Stability and Alignment in Linear Collider

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The Luminosity Challenge

- Must jump by a Factor of 10000 in Luminosity !!! (from what is achieved in the only so far linear collider SLC)
- Many improvements, to ensure this : generation of smaller emittances, their better preservation, …
- Including better focusing, dealing with beam-beam, and better stability
  - Ensure maximal possible focusing of the beams at IP — Lecture 6
  - Optimize IP parameters w.r.to beam-beam effects — Lecture 7
  - Ensure that ground motion and vibrations do not produce intolerable misalignments — Lecture 8

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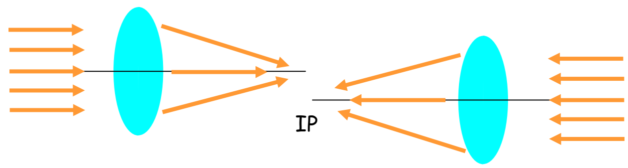
Stability – tolerance to FD motion



- Displacement of FD by dY cause displacement of the beam at IP by the same amount
- Therefore, stability of FD need to be maintained with a fraction of nanometer accuracy
- How would we detect such small offsets of FD or beams?
  - Using Beam- beam deflection !

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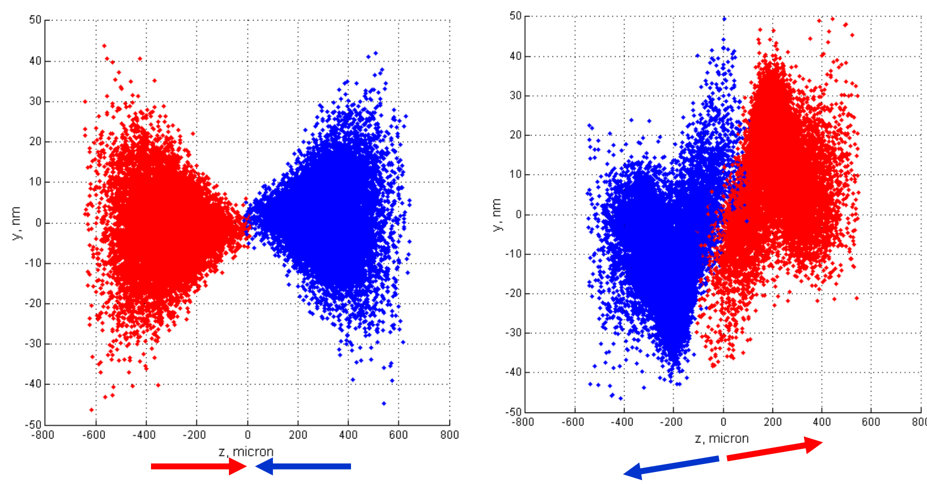
Beam-beam deflection



Sub nm offsets at IP cause large well detectable offsets (micron scale) of the beam a few meters downstream

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What can cause misalignments of FD and other quads?

- Initial installation errors
  - But if static, can eventually correct them out
- Non-static effects, such as ground motion (natural or human produced)
  - In this lecture, we will try to learn how to evaluate effect of ground motion and misalignment on linear collider

