NLC - The Next Linear Collider Project

Emittance Dilution and in Storage Rings and Linacs

M3 / T5 Join t Session

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Sources of Emittance Dilution

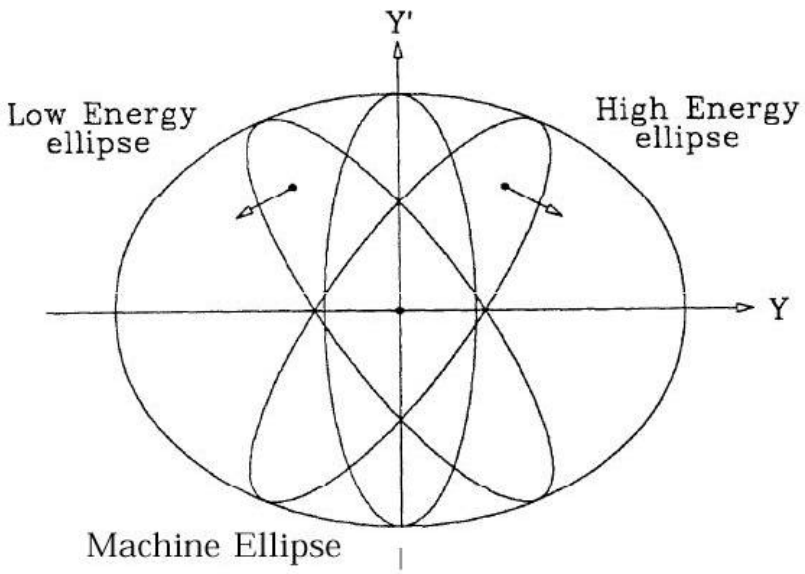
- Conservative and non-conservative dilutions
- Non-conservative
  - Synchrotron radiation – relevant in damping rings and BDS
  - Beam-gas scattering – not an issue for emittance
- Conservative
  - Dispersion
  - Wakefields; CSR
  - Betatron coupling; beta-matching
  - Multi-bunch couplings ($W_{\perp}$, photo e-, ions, etc.)
  - Nonlinearities; space charge; photo e-; ions
  - Etc.
- Conservative dilutions just couple degrees of freedom and increase the projected emittance; the 6-D emittance is not changed and the couplings can be removed (in theory)!

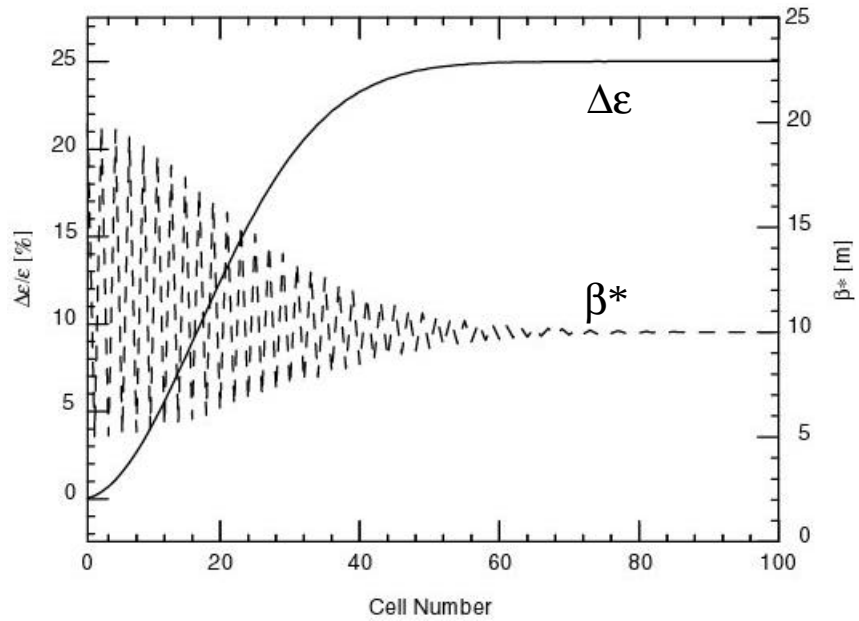
Filamentation

- Injection trajectory and betatron mismatches will filament due to chromaticity or nonlinear fields
- Betatron mismatches can be characterized in terms of B_{mag}:

$$\Delta\gamma\epsilon \approx \gamma\epsilon(B_{\mathrm{mag}} - 1) \qquad B_{\mathrm{mag}} \equiv \frac{1}{2}\left[\left(\frac{\beta}{\beta_\star} + \frac{\beta_\star}{\beta}\right) + \left(\alpha_\star\sqrt{\frac{\beta}{\beta_\star}} - \alpha\sqrt{\frac{\beta_\star}{\beta}}\right)^2\right]$$

* parameters are for the beam





Damping Rings

- Two primary terms:
  - Local increase of the beam spot (and divergence) at extraction
  - Increase of the beam emittance due to synchrotron radiation or IBS which is coupled to the vertical plane by some aberration

$$\frac{\sigma_y^2(s)}{\beta_y(s)} = \epsilon_y + \frac{\sigma_{y\,\mathrm{local}}^2(s)}{\beta_y(s)}$$

  - In the weak coupling limit, ε_y is invariant around the ring while the local increase depends on the local betatron coupling and dispersion
  - The local increase can be corrected after extraction provided this is done before the correlations are lost

  - There is also a limiting contribution from the radiation opening angle but this small:

$$\gamma\epsilon_y \approx 0.24 J_\epsilon \overline{\beta_y} \frac{\sigma_\epsilon^2}{\gamma}$$

Vertical Dispersion

- Vertical dispersion generated by sextupole misalignments and quadrupole rotations in regions of η_x and orbit errors
  - Usually tightest tolerance on sextupoles
  - Chromaticity correction reduces effect of orbit – do not over-correct
  - Simple estimates for random errors

$$\frac{\langle \eta_y^2 \rangle_{\text{sext misalign}}}{\beta_y} = \frac{1}{8\sin^2 \pi\nu_y} \sum_{sext} (K_2 L)^2 y_m^2 \beta_y \eta_x^2$$

  - Resonant denominator arises from periodicity – stay away from the integer?

$$\frac{\langle \sigma_y^2(s) \rangle_{\text{local}}}{\beta_y(s)} = \frac{\langle \eta_y^2(s) \rangle}{\beta_y(s)} \sigma_\epsilon^2 \qquad \langle \epsilon_y \rangle = 2\frac{C_q \gamma^2}{J_y} \frac{\langle \eta_y^2 \rangle}{\beta_y} \frac{\int |G|^3 ds}{\int G^2 ds} = 2J_\epsilon \frac{\langle \eta_y^2 \rangle}{\beta_y} \sigma_\epsilon^2$$

