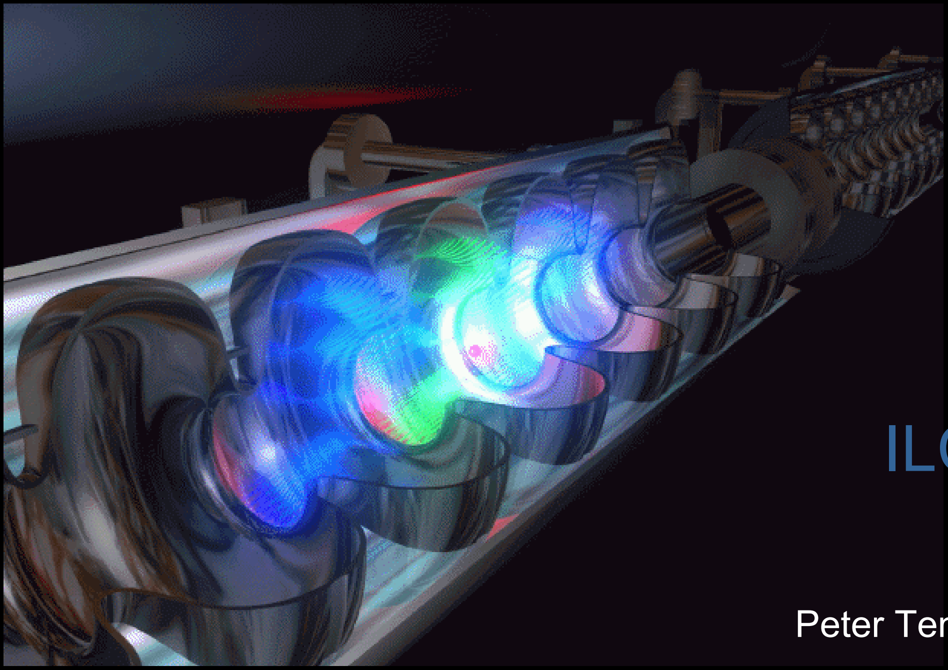
Single Bunch Emittance Preservation in the ILC Main Linac

ILC-Americas Meeting at SLAC

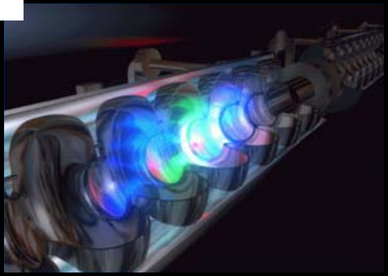


STANFORD LINEAR ACCELERATOR CENTER

ILC – International Linear Collider

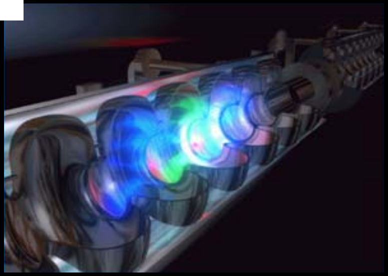
Peter Tenenbaum

14 October 2004



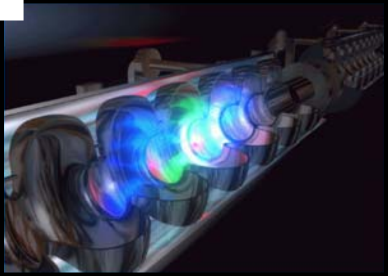
Overview

- Single bunch emittance preservation studies have been performed on:
  - TESLA TDR linac
    - 24 MV/m, 1 quad per 2 or 3 modules, 5 → 250 GeV beam energy
    - In the context of the TDR (2001) and the ILC-TRC (2002)
  - USColdLC linac
    - 28 MV/m, 1 quad per 2 modules, 5 → 250 GeV beam energy
    - In the context of the USLCSG Technology Options Study (TOS) (2003)



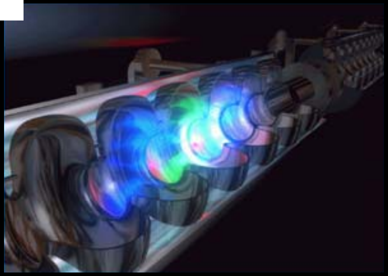
Major Issues for Emittance Preservation

- Beam curvature in yz plane
  - Time-dependent kick from pitched RF structures
- X-Y coupling
  - From rotated quadrupole magnets
  - Large (400:1) emittance ratio out of DR
- Transverse wakefields
  - From offset structures or cryomodules
- Dispersion
  - From offset quads
  - DC kick from pitched RF structures



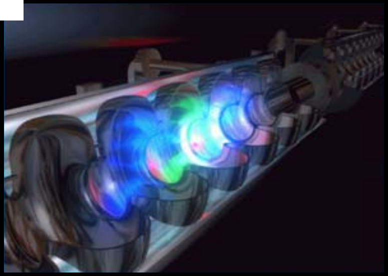
How much is a lot?