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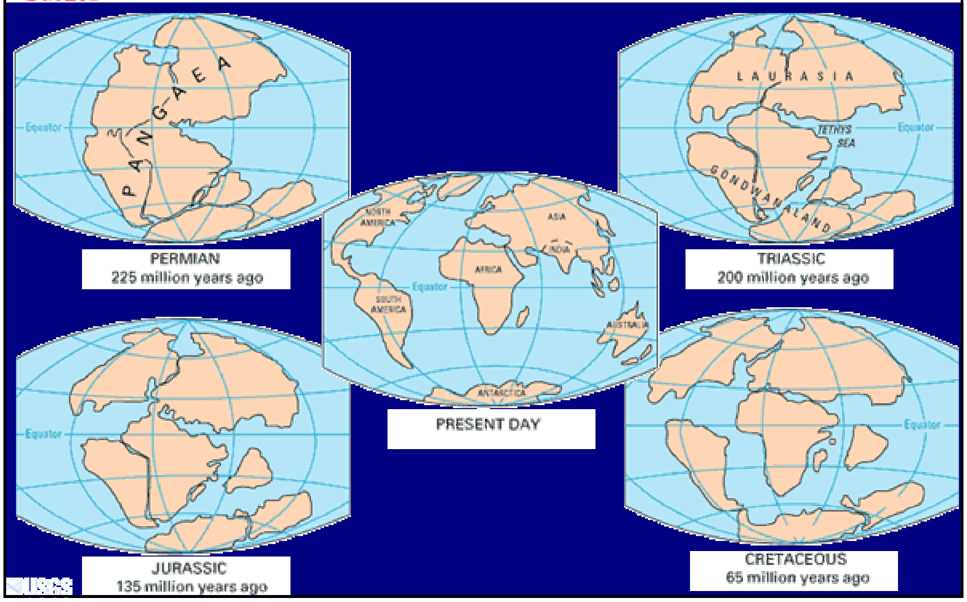
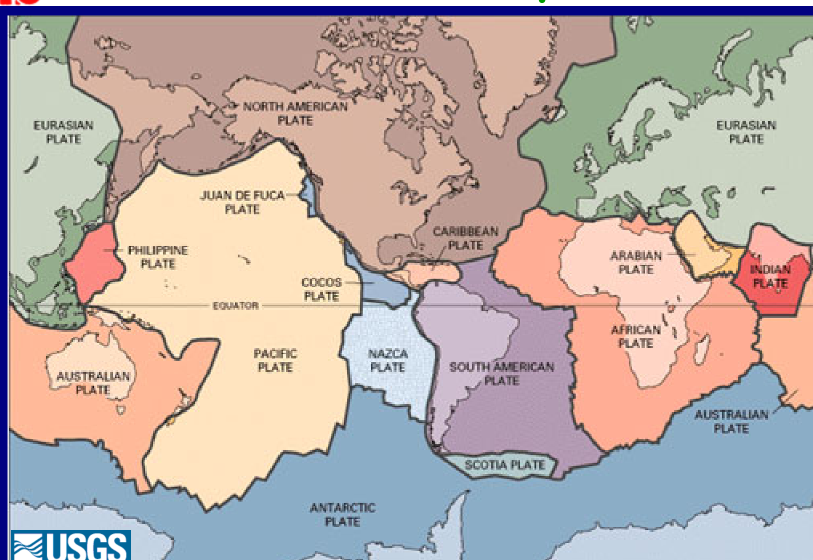
What ground motion we are talking about ?

- In some languages "Earth" and "ground" called by the same word…
- No, we are not talking about Earth orbital motion…

