Ground Motion
vs
Linear Colliders
Andrey Sery
Fermilab
... In not so many years from today we will be entering the twenty-first century and during this time some of us may also be entering (or be pushed into it, kicking and screaming) what I like to call the micron world of accelerator alignment.

... 

G. E. Fischer, 1992
Why ground motion is relevant?

- The future TeV linear collider should have very small emittance of beams to achieve required luminosity.

- Misalignments of focusing and accelerating elements produce luminosity degradation via offset of the beam trajectory or dilution of the beam.

- Thus, precise alignment of focusing and accelerating elements is necessary to prevent emittance dilution.

- Ground motion does not allow to align the elements once and forever. It continuously spoils alignment.

⇒ Understanding of ground motion is therefore an essential problem.
Ground motion studies for LC


- 1989-1991, Protvino, UNK tunnel
  Correlation properties of high frequency motion
  Diffusive ground motion - “ATL law”

- 1992-1993, CERN, TT2A and LEP tunnel
  Correlation properties of high frequency motion

- 1994, Finland
  Measurements → 2-D power spectrum $P(\omega, k)$

- 1995-1996, Saclay, France
  2-D power spectrum $P(\omega, k)$ for LC
Absolute ground motion measurements

Power spectra of absolute motion measured in different places, in UNK tunnel [B.B, et al., 91] at CERN (LEP tunnel, shutdown) [V.J. et al., 93], at DESY (HERA tunnel, operational condition) [V.S. et al., 95], in Finland (Hiidenvesi cave) [V.J. et al., 95].
What is power spectrum?

$x(t)$ – time dependent random signal, e.g. absolute motion of the ground surface,

then the power spectral density is:

$$p(f) = \lim_{T \to \infty} \frac{1}{T} \left| \int_{T/2}^{T/2} x(t)e^{-i\omega t} dt \right|^2$$

in practice $T$ is limited and $p(f)$ can only be estimated by averaging spectra obtained in several measurements

The power spectrum allows to identify contributions from different frequencies:

$$\sigma^2(f_1 < f < f_2) = \int_{f_1}^{f_2} p(f) df$$
Why absolute spectrum $P(\omega) \propto 1/\omega^4$?

What is power spectrum of the motion of a heavy body influenced by random kicks?

\[ \omega \rightarrow \Delta t \propto 1/\omega \]

number of kicks $N$ for $\Delta t$ is $N \propto \sqrt{\Delta t}$

change of momentum $\Delta p \propto \sqrt{\Delta t}$

then $\Delta x \propto \Delta p \Delta t$

then the power spectrum $P(\omega) \propto \Delta x^2 \Delta t \propto 1/\omega^4$
Fig. 4 Comparison of the seismic signal and the noise of electronics. The "noise of electronics" was measured by the probe with its coils and pendulum fixed.
Sources of motion.

Slow motion. At $f < 1$ Hz also atmospheric activity, water motion in the oceans, temperature variations etc. Peak at $0.1 - 0.2$ Hz, $\propto \mu m$ — ocean influence. Significant contribution of remote sources.

Fast motion. Cultural (technical) noises at $f > 1$ Hz usually dominate over natural. Strong dependence on local conditions (location of sources, depth of tunnel etc.). Noises of operating accelerator. May have big amplitude and bad correlation.
Fig. 4. Low frequency horizontal vibrations measured in Hiidenvesi cave in different days of August 1994.
Fig. 32. Directions of 2 Hz. signals pointing to the coast of Norway.

GROUND MOTION-- AN INTRODUCTION FOR ACCELERATION BUILDERS

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RMS Amplitude in different frequency bands. Measured in Finland, 1994.
Fig. 9. Displacement versus time during a rare faraway event detected in Petonen cave.
What should we know about ground motion?

Knowing the spectrum of absolute ground motion $p(f)$ is not sufficient.

For linear collider one deals with $x(t, s)$

$\rightarrow$ 2-D power spectrum $P(\omega, k)$

$$
P(\omega, k) = \lim_{T \to \infty} \lim_{L \to \infty} \frac{1}{T} \frac{1}{L} \left| \int_{-T/2}^{T/2} \int_{-L/2}^{L/2} x(t, s) e^{-i\omega t} e^{-iks} dt ds \right|^2
$$

The 2-D spectrum is related to 1-D as $p(\omega) = \int_{-\infty}^{\infty} P(\omega, k) dk / (2\pi)$
How to use 2-D $P(\omega, k)$?