- MDR vertical normalized emittance is 20 nm
- US Cold budgeted a total of 20 nm growth from DR exit to IP
  - 4 nm (20%) in bunch compressor
  - 10 nm (50%) in main linac
  - 6 nm (30%) in BDS
- TESLA TDR budgeted a total of 10 nm growth from DR exit to IP



Specifications and Tolerances

Specification	TESLA TDR	USCold
Quad Offset	300 µm	300 µm
Quad Rotation	None	300 µrad
Structure Offset	300 µm	300 µm
Structure Pitch	None	300 µrad
Module Offset	200 µm	200 µm
Module Pitch	None	20 µrad
BPM Offset	200 µm	200 µm
BPM Resolution	10 µm	1 µm



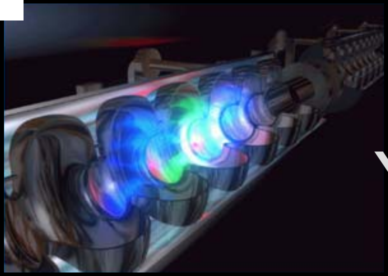
A bit of Mathematics

Emittance growth sources invariably take the form of a kick which enlarges the beam’s angular divergence.

At a point with betatron function β and Lorentz factor γ, a kick which causes a growth in quadrature of the angluar divergence of $\Delta\sigma_{y'}$ causes a growth in the normalized emittance given by:

$$\Delta\gamma\varepsilon \approx \frac{\gamma}{2}\beta\left(\Delta\sigma_{y'}\right)^2$$

Note that although the growth scales as γ, the growth in angular divergence usually scales as 1/γ, leading to an overall growth in emittance which scales as 1/γ (ie, the front of the linac is bad, the back is good). Note also that emittance growths combine linearly (not in quadrature).



YZ curvature from Pitched Structures

A pitched RF structure deflects the beam (rotation of fundamental mode into transverse plane).

Kick has sinusoidal variation over length of bunch, leading to a growth in projected emittance:

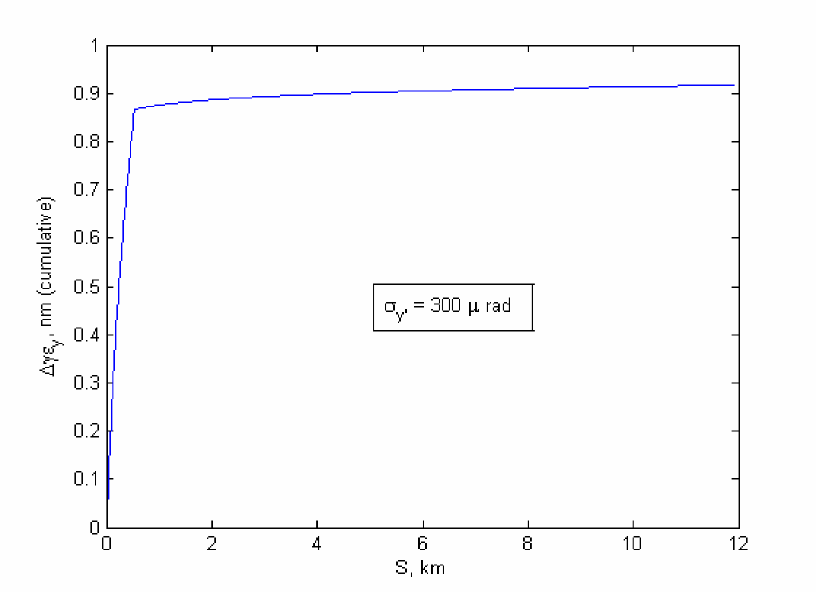
$$\Delta\gamma\varepsilon \approx \frac{\beta}{8Em_e c^2}\left(Vk_{\mathrm{RF}}\sigma_z \sin\varphi\right)^2 \theta_{\mathrm{struc}}^2$$

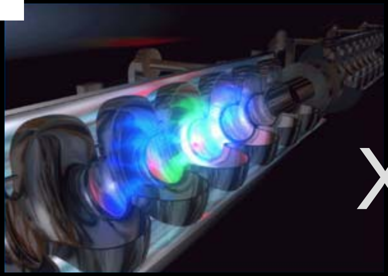
Expect 0.9 nm total growth from this source in USCold, dominated by off-crest structures in front

Correction strategy: none.