And not about continental drift…

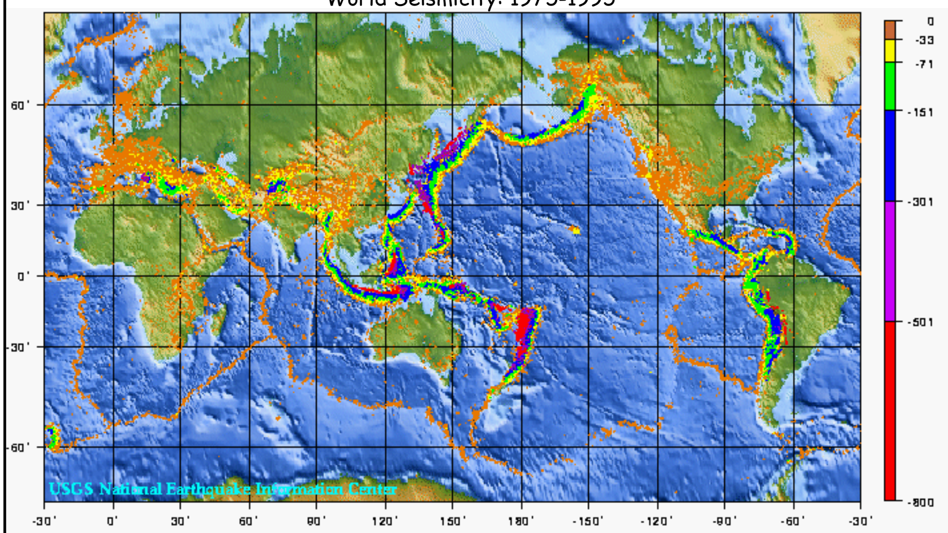


of tectonic plates…



And not so much about earthquakes…

World Seismicity: 1975-1995



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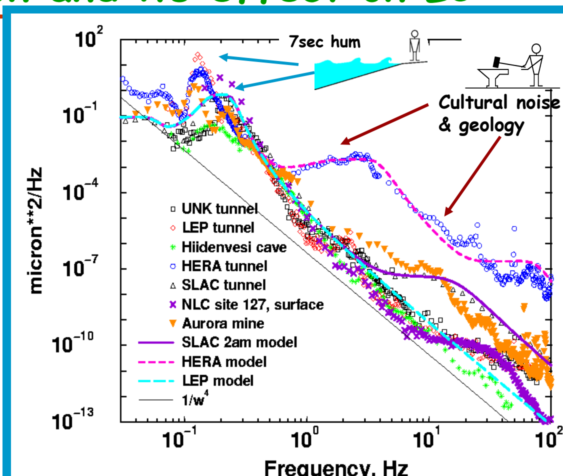
Ever-present ground motion and vibration and its effect on LC

- Fundamental – decrease as $1/\omega^4$
- Quiet & noisy sites/conditions
- Cultural noise & geology very important
- Motion is small at high frequencies…
- How small?



Power spectral density of absolute position
data from different labs 1989 - 2001

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Natural ground motion is small
at high frequencies

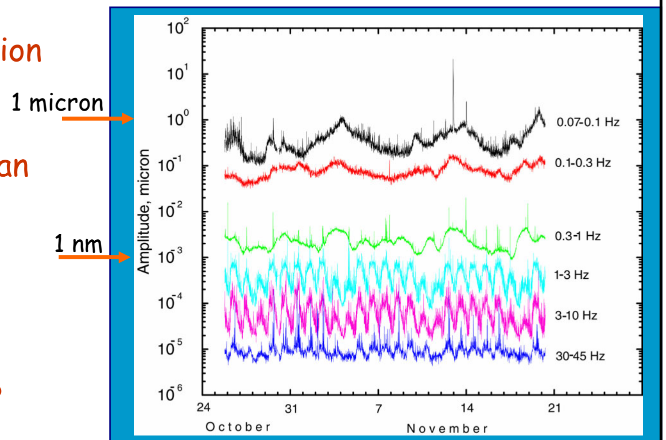
At F>1 Hz the motion can be < 1nm

(I.e. much less than beam size in LC)

Is it OK?

What about low frequency motion?

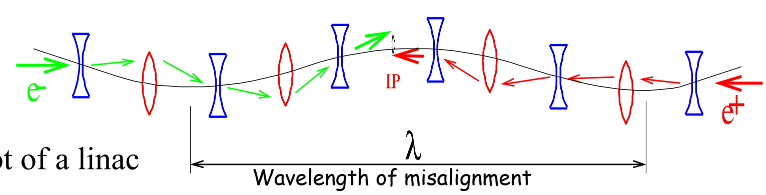
It is much larger…



Rms displacement in different frequency bands. Hiidenvesy cave, Finland

Ground motion in time and space

- To find out whether large slow ground motion relevant or not…
- One need to compare
  - Frequency of motion with repetition rate of collider
  - Spatial wavelength of motion with focusing wavelength of collider



Snapshot of a linac

Two effects of ground motion in Linear Colliders

frequency

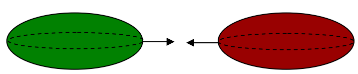
'slow motion'

'fast motion'

$F_c \sim F_{rep}/20$

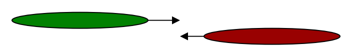
Beam offset due to **slow motion** can be compensated by feedback

May result only in beam emittance growth



Beam offset cannot be corrected by a pulse-to-pulse feedback operating at the F_{rep}

Causes beam offsets at the IP



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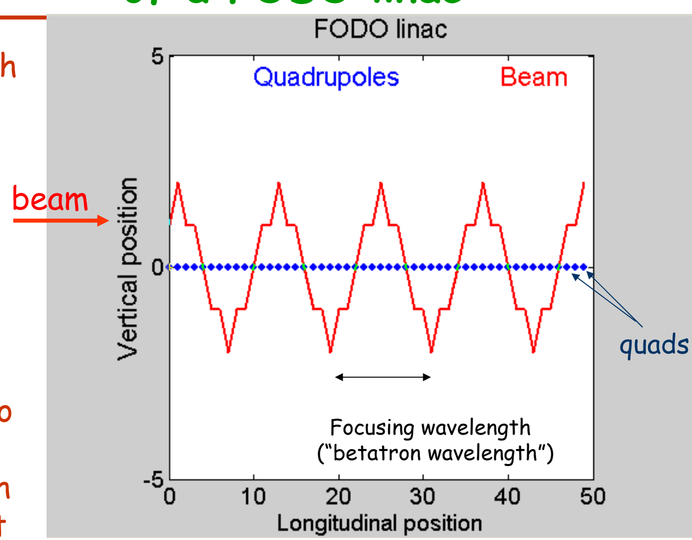
Focusing wavelength of a FODO linac