  - Expected effect on emittance is larger than that on local beam size

Betatron Coupling

- Betatron coupling generated by sextupole misalignments, quadrupole rotations, and orbit errors in sextupoles
  - Again, usually tightest tolerance on sextupoles
  - Two terms: sum and difference contributions

$$\frac{\langle \sigma_y^2 \rangle_{\text{local}}}{\beta_y} = \frac{\epsilon_x}{4} \frac{(1 - \cos 2\pi\nu_x \cos 2\pi\nu_y)}{(\cos 2\pi\nu_x - \cos 2\pi\nu_y)^2} \sum_{sext} (K_2 L)^2 y_m^2 \beta_x \beta_y$$

$$\frac{1}{\sin^2 p\Delta u_-} + \frac{1}{\sin^2 p\Delta u_+}$$

$$\langle \epsilon_y \rangle = \frac{\epsilon_x}{4} \frac{\alpha_x}{\alpha_y} \frac{(1 - \cos 2\pi\nu_x \cos 2\pi\nu_y)}{(\cos 2\pi\nu_x - \cos 2\pi\nu_y)^2} \sum_{sext} (K_2 L)^2 y_m^2 \beta_x \beta_y$$

  - Cosine expression equal sum over sum and difference resonances:

$$\frac{1}{\sin^2 p\Delta u_-} + \frac{1}{\sin^2 p\Delta u_+}$$

Emittance Correction (1)

- Lots of different techniques to measure and correct residual dispersion and coupling
  - Present generation diagnostics allow for very accurate measurements and construction of beam transport matrices
  - Tolerance on rms η_y is 1~2mm in NLC ring
    - Variation of beam energy by 0.3% with BPMs having 1μm resolution gives plenty of resolution for global correction techniques
  - Correction of betatron coupling when far from coupling resonance is probably most effectively performed by measuring 4-D transport matrix
    - Minimization of the tune separation is done at a different set-point and does not treat contribution from the sum resonance

Emittance Correction (2)

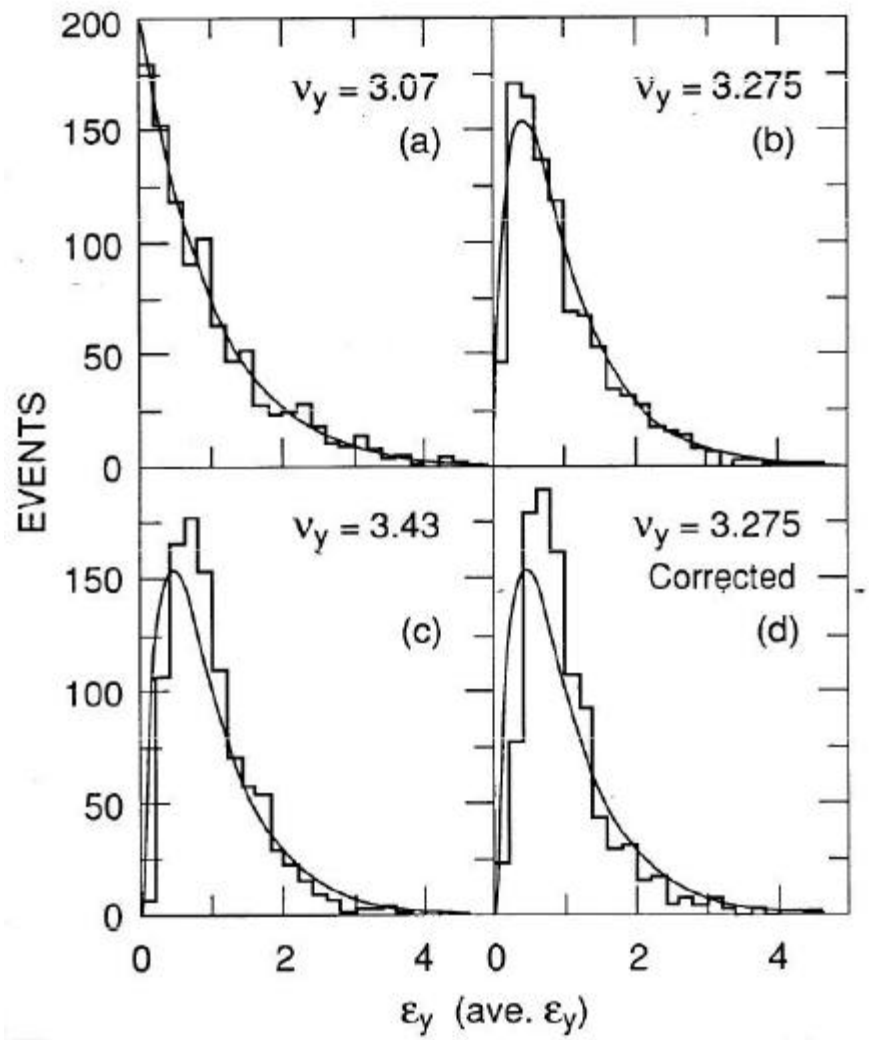
- Must correct dilutions locally at all sources of radiation/scattering to fully correct emittance
- Simple correction effectively removes resonant denominator
  - Using one pair of correctors separated by 90° to correct the average of H_y, one can expect to reduce the emittance by:

$$\langle \epsilon_y \rangle = \frac{2}{3} \sin^2 \pi \nu_y \langle \epsilon_y \rangle_0$$

  - Be careful – correction to zero H_y at one point, for example extraction, can increase average error and thus emittance
  - Additional correctors decreases residual error slowly although can be very effective for special areas such as wigglers
  - Similar performance with 4 skew quadrupoles to correct betatron coupling

Distribution of Machines

- Tolerances are set to 'ensure' that emittance will be attained
- Random errors in one degree-of-freedom, ie. dispersion (y-δ) or betatron coupling (y-x), generate an approximately exponential distribution in the emittance
- The 95% c.l. occurs at 3σ in an exponential distribution



Other Issues (1)

- Transients!
  - Linacs are very sensitive small changes in injected beam parameters
  - Non-uniform fill causes transient beam loading and variations in trajectory and tunes along bunch train
  - Tune variation can make emittance correction and dynamic aperture difficult
  - Instabilities are not a good thing!

- Stability
  - Corrections are difficult and time consuming to implement
  - Must maximize stability of trajectory
  - After establishing a ‘gold’ trajectory, stability of BPMs and sextupoles are the most important
  - Place BPMs in sextupoles??

Other Issues (2)

- Circumference control
  - Extraction energy must be maintained at fraction of $\sigma_{\Delta E/E}$
  - Small momentum compaction means large sensitivity of energy to circumference: $$\frac{\Delta E}{E} = \frac{1}{\alpha}\frac{\Delta C}{C}$$
  - Tolerance on circumference is roughly 10μm in NLC ring – need feedback and chicane for control!

- Intrabeam Scattering
  - Expected to increase emittance by 10~20% in NLC ring and similar(?) in TESLA ring – discrepancy between theory and KEK ATF measurements may be resolved but need additional data

Other Issues (2)

- Electron cloud and ions
  - These can drive single bunch dilutions as well as multi-bunch dilutions and tune variations
- Space charge
  - Can decrease dynamic aperture due to tune spread, increase vertical emittance due to coupling, and provides a 4th order coupling term which can increase the vertical emittance
- Wiggler systems
  - Large wigglers generate nonlinearities and massive radiation – are there any collective effects not seen in normal rings?