Seems small, but 9% of total budget!

Does not include DC kick effects (we'll get to those later).





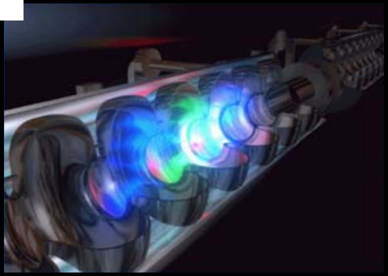
XY Coupling from Rotated Quads

One of the few sources of emittance growth which does not depend on the beam energy at the source of the problem. For one FODO cell:

$$\Delta\gamma\varepsilon_y \approx 16\gamma\varepsilon_x\theta_{\mathrm{quad}}^2$$

Both TESLA and USCold have ~180 FODO cells, leading to an emittance growth of ~2.1 nm (10.5%).

Some growth can be eliminated by tuning corrector skew quads to minimize projected emittance.



Transverse Wakefields

A clear case of good news and bad news:

Good news:

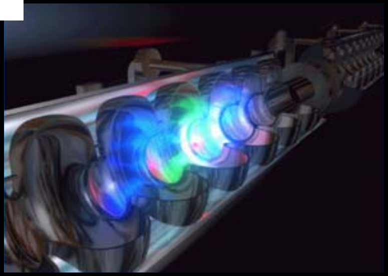
Wakefields in 1.3 GHz structures are weak wrt higher frequencies (even lower than SLAC 2.856 GHz structures)

Bad news:

Structures in cryomodules are hard to align with pinpoint accuracy

Cryomodules themselves are pretty darn hard to align

Bunch length in TESLA/USCold is large (300 um RMS)



Wakefields (2)

We can approximate the emittance growth from a misaligned RF structure:

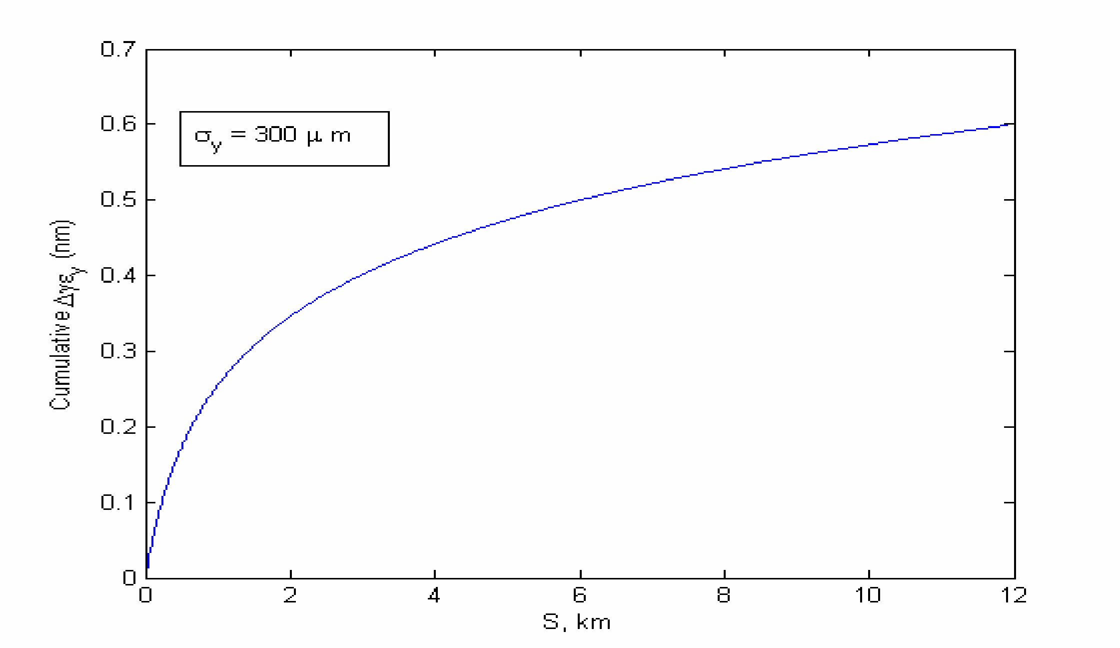
$$\Delta\gamma\varepsilon_y \approx \frac{\beta Q^2}{8Em_ec^2}\left[W_\perp(2\sigma_z)\right]^2(\Delta y)^2$$

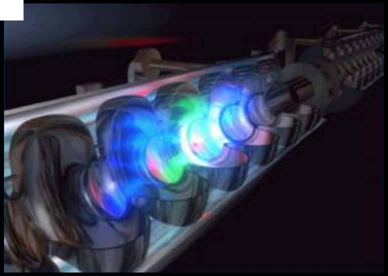
Where Q = bunch charge,

Δy = beam-to-structure offset,

W = wake kick (in V/C/m) for 2 σ_z trailing particle.

