to Zero”

- Need some way to find set of BPM readings that minimizes e growth
  - Sometimes known as problem of “Finding a Gold Orbit”
Finding a Gold Orbit

• **Typically an Invasive Procedure**
  - can’t deliver luminosity while looking for gold orbit
  - Tradeoff between how long procedure takes and how often you need to do it

• **Has to locally correct emittance growth**
Gold Orbit (2): How to Find

Historically, Two Techniques Widely Studied:

• **Quad Variation**
  – shunt quad, measure deflection
  – tells beam-to-quad offset, thus BPM-to-quad offset
  – Very local
  – Requires EM quads
  – Subject to systematics when quad strength varied

• **Dispersion Free Steering (DFS)**
  – Change energy gain in linac, measure deflection
  – Allows determination of orbit that minimizes RMS dispersion in linac
  – Less Local; solution may be less stable in time
  – Any kind of quad permitted
  – Depends only on BPM resolution
Gold Orbit (3)

- Both Quad Variation and DFS widely used in accelerator world

- Simulation studies: either technique will reduce e growth in linac to ~ desired level
  - Imperfect optics knowledge may limit resolution

- Which would we use?
  - depends on details of linac!
Global Corrections

- Use closed orbit bumps to correct remaining e growth in linac
  - Minimize beam on profile monitor by varying bump amplitude
  - Technique used intensively in SLC
- Definitely will want to use them even if local correction hits e tolerances
  - Smaller is always better!
- Simulation studies: can reduce e growth by factor of 3-4
- Simulation: Combination of bumps and DFS/Quad Variation always achieves e tolerances
Additional Methods (with thanks to: C. Adolphsen, P. Raimondi, M. Ross)

- **Cavity BPM:** quadrature signal ~ beam tilt (pitch/yaw)

  - \( \perp \) WF’s deflect tail of bunch
  - Quad misalign causes a beam tilt
    - BNS damping: E spread has huge z correlation

- **Quadrature signal gives e information**
  - better in many respects than in-phase position signal!
Beam Tilt Signals

- **Has many advantages of BPM signal:**
  - has a sign (positive or negative tilt?)
  - Non-invasively available throughout linac
  - Available on every machine pulse

- **Has advantage of a beam profile signal**
  - Proportional to beam size

- **Implications are Staggering**
  - Can localize source of emittance dilution and determine amplitude/sign of correction needed
Two Potential Applications Studied

- **Local Correction**
  - by minimizing RMS tilt signal
  - Results Comparable to DFS or Quad Variation
  - Less cumbersome than either DFS or Q.V.

- **Global Correction**
  - Use tilt signals to determine
    - which linac bumps to use
    - which sign required
    - Amplitude required
  - Easier and quicker convergence than tuning on profile monitors, quality of solution ~ same

- Further study of the beam tilt signal is worthwhile
Single-Bunch Dilutions: Stability

- Slow motion of quads, etc causes gradual e growth
- Steering feedback in linac reduces impact
  - EM steering dipoles at discrete locations
- Periodically re-steer entire linac with quad movers
  - steer to “gold orbit”
- Over some long time (weeks?) “gold orbit” becomes invalid
  - changes in BPM offsets, etc
  - Need to repeat invasive procedure to find new gold orbit
Single-Bunch Stability (2)

- How often do we need to find gold orbit?
  - depends on stability time
  - BPM offset stability crucial
- FFTB BPMs:
  - over 1 week: \( s \approx 2.7 \, \mu m \)
  - Over 26 months: \( s \approx 26 \, \mu m \)
  - both upper bounds
- Expect to do better in NLC by:
  - short cables
  - better supports
  - Cavity BPMs (not trying to cancel 2 large #’s)
Multi-Bunch Dilutions

- Due to small imperfections in RF structures
  - bowing
  - cell-to-cell assy. errors
  - HOM freq errors
- For small errors, produce quasi-static dilution
- Can be corrected with FB that “straightens” bunch train
  - Need BW ~ 250 MHz for 90% correction
  - Peak power: 80 W to correct ~10% emittance growth @ 500 GeV/beam
## Linac Emittance Dilutions: Summary