FODO linac with beam entering with an offset



Betatron wavelength is to be compared with wavelength of misalignment

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Movie of a Misaligned FODO linac
next page

Note the following:

Beam follows the linac if misalignment is more smooth than betatron wavelength

Resonance if wavelength of misalignment ~ focusing wavelength

Spectral response function – how much beam motion due to misalignment with certain wavelength

Below, we will try to understand this behavior step by step…

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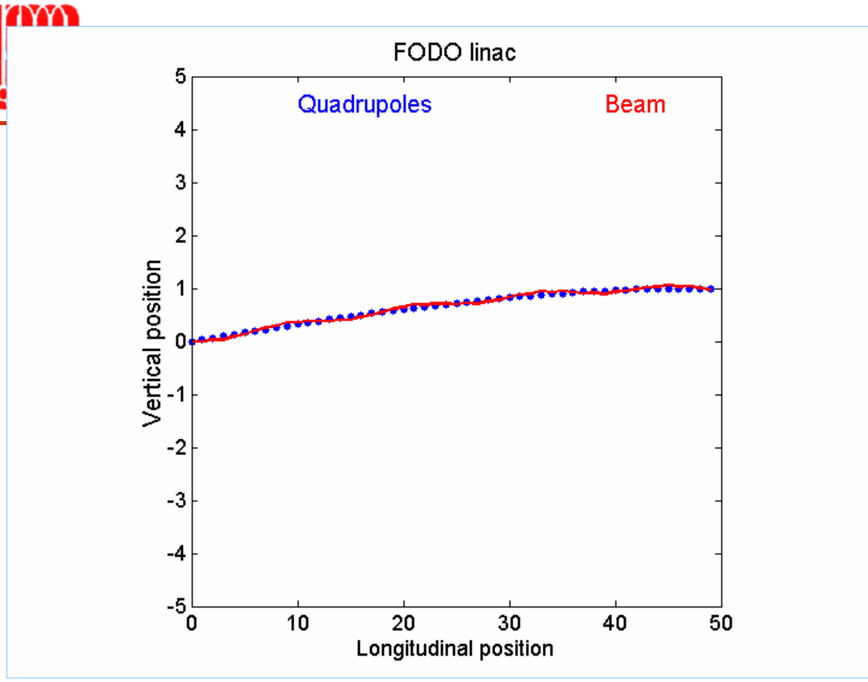

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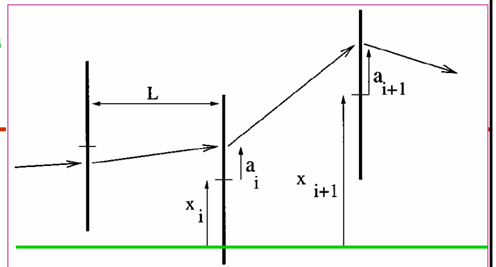
How to predict orbit motion or chromatic dilution



Misaligned quads. Here $\mathbf{x_i}$ is quad displacement relative to reference line, and $\mathbf{a_i}$ is BPM readings.

Let's consider a beamline consisting of misaligned quadrupoles with position $\mathbf{x_i(t)=x(t,s_i)}$ of the **i**-th element measured with respect to a reference line. Here $\mathbf{s_i}$ is longitudinal position of the quads. If $\mathbf{x_{abs}(t,s)}$ is a coordinate measured in an inertial frame and the reference line passes through the entrance, than $\mathbf{x(t,s)= x_{abs}(t,s)- x_{abs}(t,0)}$. We also assume that at **t=0** the quads were aligned **x(0,s)=0**.

We are interested to find the beam offset at the exit $\mathbf{x_*}$ or the dispersion η_x, produced by misaligned quadrupoles. Let's assume that $\mathbf{b_i}$ and $\mathbf{d_i}$ are the first derivatives of the beam offset and beam dispersion at the exit versus displacement of the element **i**. Then the final offset, measured with respect to the reference line, and dispersion are given by summation over all elements:

$$x_*(t) = R_{11}\, x_{inj}(t) + R_{12}\, x'_{inj}(t) + \sum_{i=1}^{N} b_i\, x_i(t)$$

$$\eta_x(t) = T_{116}\, x_{inj}(t) + T_{126}\, x'_{inj}(t) + \sum_{i=1}^{N} d_i\, x_i(t)$$

Is it clear why there is no $\mathbf{a_i}$ in this formula?