Note: simulation results indicate ~2x larger growth (wake slope @ z=0 very steep)

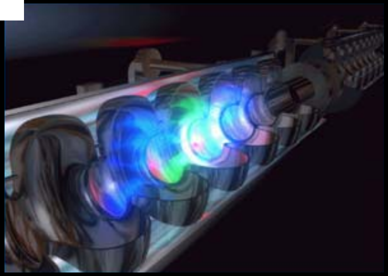




Wakefields (3)

- What about misaligned cryomodules?
  - $W_\perp$ larger than for 12 randomly misaligned structures by sqrt(12)
  - Expect alignment of modules to be better than for structures (200 um vs 300 um)

  - Expect ~5 times as much growth from misaligned modules (almost 5 nm or 25% in simulation)



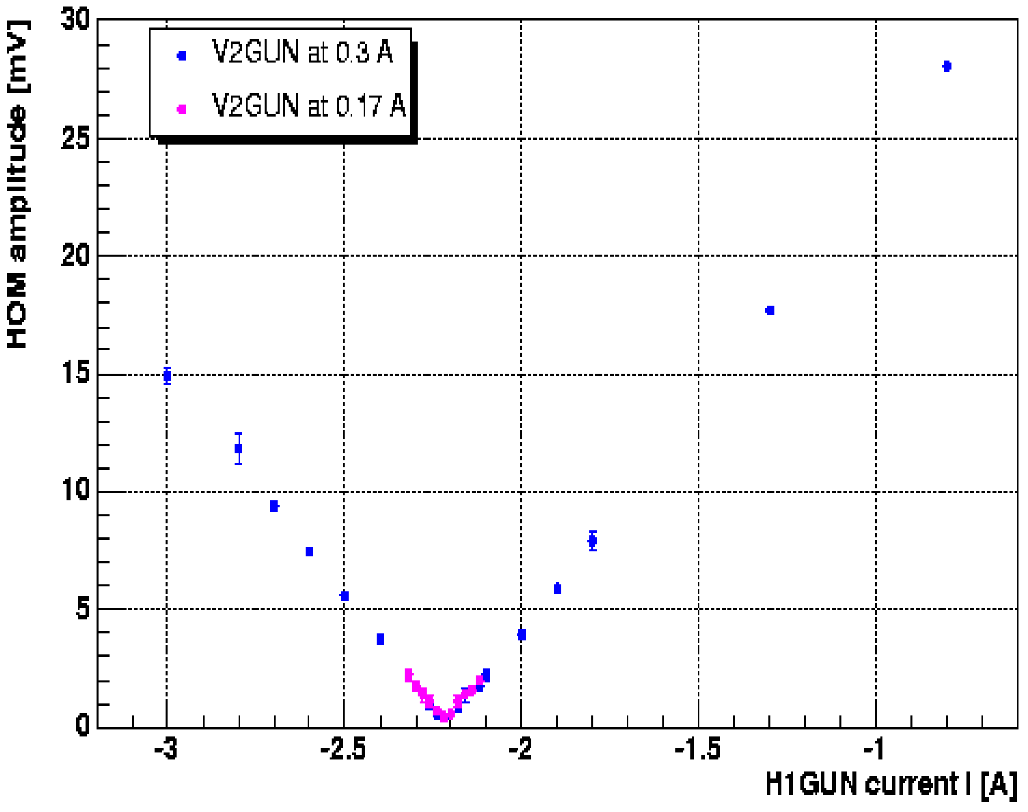
Wakefields (4) -- Mitigation

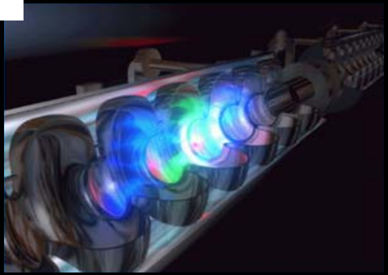
We can mitigate wakefields through use of orbit bumps – use bumps which change wake effects w/o changing dispersion; effectiveness unclear

Better approach: use structure HOMs to measure beam offsets

~50 um accuracy demonstrated at TTF (preliminary!)

Go in once / year and align all cryomodules to ~50 um from beam data?