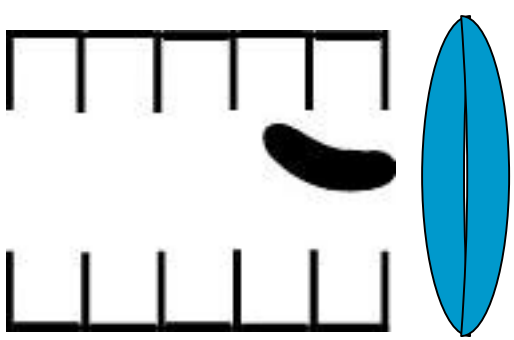
Linac Dilutions

- Trajectory and energy jitter
  - Sets quad vibration and rf stability (esp. in bunch compressors)
- Dispersion errors
  - Sets quad-to-bpm alignment for $\Delta\varepsilon$
  - Three E sources: incoming ΔE, E jitter, and BNS energy spread
- Short-range wakefields
  - BBU $\Rightarrow$ BNS - requires rf energy overhead or rf quadrupoles
  - Sets tolerances on structure-to-beam alignment for $\Delta\varepsilon$
- Long-range wakefields
  - BBU $\Rightarrow$ wake reduction - sets dipole frequency errors
  - Sets internal structure alignment tolerances for $\Delta\varepsilon$
  - Sets charge tolerances
- Other (coupling, bookshelf, slow component motion)

- Dynamics in linacs are ‘simple’ compared to rings

BBU and BNS Damping (1)

- Short-range wakefield will amplify incoming trajectory jitter
- Single bunch BBU well studied theoretically and experimentally – analytic models are quite good
- BNS technique prevents BBU due to short-range wakefields
- Add correlated energy spread to compensate dipole wakefield deflection with quadrupole chromaticity or use rf quadrupoles
  - Works locally in smooth focusing and on average in strong focusing



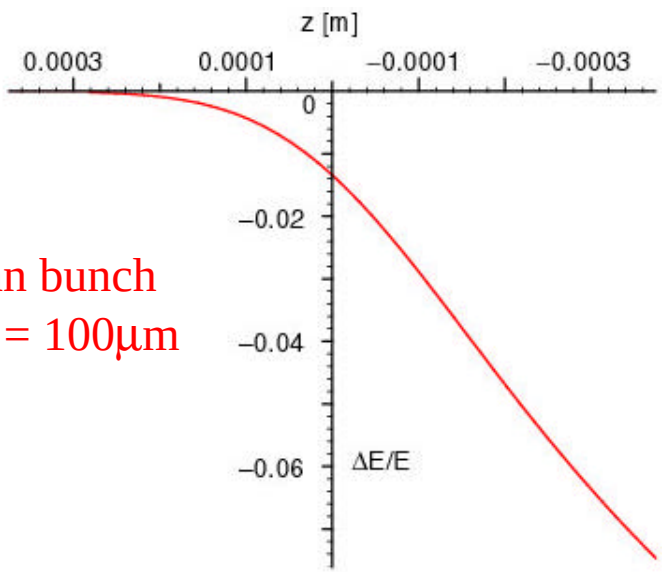
$$\frac{1}{\gamma}\frac{d}{ds}\gamma\frac{d}{ds}y(s,z) - (1-\delta)K(y-y_q)$$
$$= (1-\delta)G - 4\pi\epsilon_0 N r_e \frac{1-\delta}{\gamma_0}$$
$$\times \int_z^\infty W_\perp(s,z'-z)(y(z)-y_a)\rho(z')\,dz'$$

BNS Damping (2)

- Different regimes: autophasing; BNS damping; filamentation

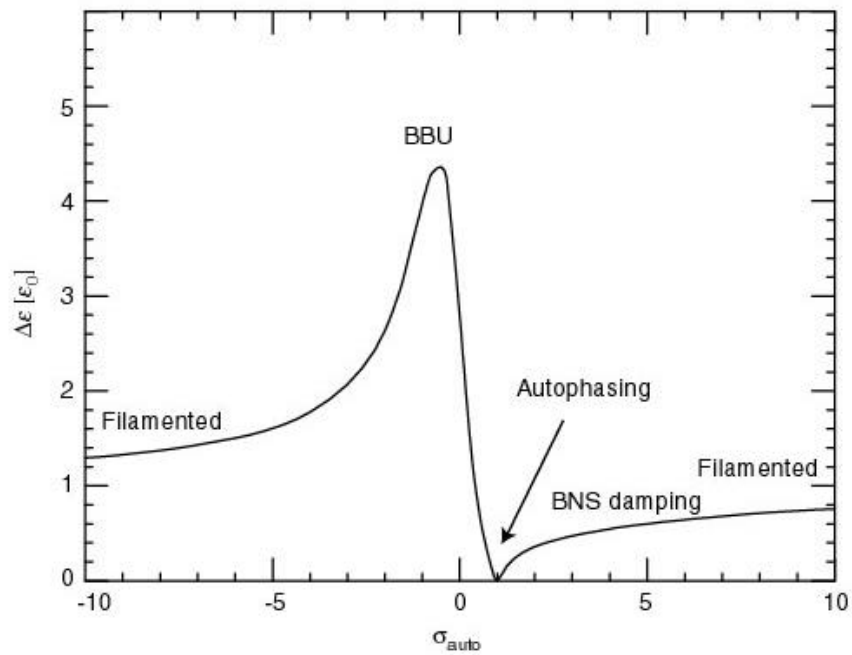
Rigid oscillation: $$\delta_{\text{auto}}(z) = \frac{4\pi\epsilon_0 N r_e}{K\gamma_0}\int_z^\infty W_\perp(z'-z)\rho(z')\,dz'$$