For linear collider one needs to know behaviour of relative displacements of two elements.

![Graph showing relative displacements](image)

e.g., assuming at $t = 0$ the collider is perfectly aligned, we then interested in relative misalignment $X(T, s) = x(t = T, s) - x(t = 0, s)$

The variance of the relative misalignment after a time $T$ and over a distance $L$ is

$$
\sigma^2(T, L) = \langle [X(T, s + L) - X(T, s)]^2 \rangle =
$$

$$
= \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} P(\omega, k) 2[1 - \cos(\omega T)] 2[1 - \cos(kL)] \, d\omega \, dk / (2\pi)^2
$$
How to find 2-D $P(\omega, k)$?

2-D power spectrum $P(\omega, k)$ is hard to measure directly.

One can use spectrum of absolute motion $p(\omega)$ and correlation measurements, or spectrum of relative motion $\rho(\omega, L)$ (which is connected with $P(\omega, k)$).

Correlation measurements: measurements of absolute motion performed simultaneously by two probes that give $x_1(t, s_1)$ and $x_2(t, s_2)$. Correlation is then

$$N_{12}(f) = \frac{p_{12}}{\sqrt{p_1 p_2}}$$

where $p_{12}$ is mutual power spectrum

$$p_{12}(f) = \lim_{T \to \infty} \frac{1}{T} \int_{T/2}^{T/2} x_1(t) e^{-i\omega t} dt \int_{T/2}^{T/2} x_2^*(t') e^{-i\omega t'} dt'$$

Perfect correlation $\rightarrow N_{12} = 1$
Correlation of fast motion.
(from \(p(f)\) to \(P(\omega, k)\))

Measurements \(\Rightarrow\) in quiet conditions in \(f > 0.1\) Hz the motion is wave-like [V.J. et.al., 93, C.A. et.al., 95], i.e. \(w\) and \(k\) are connected via phase velocity \(v\).

\(v\) is close to the sound velocity. \(\approx 3000\) m/s at LEP, \(\approx 2300\) m/s at SLC tunnel (at \(f \approx 0.1\) Hz).

Decreasing of \(v\) at \(f > 1\) Hz. Effect of cultural noises.
SLAC: \(v \approx 450 + 1900 \exp\left(-\frac{f}{2}\right)\) m/s (for \(f > 0.1\) Hz) [C.A. et.al., 95].
HERA: \(v \approx 400\) m/s [V.S. et.al., 95].

SLAC measurements [C.A. et.al., 95] \(\Rightarrow\) non-wave motion contribution (if there is any not resolved by probes) is negligible at \(f > 0.1\) Hz (at that place at least).
Fig. 1a Plan view of the LEP tunnel showing the location of points 4 and 5.
Fig. 7 Correlation (real part) between two horizontal probes oriented transverse to the LEP tunnel. Probes are 0 m, 100 m, 200 m and 500 m apart.
The correlations (real part) between two horizontal probe channel transverses in the LEP tunnel probes at 1000 m, 1400 m, 2000 m, and 3000 m span.
Correlation measured in the LEP tunnel in 1993.
Figure C-13. Vertical power spectra (weighted by $f^4$) measured by two STS-2 seismometers placed side-by-side (solid and dotted lines). Also shown are the difference (dashed line) and corrected difference (line with crosses) power spectra.
Figure C-16. Correlation spectrum (solid line) measured with the seismometers separated by 1000 m. The dashed line is described in the text.

Figure C-17. Dependence of (1 - correlation) on the separation ($\Delta z$) of the seismometers for $0.8 < f < 0.9$ Hz. The data in this frequency range has been averaged (solid line). Also shown is the fit to the data (dashed line) which is described in the text.
Figure C-18. Velocity derived from fits to the correlation data (solid line). The dashed line is an empirical fit to the data: \( v = 450 + 1900 \exp(-f/2.0) \).
ATL motion

“ATL law” [B.B, et al., 91]: relative rms displacement after a time $T$ of two points separated by $L$ is

$$\langle \Delta X^2 \rangle = A \cdot T \cdot L$$

$A \sim 10^{-7} - 10^{-4} \mu m^2 s^{-1} m^{-1}$ is a place dependent parameter.