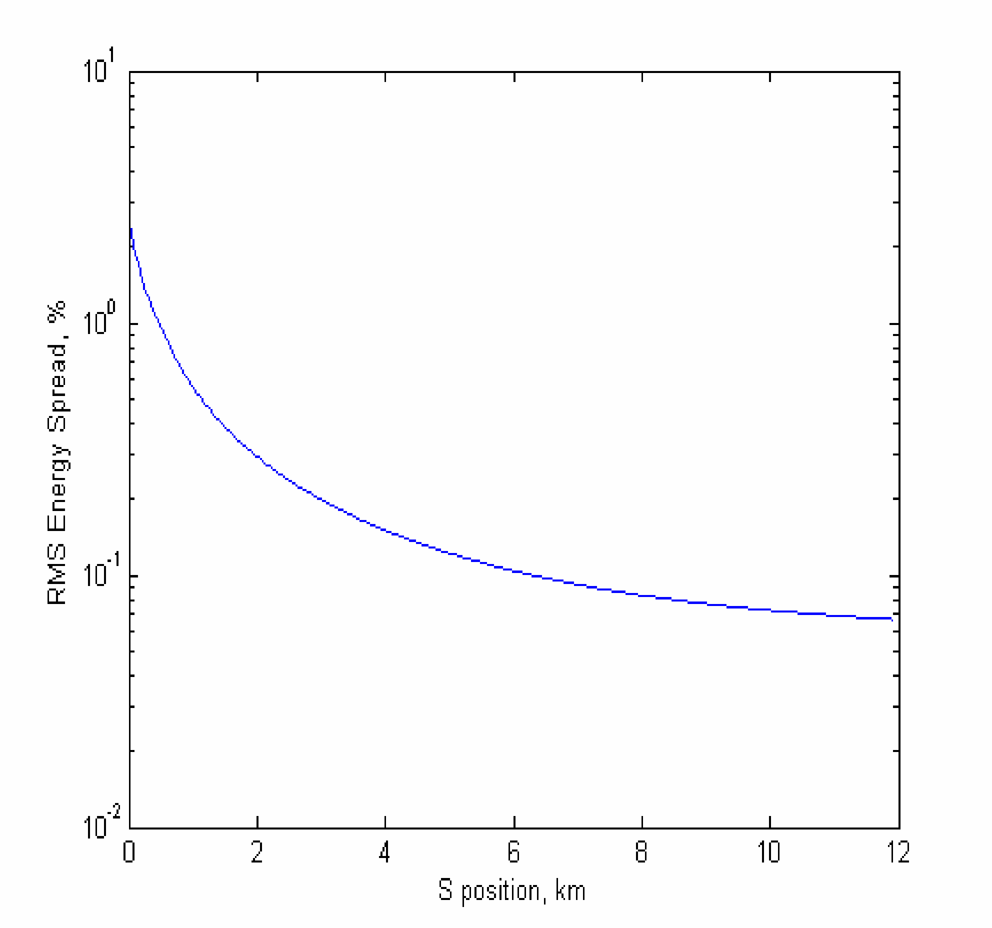


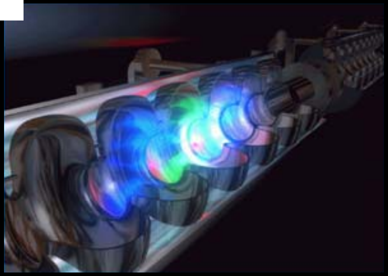
Wakefields (5) – Loose Ends

- The preceding calculations were done with the TDR wakefield
- In 2003 a more refined calculation was done
  - TDR slope was too steep @ z=0
  - TDR kicks too strong by ~30%
  - Emittance growth might be ½ of what was simulated
- Some interest in going to geometry which supports higher gradient
  - Stronger wakes in this case

Dispersion

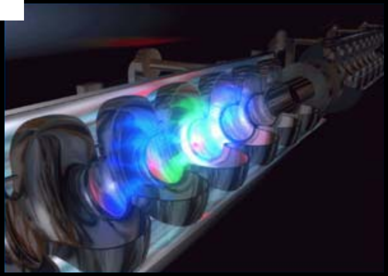
- Many possible sources
  - Beam-to-quad offsets
  - DC kick from pitched RF structures or modules
  - Stray fields
  - Earth's magnetic field
  - Etc
- Worst in upstream end of linac
  - Large (~3%) energy spread from bunch compressor
  - (almost) adiabatically damps





Dispersion (2)

- If BPMs were in a perfectly straight line, this would not matter
  - Use correctors to steer beam to zero BPMs
  - Combination of correctors and error fields would form a chicane between BPM pairs, no net emittance growth
- Dispersive emittance growth depends mainly on BPM offsets
  - Actual sources basically irrelevant!