Autophasing ΔE/E



Gaussian bunch with σ_z = 100μm

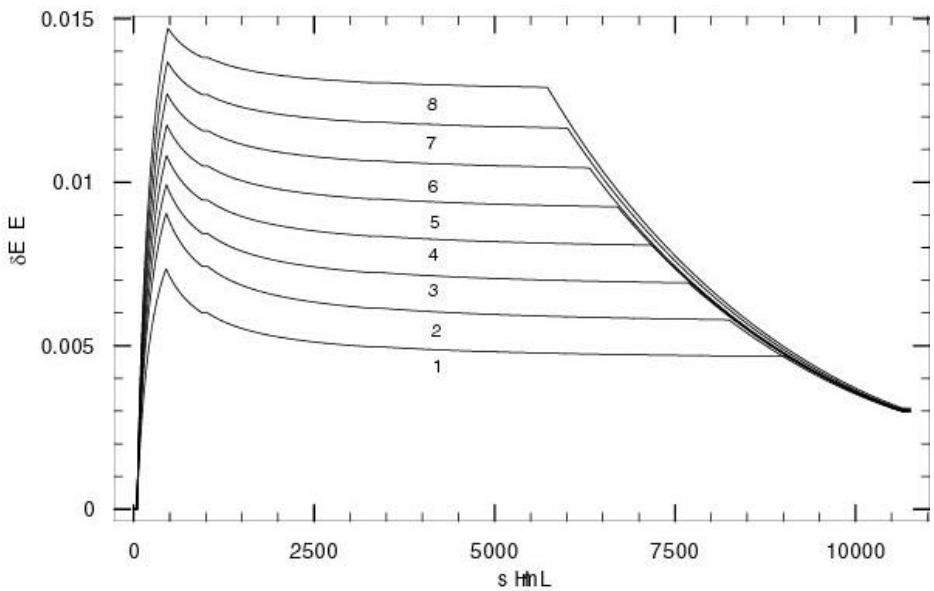
Δε versus ΔE/E

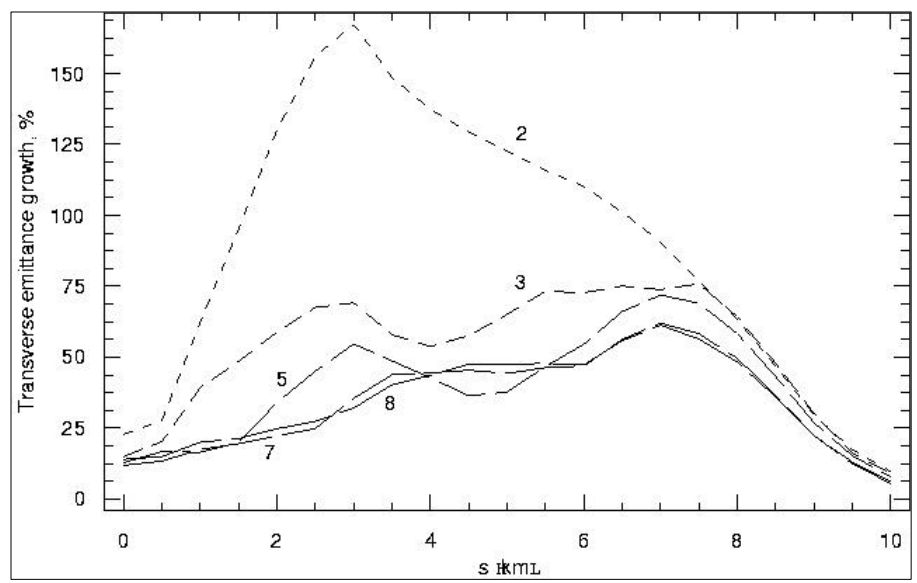


- BNS energy spread also reduces growth of other correlations: y-z tilts etc.

BNS Damping (3)

- BNS damping reduces sensitivity to disturbances along the linac – cannot operate linac with significant BBU
  - single bunch is handled with BNS presently induced by running off the rf crest - requires energy overhead
  - rf quadrupoles allow for more uniform compensation and looser quadrupole tolerances but tight tolerances on rf quad alignment





Multiple Bunch BBU

- Long-range wakefield drives coupled bunch BBU
- First observed at SLAC in 60's (sometime) – well studied!
- Primary solution is direct reduction of (averaged) wake between bunches, ie. detuning mode freq. or damping

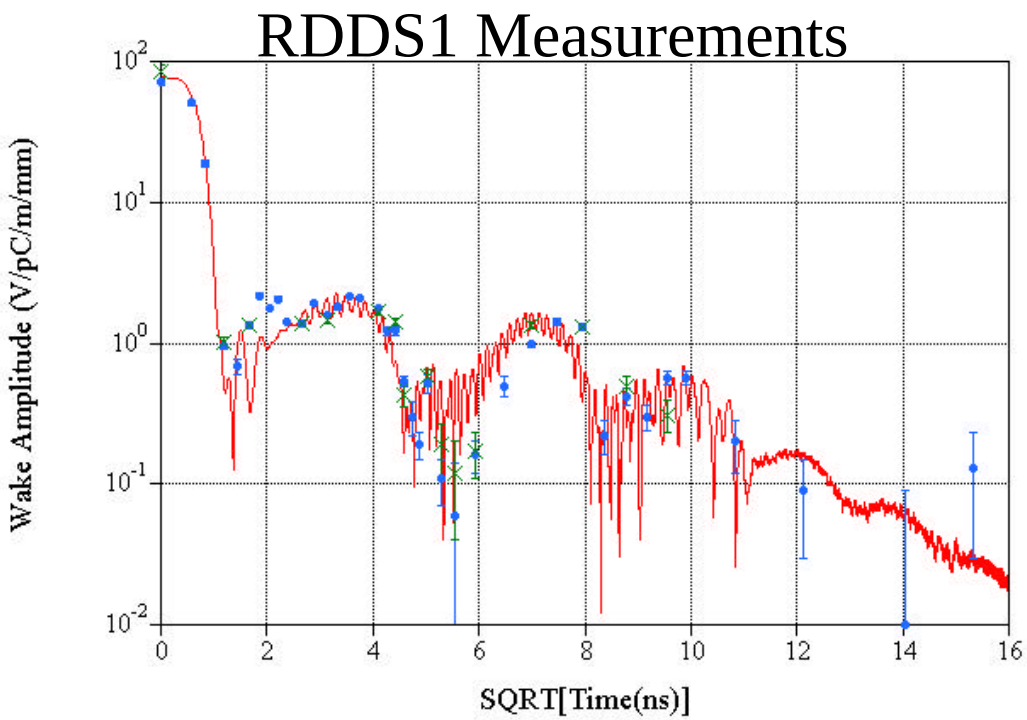
- Calculation of MB-BBU is difficult: nearest neighbor or daisy chain model, single mode models, etc.

$$\left| \frac{2\pi\epsilon_0 N r_e W_\perp(\Delta_b)\overline{\beta}_i}{\alpha G} \right| \left(\frac{\gamma_f}{\gamma_i}\right)^\alpha < 1$$

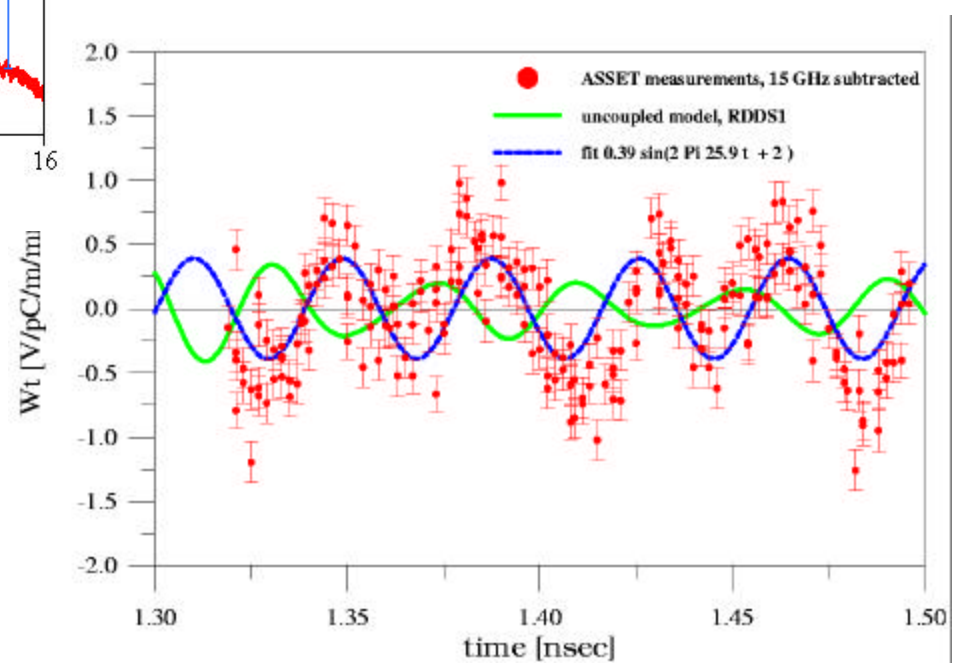
For NLC parameters,
$W_\perp(\Delta_b) \leq 1\%\ W_\perp$