Non wavelike, diffusion character

$$x \propto \sqrt{TL} \rightarrow \text{the number of random step-like breaks appeared between two points is proportional to their separation and elapsed time.}$$

2-D spectrum for ATL is $P(\omega, k) = \frac{A}{\omega^2 k^2}$
Ranges of parameters where indications for the ATL motion were seen (data collected in [V.S., 95]). Observations not only from ground motion, also from beam motion. E.g. beam orbit motion in HERA [R.B., J.R., 94].

Ranges of wave motion [V.J. et.al., 93],[C.A. et.al., 95].
Systematic motion

The very slow motion can be systematic (not described by power spectrum), e.g. LEP Point 1 and PEP [R.P., 95].

Some quads move unidirectionally during many years with rate about 0.1 – 1 mm/year.

Close (tens of meters) points can move in opposite direction.

Big amplitude (> diffusive motion).

Geological peculiarities of the place? Relaxation if the tunnel after it is constructed?
Girder problems

Elements of the linac will be placed not on the floor, but on some girder.

Girder may amplify some frequencies due to its own resonances.

Not identical girders may amplify or change the floor motion by different way. It may spoil correlation of the floor motion.

Preferable to push the girder resonances to high frequencies (where the correlation is poor anyway and floor amplitudes are smaller).

Firm connection of the girder with the floor.

Active support systems [C.M., 96] can in certain extend isolate the quads from cultural floor motion. They must be insensitive to slow motion (< 1 Hz), otherwise long λ may create more dangerous short λ due to inequality of active supports.
Ground motion model

Approximation for $P(\omega,k)$ [A.S., O.N., 95]:

Slow motion – “ATL law” (corrected at high $w$).

Fast motion – elastic waves.

An example of the modeling power spectra $P(\omega, k)$. Waves $+$ corrected ATL.
**Waves in** $P(\omega, k)$

Fast motion is represented by waves in the modeling $P(\omega, k)$.

Elastic, transverse, propagating at the surface with uniform distribution over azimuthal angle.

Wave with frequency $\omega$ and phase velocity $v$ give

$$k_{\text{seen}} = \frac{\omega}{v} \sin(\theta) \text{ (seen by linac)}. \text{ Uniform distribution on } \theta \text{ gives distribution on } k:$$

$$U_i(\omega, k) = \frac{2}{\sqrt{(\omega/v)^2 - k^2}} \text{ if } |k| < \omega/v \text{ and zero otherwise.}$$

Wave contribution to the 2-D spectrum $P(\omega, k) = \sum_i D_i(\omega) U_i(\omega, k)$

here $D(\omega)$ – contribution of waves to absolute spectrum $p(\omega)$,

e.g. $D_i(\omega) = a_i / (1 + [d_i(\omega - \omega_i)/\omega_i]^4)$. 
“ATL” in $P(\omega, k)$

Slow “ATL” motion needs to be corrected to be included into $P(\omega, k)$.

Pure ATL overestimates fast motion:
the spectrum of relative motion $\rho_{\text{ATL}}(\omega, L) = AL/\omega^2$ at some frequencies can be > than spectrum of absolute motion $2p(\omega) = B/\omega^4$, that is impossible.

Let’s correct the ATL by taking the upper approximation:

$\rho_{\text{corr. ATL}}(\omega, L) = \min(AL/\omega^2, B/\omega^4)$

Corresponded contribution to 2-D spectrum is $P(\omega, k) = \frac{A}{\omega^2k^2}(1 - \cos(\frac{kB}{A\omega^2}))$
(ax') = $\frac{ATL}{1 + T_0/T}$ for the corrected ATL, where $T_0 \approx \sqrt{AL/B}$.

It still rather overestimate the effect. Needs measured data on transition region.
Modeling the ground motion

Absolute power spectrum measured in a quiet conditions (CERN [V.J. et.al., 93]) and the modeling spectrum of relative morion $\rho(\omega, L)$ for different $L$.

Parameters of the modeling $P(\omega, k)$ spectrum.

ATL part: $A = 10^{-5} \mu m^2 s^{-1} m^{-1}$, $B = 10^{-6} \mu m^2 s^{-3}$.

Wave part (single peak): $f_1 = 0.14$ Hz, $a_1 = 10 \mu m^2 / Hz$, $d_1 = 5$, $v_1 = 1000$ m/s.