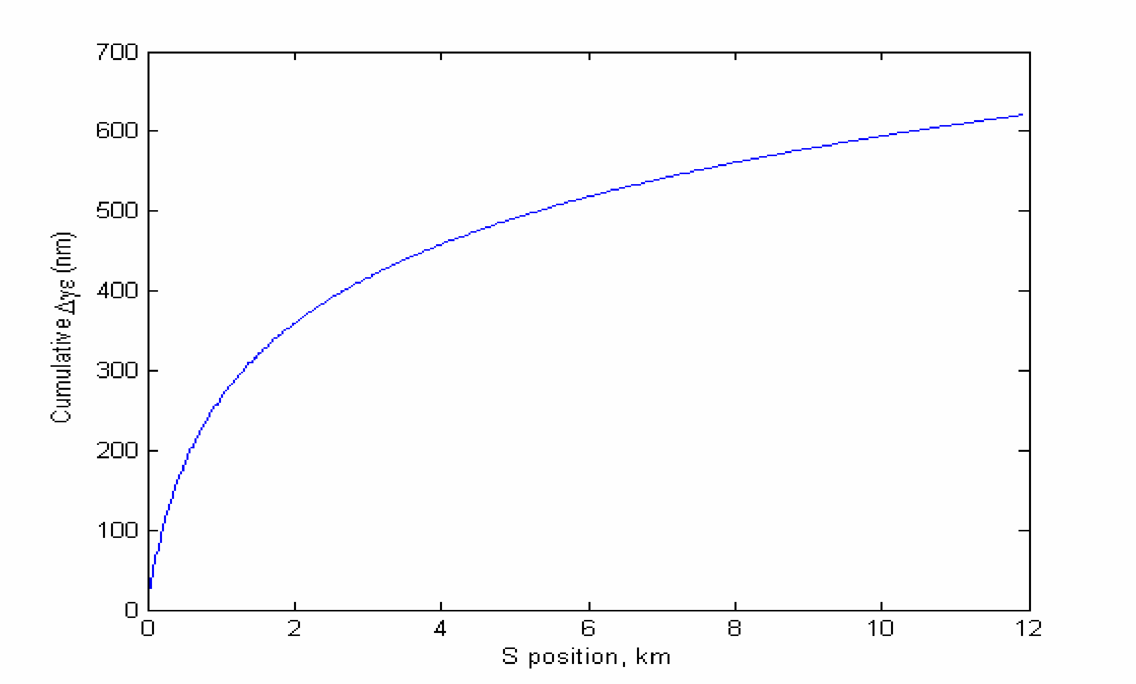


Dispersion (3)

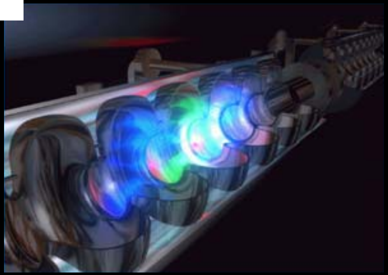
For BPMs with RMS offsets of σ_B and separation ΔS, the emittance growth should be given by: (assumes 1 BPM per quad used)

$$\Delta\gamma\varepsilon \approx \frac{\beta}{E m_e c^2}\left(\frac{\sigma_{\delta 0} E_0}{\Delta S}\right)^2 \sigma_B^2$$

Where E_0 is the injection energy (5 GeV) and $\sigma_{\delta 0}$ is the initial RMS energy spread (~2.8%)



Note that growth >> initial emittance of 20 nm – more sophisticated beam-based steering techniques needed (need to get to ~25 um RMS BPM offsets)