- Difficult to get accurate representation of wakefield
- Computer simulation is straight-forward

Long-Range Wakefield Measurements



- Three DDS-style structures have been built and tested
- Wakefield model agrees well with measurements



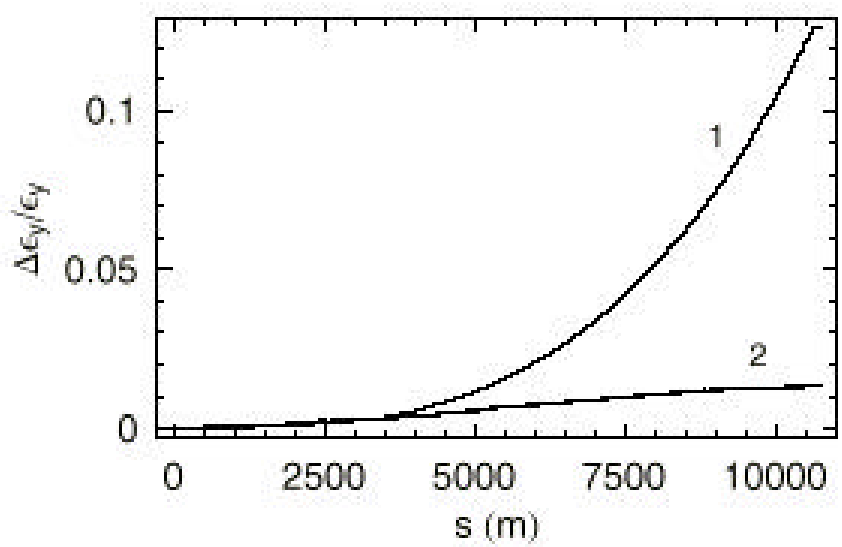
- Lowest band is around 15 GHz
- Next band (25 GHz) is visible after 1.4 ns

‘BNS’ for Long-Range Wakefield

- LR wake tends to be much larger than SR: ($\lambda/6 >> \sigma_z$)
- If magnitude can be made comparable to that of the short-range across a bunch

$\Rightarrow$ Use BNS damping-like technique, i.e. add bunch-to-bunch energy deviation to bunch train - actually more detuning than BNS damping but ...

- Long-range longitudinal wake and rf compensation provides route: need 0.5% rms for ‘worst-case’ DDS3 wakefield



Jitter and Static Errors

- Linear colliders cannot operate in BBU regime!
- If BBU is small and operating close to autophasing condition, transport matrices are close to nominal optics
- First-order perturbations are all that are important!
- Beam jitter arises from incoming errors and quadrupole motion (faster than that correctable)
  - Typical jitter tolerances are 10nm in NLC and TESLA
- Correct 'static' alignment errors to reduce emittance dilution
- Alignment scales are roughly ~1000 times larger than beam jitter scales: $1/\sigma_{\Delta E/E}$

Example 'Bare' Machine Tolerances

- 'Bare' machine tolerances are the component alignment tolerances without any non-local tuning or correction
  - NLC is designed with emittance correction like storage rings are designed with orbit correction (many rings use η-correction)

Bare Tolerances for 500 GeV cms

	Injector	**Main Linac**	**BDS**
Quad jitter	10 nm	10 nm	1-10 nm
Quad alignment	10 μm	2 μm	2-5 μm
Structure alignment	40 μm	10 μm	-
Quad roll	100 μr	300 μr	300 μr
$\Delta\varepsilon/\varepsilon$	10%	40%	25%

Local and Non-Local Alignment

- To preserve emittance must correct **net** effect of individual dilution sources
- ‘Local’ correction - directly correct dilution sources
  - Beam-based alignment
  - Most robust solution / least sensitive to energy or strength errors
- ‘Quasi-Local’ correction - correct dilution effects over short distance, i.e. betatron wavelength
  - Dispersion-Free steering
  - Based on ‘measurements’ of dilution / sensitive to systematics
- ‘Global’ correction - tune emittance using direct ε diagnostics
  - Directly corrects desired quantity / sensitive to phase advance

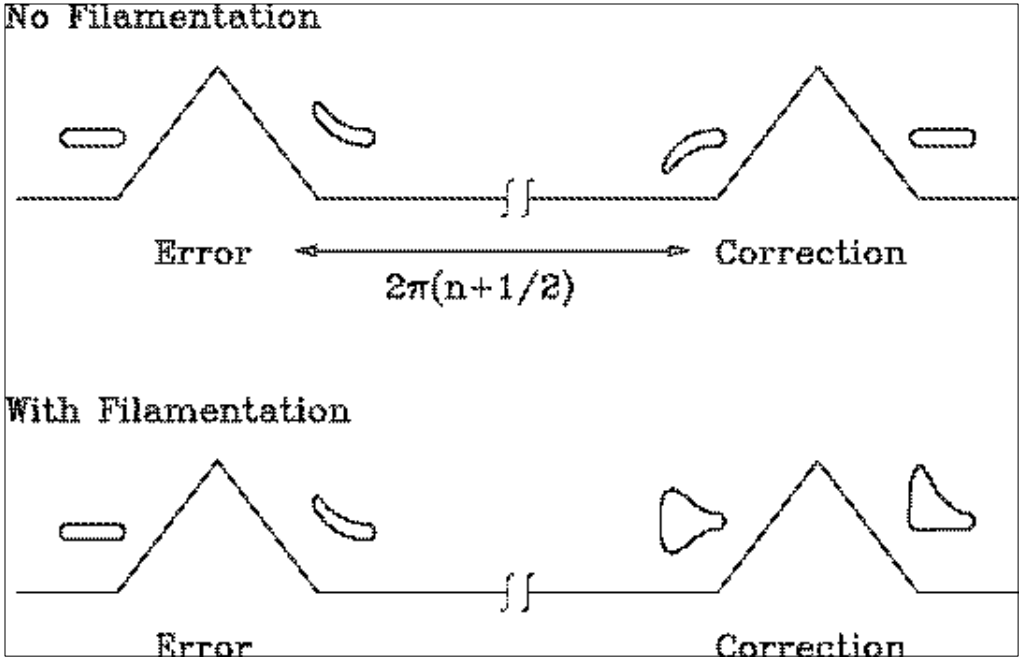
Emittance Correction (Global Correction)

- Most sources of emittance dilution come from conservative processes: transverse wakefields, dispersive errors, etc.