<table>
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<tr>
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<th>Tolerance</th>
<th>$\gamma_{xy}, \text{mm.mrad}$</th>
</tr>
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<tbody>
<tr>
<td>Beam-to-Quad Offsets</td>
<td>2.0 µm</td>
<td>0.005</td>
</tr>
<tr>
<td>Quad Strength Errors</td>
<td>0.1%</td>
<td>0.00001</td>
</tr>
<tr>
<td>Struc-to-Girder Misalignments</td>
<td>30 µm</td>
<td>$0.0014$ (single-bunch) $0.0002$ (multi-bunch)*</td>
</tr>
<tr>
<td>Struc-to-Girder Tilts</td>
<td>30 µrad</td>
<td>0.0008</td>
</tr>
<tr>
<td>Struc BPM Resolution</td>
<td>5 µm</td>
<td>0.0006</td>
</tr>
<tr>
<td>Quad Rotations</td>
<td>200 µrad</td>
<td>0.0008</td>
</tr>
<tr>
<td>Mover Steering Interval</td>
<td>30 minutes</td>
<td>0.0004</td>
</tr>
<tr>
<td>Structure Bow</td>
<td>50 µm</td>
<td>$0.0002^*$</td>
</tr>
<tr>
<td>Cell-to-Cell Errors</td>
<td>3.5 µm</td>
<td>$0.0002^*$</td>
</tr>
<tr>
<td>HOM Freq Errors</td>
<td>1 MHz</td>
<td>$0.0002^*$</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td>$0.0099$ (50%)</td>
</tr>
</tbody>
</table>
Beam Delivery System

- Very Different System from Main Linac
  - Some challenges easier
    - fewer $\beta$ wavelengths
    - Lower RMS energy spread
    - Global knobs (waist, coupling, ?) simpler
    - IP diagnostics from collision (beam-beam offset, luminosity)
  - Some challenges harder
    - Sextupole and other multipole magnets
    - Large $\beta$'s at sextupoles and final doublet
    - Delicate cancellation of aberrations
    - Single-beam IP diagnostic challenging
- Static tolerances typically looser, but stability tolerances much tighter
Tuning of the BDS

Based on the sequence used for SLC-FF, FFTB

- **Beam-to-Quad Alignment**
  - via quadrupole variation, 5-10 µm RMS

- **Sextupole-to-Beam Alignment**
  - Scan x/y position, measure x deflection
  - ~10 µm RMS

- **Tune global aberration knobs**
  - waists, coupling, dispersions, crab cavity phases
  - Use luminosity monitor signal
Stability of the BDS

- Active position control of final doublets
  - motion sensors or interferometer
- Beam-based feedback on IP collision offset
  - (looks at beam-beam deflection)
- Steering feedbacks maintain orbit through sextupoles
- “Dither Feedback” on linear aberrations at IP
Conclusions

- Tolerances required to achieve NLC e goals are impressive but attainable

- **Requirements on diagnostics, correction devices, stability, algorithms, etc., are at worst modest extrapolations from existing “proofs of principle”**

- **RF cavity beam tilt monitors appear to provide useful information**
  - need to study actual device – “deity is in the details”
Future Work

• Improve understanding of Beam Tilt Monitors as real devices

• Revisit main linac studies as RF structure design matures
Future Work (2)

• Improved Simulation Tools – LIAR
  – LIAR is a simulation tool which allows advanced simulation of errors & correction algorithms
  – Historically only for linacs
  – L. Hendrickson leading serious revision of LIAR
    • improve ease of maintenance / use
    • improve execution speed
    • improve simulation of LR wakefields
    • more realistic simulation of ground motion effects on beamline
    • extend LIAR to bunch compressors and beam delivery systems
Future Work (3)

- **Devise similarly robust BDS tolerance table**
  - new-LIAR will help here

- **DR extraction to IP integrated simulations with diagnostics and corrections**