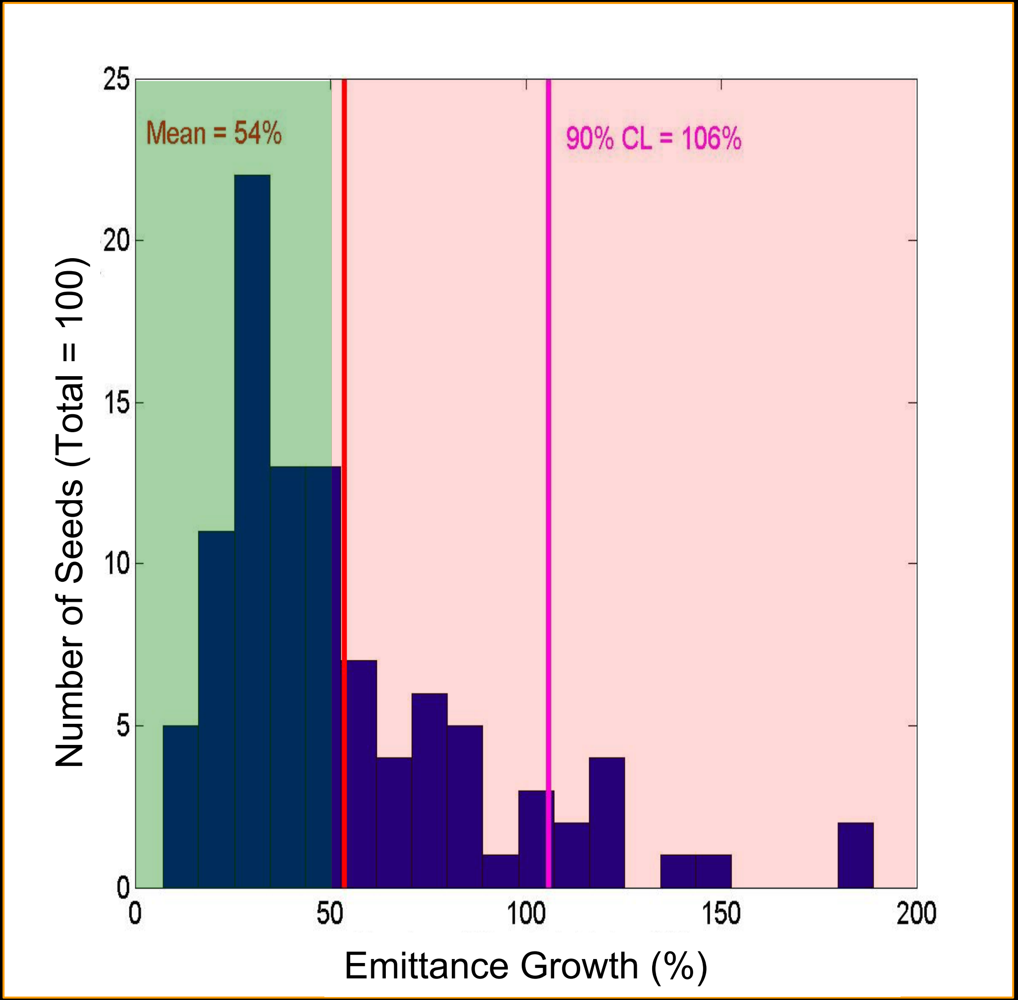


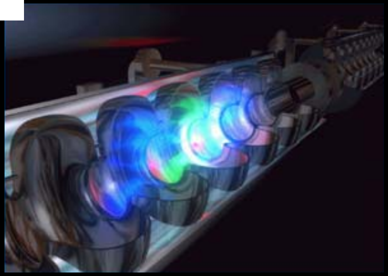
Dispersion (4)

- Techniques for improving on installed BPM resolution
  - Quad variation ("beam-based alignment")
    - Probably too slow in SC quads
    - Systematic problems (change in quad center as fn of current)
    - Doesn't address pitched structures or stray fields
  - Dispersion Free Steering
  - Ballistic Alignment

Dispersion Free Steering

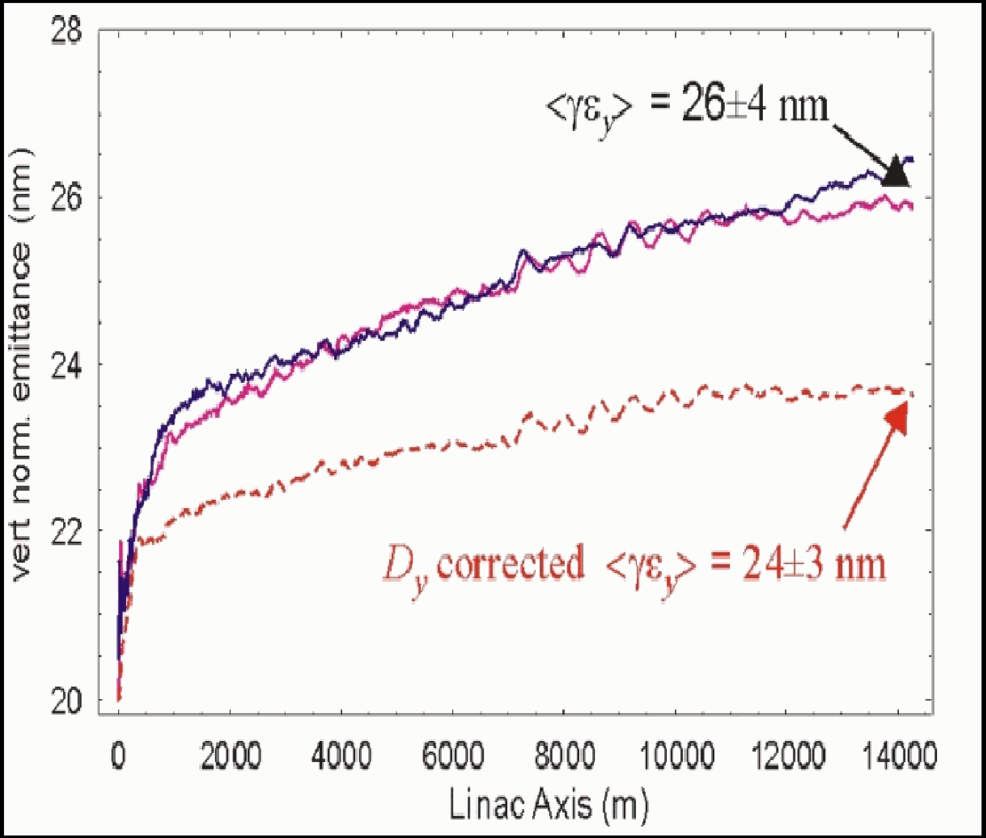
- Nullify orbit change as a function of beam energy
- In simulation: change RF complement
  - Need alternate technique for front of linac
  - Pitched RF cavities change orbit – systematic error which confuses fit
  - Does see all dispersive effects
- Results somewhat disappointing