⇒ 6-D phase space *does not* increase
(only the projected phase space increases)

- Any conservative dilution can be removed but this is difficult after phase space mixing from betatron frequency variations

- Filamentation is significant in NLC

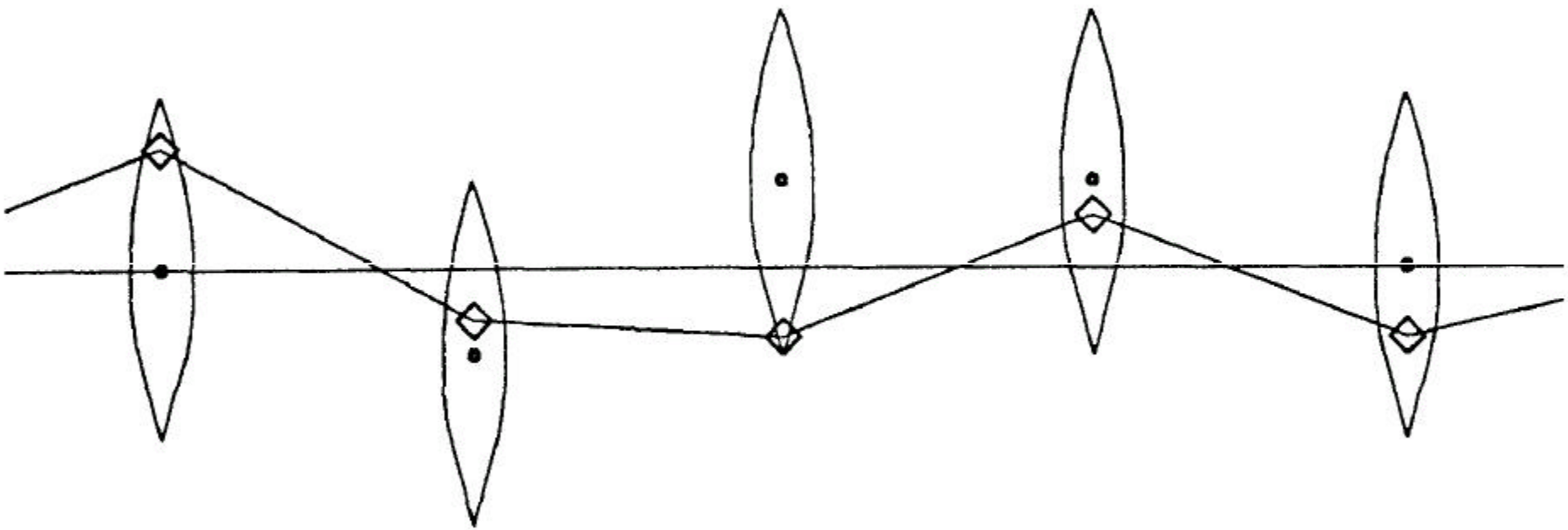


Examples of Global Correction

- Create knobs for orthogonal control of dilution:
- Dispersion:
  - Quadrupole and skew quadrupoles in regions of dispersion
  - Sextupoles for 2nd-order dispersion
  - Betatron oscillations with acc. structures aligned to beam
- Wakefields and RF deflections
  - Movable accelerator structures
  - RF deflecting cavities
- Multi-bunch wakefields / alignment
  - Fast kickers (350 MHz)
- Betatron coupling
  - Skew quadrupoles or rotational control on quadrupole magnets

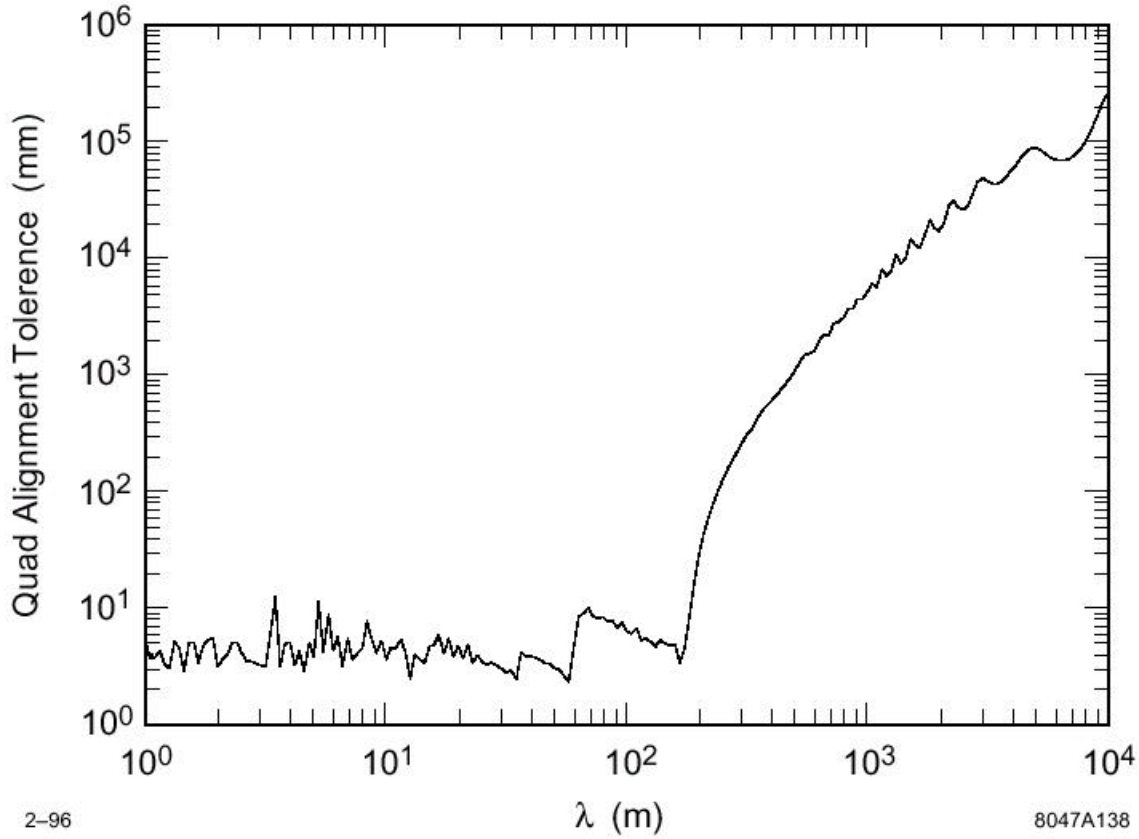
Dispersive Errors (1)

- Dispersion errors arise from misaligned quadrupoles and/or BPMs, rf and wakefield deflections, and stray fields and beam energy spread
- In a 90° FODO lattice, correction to a single offset BPMs generates a dispersion with amplitude ~4x the BPM offset



Dispersive Errors (2)

- Component of errors that is important is that at the betatron oscillation frequency – insensitive to long wave lengths



Dispersive Errors (3)

- Different approaches to problem:
  - Local correction – measure offset of individual quadrupole magnetic center to trajectory (and local BPM) by shunting or similar technique
  - Quasi-local – measure offsets of quadrupoles by varying beam energy or the strength of strings of quadrupole
    - Can be used to correct for errors other than just quadrupoles
    - Sensitive to systematics
  - Global correction – measure beam emittance and minimize by introducing beam bumps, skew quadrupoles in regions of η_x, etc.
    - Sensitive to variation of phase advance along linac and filamentation
- Limitations due to:
  - 'Alignment' resolution scales with BPM resolution
  - Variation of quadrupole centers with excitation
  - Knowledge and stability of beam optics

Wakefield Dilutions (1)