The shown relative spectrum

$$\rho(\omega, L) = \int_{-\infty}^{\infty} P(\omega, k) 2 [1 - \cos(kL)] \frac{dk}{2\pi}$$

$\rho(\omega, \infty) = 2p(\omega)$.
Modeling the ground motion

Absolute power spectrum measured in a noisy place (HERA [V.S.et.al., 95]) and the modeling spectrum. Modeling relative spectra for different $L$.

Parameters of the modeling $P(\omega, k)$: ATL part: $A = 10^{-5} \mu m^2 s^{-1} m^{-1}$, $B = 10^{-3} \mu m^2 s^{-3}$.

Wave part (three peaks):
$f_1 = 0.14, f_2 = 2.5, f_3 = 50$ Hz;
$a_1 = 10$, $a_2 = 10^{-3}$, $a_3 = 10^{-7} \mu m^2/Hz$;
$d_1 = 5, d_2 = 1.5, d_3 = 1.5$;
$v_1 = 1000, v_2 = 400, v_3 = 400$ m/s.
Modeling the ground motion

Absolute power spectrum measured in a quiet conditions (CERN [V.J.et.al., 93]) and the modeling spectrum of relative motion \( \rho(\omega,L) \) for different \( L \).

Parameters of the modeling \( P(\omega,k) \): ATL part: \( A = 10^{-5} \) \( \mu m^2 s^{-1} m^{-1} \), \( B = 10^{-6} \) \( \mu m^2 s^{-3} \).

Wave part is given by SLAC fit of \( v(f) \) [C.A. et.al., 95].
Correlation calculated using a model of $P(\omega, k)$ for different distances between probes.
How to find effect on the beam?

For a given ground motion model and beam optics, how to find, say, trajectory offset and beam dilution?

Relative beam offset at the exit and dispersion:

\[ x^*(t) = \sum_{i=1}^{N} c_i x_i(t) - x_{\text{fin}} \quad \text{and} \quad \eta(t) = \sum_{i=1}^{N} d_i x_i(t) \]

Linear model: \( c_i = dx^*/dx_i \) and \( d_i = d\eta/dx_i \).
How to find effect on the beam?

For example, the dispersive error

$$\langle \eta^2(t) \rangle = \int_{-\infty}^{\infty} P(t, k) G_\eta(k) \frac{dk}{2\pi}$$

via $P(t, k)$, which is given by $P(\omega, k)$:

$$P(t, k) = \int_{-\infty}^{\infty} P(\omega, k) 2 \left[ 1 - \cos(\omega t) \right] \frac{d\omega}{2\pi}$$

and spectra response function $G_\eta(k)$:

$$G_\eta(k) = \left( \sum_{i=1}^{N} d_i (\cos(ks_i) - 1) \right)^2 + \left( \sum_{i=1}^{N} d_i \sin(ks_i) \right)^2$$

Thin lens. Linear order. $c_i = -K_i r_{12}^i$ and $d_i = K_i (r_{12}^i - t_{126}^i)$.

Here $K_i$ is $r_{21}$ of the quad matrix, $r_{12}^i$ and $t_{126}^i$ are the matrix elements from the $i$-th quadrapole to the exit.

Sum rules. E.g. $\sum d_i s_i = -T_{126}$. At small $k$ one has $G_{\text{off}}(k) \approx k^2 R_{12}^2$ and $G_\eta(k) \approx k^2 T_{126}^2$ unless $R_{12}$ or $T_{126} = 0$. 
Spectral response functions for offset and dispersion of a modeling FODO linac.

Linac parameters: Number of quads $N = 600$, spacing $L = 25\,\text{m}$, $\mu = 60$ degree, $\gamma_{\text{ini}} = 6000$, $\gamma_{\text{fin}} = 5 \cdot 10^2$. Beta functions $\beta_{\text{ini}} = 28.86\,\text{m}$ at the even defocusing quads and at the exit.
Beam offset evolution

Relative beam offset at the exit of a modeling linac. Free evo-
Mon. Quiet and noisy ground motion models. Analytical re-
sults \( P(\omega, k) \) and \( G(k) \) — lines, and simulations \( x(t, s, \) by harmonics model + tracking).

If \( \varepsilon_{\eta} = 2.5 \cdot 10^{-7} \) m, then \( c_T \approx 3.5 \cdot 10^{-6} \) m — critical time \( \approx 1 \) minute.
Smaller \( \varepsilon_{\eta} \) cultural noises \( \rightarrow \) much smaller time.
Simulation of ground motion.

ATL motion is too easy to simulate.