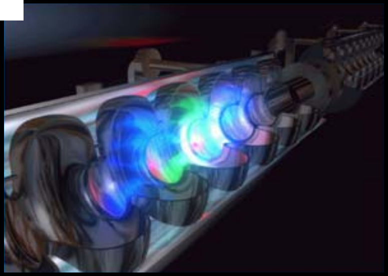


Ballistic Alignment

- Turn off RF + quads
  - Measure BPM orbit
    - Beam is straight line fiducial
- Turn back on, resteer to “all-off” line
  - Gets quad + RF structure deflections
  - Doesn’t get stray fields
  - May be slow (turning off quads)
- Results not bad in simulation

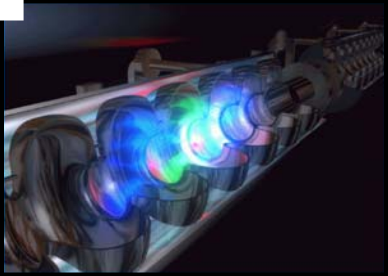


Note: This is a TESLA result, not USCold!



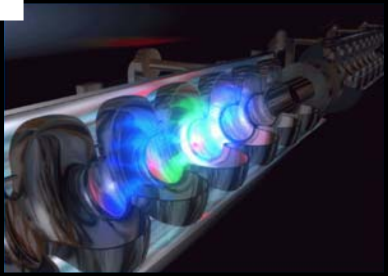
Dispersion Bumps

- Local orbit distortion which introduces dispersion in controlled manner
- Reasonably effective in USCold simulation studies
  - Applied dispersion + wake bumps after DFS
  - Mean emit growth over 100 seeds = 23%
  - 90% CL emit growth = 40%
  - Probably not quite good enough when RF kicks and coupling included, but more complete sims needed



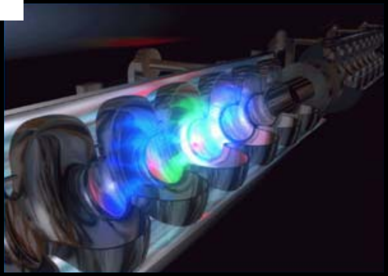
Notes on Dispersion

- Basically not solved to anybody's satisfaction
- Weakening quad lattice will help
  - Probably won't do the whole job
  - May make DFS cavity-steering systematic worse
  - Definitely makes wakefields worse
- Redesign BC to reduce incoming energy spread?
  - Will help but probably won't be enough
  - May make BC emittance growth bigger
- Steering algorithm affected by tunnel layout
  - All simulations assumed a laser-straight tunnel
  - Tunnel on gravitational equipotential will require different solutions!



Conclusions

- Single-bunch emittance preservation in ILC not a solved problem
- Satisfactory solution may require modifications in hardware design of linac, or changes in bunch compressor
- Definitely need to consider fully integrated model of all linac misalignments, errors, etc.



What SLAC Can Contribute

- Emittance preservation in single-pass electron beamlines a longtime SLAC obsession
  - SLC, FFTB, NLC, SPPS, LCLS
  - Lots of experience and lots of talented people
  - Good design and simulation tools
  - Ideas about how to test stuff in a real accelerator
- Strong involvement with collaborators from other labs
  - “Laptops at Dawn” emittance crew from TRC era
- We are very excited about continuing to participate in the aforementioned emittance preservation study group