- Transverse wakefields are very strong functions of rf frequency: $dW_\perp/ds \sim 1/a^4$ $\quad W_\perp \sim 1/a^3$

- Short-range wakefield depends on **average** offset of beam in structure irises
  - For an offset structure: $\Delta e \approx 0.9 \frac{b}{8p} y^2 \left(\frac{N r_e}{g} W_\perp(2s_z) \right)^2 L_a^2$
  - Length scales and alignment procedures are important: random offsets of single cells is less important that offsets of all structures between quadrupoles
  - Ability to measure structure offsets and move structures to beam trajectory can remove this sensitivity

Wakefield Dilutions (2)

- Long-range wakefield has similar dependence although some details differ
  - Replace $W_\perp(2\sigma_z)$ with the rms 'sum' wakefield $4W_{rms}$:

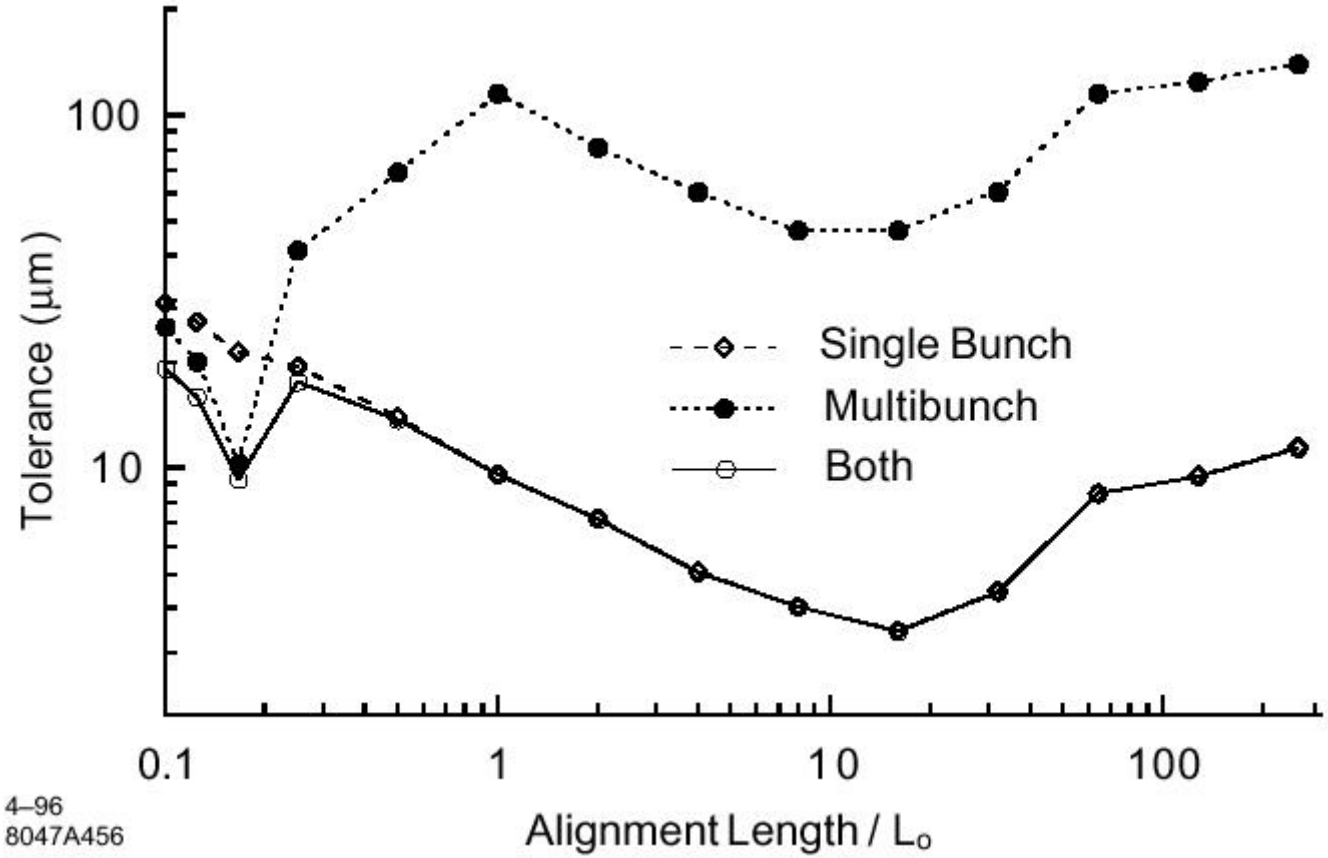
$$W_{\rm rms}^2 \equiv \frac{1}{n_b}\sum_{j=0}^{n_b-1} W_{\rm sum}^2(j\Delta s) - \left(\frac{1}{n_b}\sum_{j=}^{n_b-1} W_{\rm sum}(j\Delta s)\right)^2$$

$$W_{\rm sum}(n\Delta s) \equiv \sum_{j=0}^{n} W_\perp(j\Delta s)$$

  - However offset now depends on 'location' of dipole mode along the structure
  - Internal deformation of structures can reduce effectiveness of detuning techniques
  - Frequency errors in fabrication can help or hurt

Wakefield Dilutions (3)

- In NLC, length scales are different for short-range and long-range wakefields because of detuning techniques



Wakefield Dilutions (4)

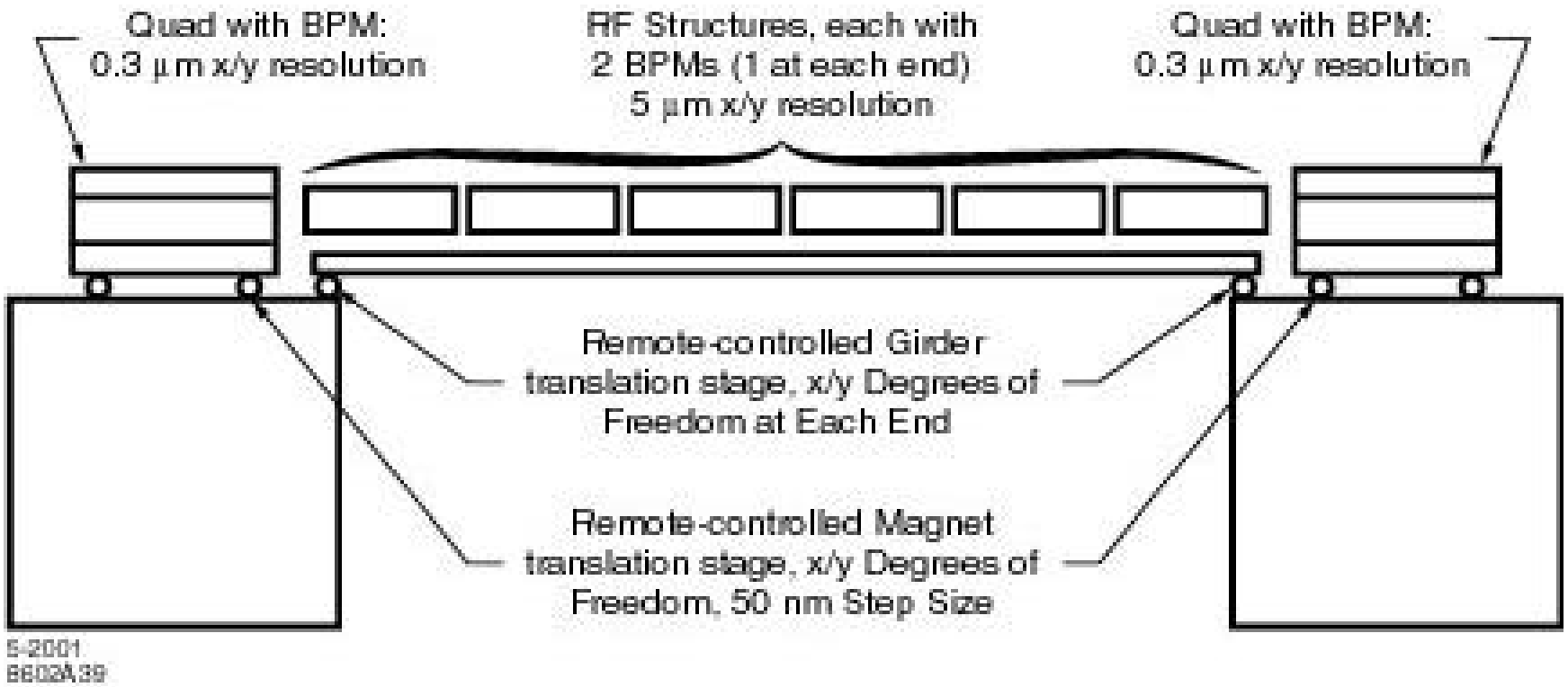
- Dipole frequency errors will cause a breakdown of the intentional detuning but can also help