How to simulate ground motion given by an arbitrary $P(\omega, k)$?

Ground motion displacement $x(t, s)$ is modelized by summation of harmonics.

$[T_{\text{min}}, T_{\text{max}}], [L_{\text{min}}, L_{\text{max}}]$ are given. Analyze the modeling $P(\omega, k)$ to find the band of relevant $\omega$ and $k$. Split by cells ($\times 50 \times 50$) equidistantly in logarithmic sense. Find rms amplitude $a_{ij}$. Seed two sets of random phases $\phi_{ij}$ and $\psi_{ij}$ and choose $\omega_i$ and $k_j$ randomly within cell.

The modeling displacement $x(t, s)$ for this seed $x(t, s) =$

$$= \sum_i \sum_j a_{ij} \left[ \sin(\omega_i t) \sin(k_j s + \phi_{ij}) + (\cos(\omega_i t) - 1) \sin(k_j s + \psi_{ij}) \right]$$
Simulation of ground motion.

Simulation of $x(t, s)$ for a given $P(\omega, k)$.

Modeling power spectra $P(t, k)$ for a noisy ground motion model. **Analytical** results (smooth lines) and spectra obtained in **simulations** using the harmonics model.
Ground motion and Final Focus

The TESLA Beam Delivery System.
Spectral response function of the offset and dispersion for the TESLA FFS.
FIG. 9. Coefficients (a) $a_i$ and (b) $b_i$, the ratios of the vertical beam displacement and dispersion at the IP to the displacement of each magnet, versus the magnet name for TESLA FFS. White bars correspond to positive values, black bars to negative ones.
Ground motion and Final Focus

Vertical relative rms offset of the beams and the vertical beam dispersion at the IP of the TESLA FFS for different models of ground motion.
Ground motion and Final Focus

Vertical spot size growth at the IP for the FFS of different linear colliders for a (very noisy!) model of ground motion. Effects of dispersion, waist shift and coupling are included.
TABLE II. Number of pulses corresponding to 2% luminosity loss due to relative vertical offset ($N_{\delta y}$) or vertical spot size growth ($N_{\sigma y^*}$) at the IP of different projects for models 1-3 of ground motion in quiet conditions.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Model</th>
<th>TESLA</th>
<th>SBLC</th>
<th>JLC</th>
<th>NLC</th>
<th>VLEPP</th>
<th>CLIC</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_{\delta y}$</td>
<td>1</td>
<td>1 (≥1000)</td>
<td>15</td>
<td>4</td>
<td>5</td>
<td>15</td>
<td>220</td>
</tr>
<tr>
<td>$N_{\delta y}$</td>
<td>2</td>
<td>4 (≥1000)</td>
<td>75</td>
<td>22</td>
<td>27</td>
<td>77</td>
<td>1200</td>
</tr>
<tr>
<td>$N_{\delta y}$</td>
<td>3</td>
<td>15 (≥1000)</td>
<td>370</td>
<td>60</td>
<td>75</td>
<td>260</td>
<td>4200</td>
</tr>
<tr>
<td>$N_{\sigma y^*}$</td>
<td>1</td>
<td>210</td>
<td>650</td>
<td>370</td>
<td>450</td>
<td>540</td>
<td>17000</td>
</tr>
<tr>
<td>$N_{\sigma y^*}$</td>
<td>2</td>
<td>350</td>
<td>1700</td>
<td>1800</td>
<td>2100</td>
<td>2700</td>
<td>66000</td>
</tr>
<tr>
<td>$N_{\sigma y^*}$</td>
<td>3</td>
<td>21000</td>
<td>65000</td>
<td>18000</td>
<td>22000</td>
<td>30000</td>
<td>$1.7 \times 10^6$</td>
</tr>
</tbody>
</table>

Effect of feedback

offset in the presence of the feedback is

$$\langle (x^+ - x^-)^2 \rangle \rightarrow \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} P(\omega, k) 2F(\omega) G(k) \frac{d\omega}{2\pi} \frac{dk}{2\pi}$$

TABLE III. Estimations of equilibrium values of the rms vertical beam offset ($\delta y/\sigma_{y^*}$) caused by ground motion in quiet (models 1-3) and in noisy (model 4) conditions, in the presence of an ideal feedback with $f_c = f_{rep}/30$.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Model</th>
<th>TESLA</th>
<th>SBLC</th>
<th>JLC</th>
<th>NLC</th>
<th>VLEPP</th>
<th>CLIC</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\delta y/\sigma_{y^*}$</td>
<td>1</td>
<td>1.9 (≤1)</td>
<td>0.18</td>
<td>0.5</td>
<td>0.47</td>
<td>0.15</td>
<td>0.013</td>
</tr>
<tr>
<td>$\delta y/\sigma_{y^*}$</td>
<td>2</td>
<td>0.5 (≤1)</td>
<td>0.03</td>
<td>0.1</td>
<td>0.09</td>
<td>0.03</td>
<td>0.003</td>
</tr>
<tr>
<td>$\delta y/\sigma_{y^*}$</td>
<td>3</td>
<td>0.14 (≤1)</td>
<td>0.01</td>
<td>0.04</td>
<td>0.04</td>
<td>0.015</td>
<td>0.002</td>
</tr>
<tr>
<td>$\delta y/\sigma_{y^*}$</td>
<td>4</td>
<td>2.9 (≤1)</td>
<td>2.0</td>
<td>10</td>
<td>9</td>
<td>3.5</td>
<td>1.2</td>
</tr>
</tbody>
</table>
Elements of the normalized rms beam matrix $\sigma_{ij}$ for the FFS (top plot) and for the complete TESLA BDS versus $\Delta T$. Linear model prediction (lines) and tracking results (symbols)

Disagreement of the linear model with tracking is due to nonlinear effect of the vertical misalignment of quads located in maxima of beta function in the IP-phase part of the collimation. Misalignments of these quads produce a vertical beam offset in sextupoles of the Chromatic Correction Section (CCSY). If the matrix between paired sextupoles in CCSY is not perfectly $\mathbf{M} = -1$, then the beam distortion at IP will appear.
The TESLA Beam Delivery System.
TESLA BDS Tuning and alignment

History of spotsize recovering procedures of TESLA BDS. Start from misaligned system, then perform orbit correction, then the knob scan one by one, several iterations.
Feedback controlled evolution

Dispersion error in the case of free evolution:

\[ \langle \eta^2(t) \rangle = \int_{-\infty}^{\infty} P(t, k) G(k) \frac{dk}{2\pi} \]

(independent spatial harmonics, i.e. no correction yet)

Correction procedure: \( P(t, k) \) also changed by correction procedure.

Corrections like “one to one” in a regular linac can be considered analytically.

Corrections may introduce correlation of phases between harmonics with different \( k \).

The dispersion error when correction is applied [A.S., A.M., 96]:

\[ \langle \eta^2(t) \rangle = \int \left( \hat{P}(t, k) G(k) + P(t, k) G(k) + \ldots \right) \frac{dk}{2\pi} \]

where \( P(t, k) \) is spectrum of self correlation.
Position of quadrupoles (squares) before correction, beam trajectories (lines) and dispersion before (red) and after (green) one-to-one correction.
Beam dispersion. No corrections (upper curves) and one-to-one correction (lower curves) for a modeling linac and two ground motion models.

For the beam with $\sigma_{y}^{\text{exit}} \approx 3.5 \times 10^{-6}$ m and $\Delta \rho / \rho = 10^{-3}$ the critical time is a few hours without and about one year with correction.

Reduction of $\langle \eta^2 \rangle$ (emittance growth) for "one-to-one" $\propto N^2$
Adaptive alignment

Mean squared dispersion versus number of iterations for the “adaptive alignment” [v.B., 91] method, theory and simulations. a) ground motion by “ATL law” with \( A \Delta t L = 10^{-12} \text{ m}^2 \) solely; b) ground motion and initial misalignment with \( \sigma_{\text{ini}} = 100 \mu\text{m} \); c) ground motion, initial misalignment and BPM errors \( \sigma_{\text{res}} = \sigma_{\text{off}} = 10 \mu\text{m} \).
Conclusion

A future TeV linear collider, having extremely small emittance of beams, will suffer from the ground motion, which will spoil alignment of focusing and accelerating elements and result in offset and emittance growth.

The ground motion studies, performed by different laboratories, resulted in significant improvement of understanding of this phenomenon. Different types of motion have been investigated, many factors that the motion depends on are learned. The mathematical formalism allowing prediction of the beam behavior is developed.

Though many ground motion features are still to be carefully investigated, one may reasonably believe that the ground motion problem of the future linear collider can be overcame provided that stored knowledge will be used at each step of design and construction.
References