- Different categories of errors with different effects:
  - **random/random** -- random cell-to-cell and random from structure-to-structure (very likely)
  - **systematic/random** -- systematic error in each cell but random from structure-to-structure (depends on manufacturing model)
  - **systematic/systematic** and **random/systematic** -- arise from modeling errors (these are most damaging -- important to verify model and perhaps design in errors in manufacturing!)

- TESLA is relying on random frequency errors to generate detuning

Alignment Schemes (1)

- NLC first aligns quadrupoles and then aligns structures to the beam trajectory
  - Have to iterate a few times to reduce kicks from structure moves

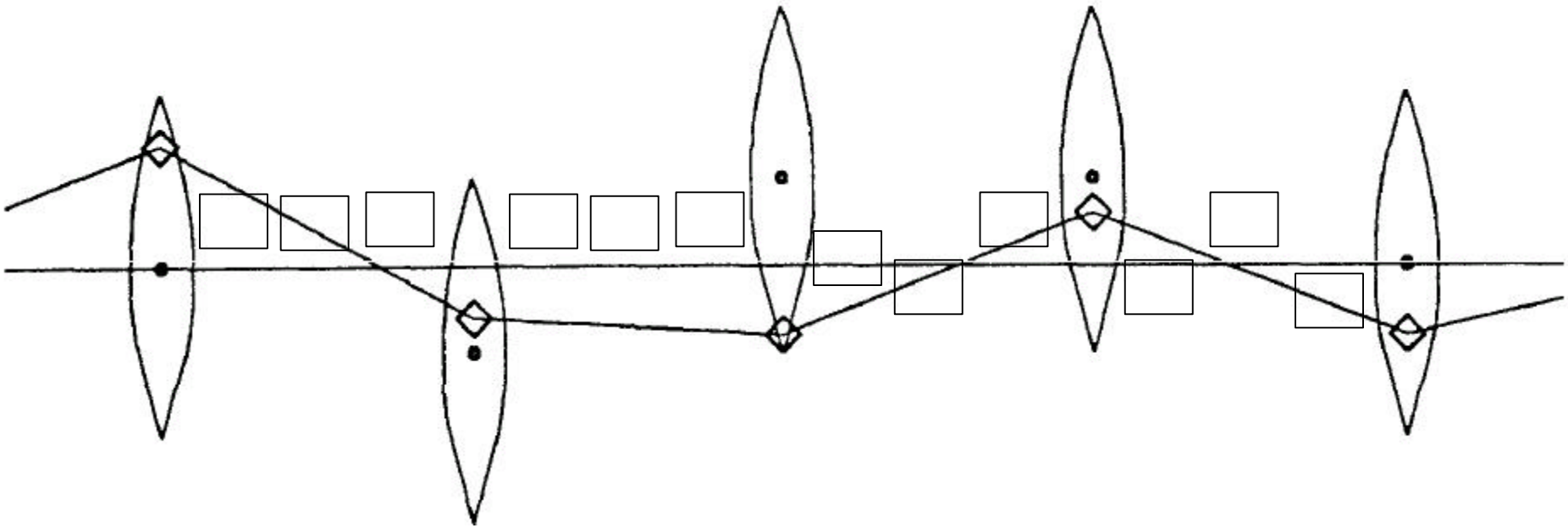


Alignment Schemes (2)

- For NLC – further details from Peter Tenenbaum
- Conventional alignment at installation and after long down periods
  - 100 μm rms variation of magnets and girders over 100 m lengths
- Establish 'gold' trajectory using local and/or quasi-local correction techniques
  - Use quadrupole shunting techniques align BPMs to quadrupoles at the level of 1 to 20 μm depending on **variation of quadrupole centers**
  - Dispersion-Free steering to establish a **'gold'** trajectory which minimizes the dispersion - need to correct η to 100 μm level
- Steer to 'gold' trajectory as magnets move (few hr timescale)
  - Use feedbacks to maintain trajectory between steering
- Beam-bumps to tune emittance based on emittance meas.
  - Ideally create 'dither' feedbacks to tune emittance bumps

Alignment Schemes (3)

- TESLA fixes structures and steers between quadrupoles
  - Same technique as used in SLC
  - Results are sensitive to details of alignment and steering approach
    - If reasonable alignment – steer to BPMs at focusing quadrupoles only
    - Alignment of structure girders more important than alignment of cavities



Diagnostic Requirements

- Resolution of alignment procedures depends on diagnostics!
- Lesson from SLC: diagnostics and control
  - Need 300 nm Beam Position Monitor resolution
    - FFTB/SLC FF striplines have 1 μm resolution
    - FFTB RF cavity BPM had 25 nm resolution
  - Need 10 μm accelerator structure alignment
    - DDS3 and RDDS1 S-BPM has 1-2 μm absolute precision
  - Need beam size resolution of 300 nm
    - SLC laser wire had between 500 and 230 nm resolution
    - FFTB ‘Shintake’ BSM had 40 nm resolution
  - Need magnet movers with 50 nm step size (for *L* during steering)
    - FFTB magnet movers have 300 nm step sizes

Summary

- Microns are small numbers!
- Alignment/correction procedures are only as good as diagnostics
- Damping ring req. are close to tolerances attained elsewhere
  - Stability is very important!
- Linac issues are well understood
- Dispersion in NLC linac must be limited to ~100μm
  - With a 10% energy change, this implies a 10μm trajectory change
  - More difficult because cannot correct entire linac at once
    - 25 sections → 2μm trajectory changes
- Global emittance correction is sensitive to optics changes
  - Maintain energy profile along linac