Where **N** is the total number of quads, **R** and **T** are 1st and 2nd order matrices of the total beamline, and we also took into account nonzero position and angle of the injected beam at the entrance.

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Predicting orbit motion and chromatic dilution … random case

Let's assume now that the beam is injected along the reference line, then:

$$x_*(t) = \sum_{i=1}^{N} b_i\, x_i(t) \qquad \eta_x(t) = \sum_{i=1}^{N} d_i\, x_i(t)$$

Assume that quads misalignments, averaged over many cases, is zero. Let's find the nonzero variance

$$\langle x_*^2(t)\rangle = \sum_{i=1}^{N}\sum_{j=1}^{N} b_i\, b_j\, \langle x_i(t)\cdot x_j(t)\rangle \qquad \langle \eta_x^2(t)\rangle = \sum_{i=1}^{N}\sum_{j=1}^{N} d_i\, d_j\, \langle x_i(t)\cdot x_j(t)\rangle$$

Let's first consider a very simple case.

In case of **random** uncorrelated misalignment we have $\langle x_j(t)\cdot x_j(t)\rangle = \sigma_x^2\,\delta_{ij}$ (σ_x is rms misalignment, not the beam size)

So that, for example $\langle x_*^2(t)\rangle = \sigma_x^2 \sum_{i=1}^{N} b_i^2$ And similar for dispersion

Now we would like to know what are these **b** and **d** coefficients.

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Predicting x_* and η … what are these b_i and d_i coefficients

Let's consider a thin lens approximation. In this case, transfer matrix of **i**-th quadrupole is (**K**>0 for focusing and **K**<0 for defocusing)

$$\begin{pmatrix} 1 & 0 \\ -K_i & 1 \end{pmatrix}$$

A quad displaced by $\mathbf{x_i}$ produces an angular kick $\boldsymbol{\theta = K_i x_i}$ and the resulting offset at the exit will be $x_* = r_{12}^i \; K_i \; x_i$

Where r_{12}^i is the element of transfer matrix from i-th element to the exit

The coefficient $\mathbf{b_i}$ is therefore $b_i = r_{12}^i \; K_i$

The coefficient $\mathbf{d_i}$ is the derivative of $\mathbf{d_i}$ with respect to energy deviation δ :

$$d_i = \frac{d}{d\delta}\left(r_{12}^i \; K_i\right) = \frac{d}{d\delta}\left(r_{12}^i \; \frac{K_i(0)}{1+\delta}\right)$$

Which is equal to $d_i = -K_i \left(r_{12}^i - t_{126}^i\right)$

Where t_{126}^i is the 2nd order transfer matrix from i-th element to the exit

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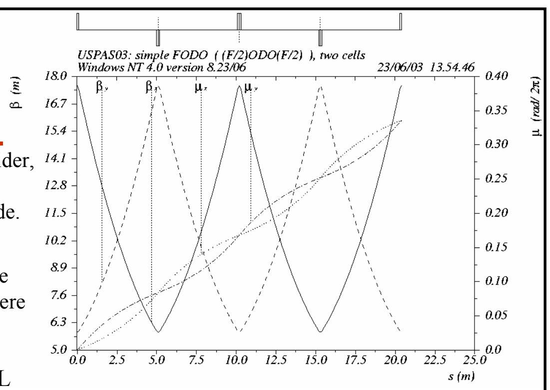
Transfer matrices for FODO linac



Let's consider a FODO linac… No, let's consider, for better symmetry, a (F/2 O D O F/2) linac. Example is shown in the figure on the right side.

The quadrupole strength is $\mathbf{K_i = K\,(-1)^{i+1}}$ (ignoring that first quad is half the length). The position of the quadrupoles is $\mathbf{S_i = (i-1)L}$ where L is quad spacing.

The betatron phase advance μ per FODO cell is given by $2\sin\left(\frac{\mu}{2}\right) = |K|\,L$

The matrix element r_{12}^i from the i-th quad to the exit (N-th quad) is $r_{12}^i = \sqrt{\beta_i\,\beta_N}\;\sin(\Psi_i)$

Where Ψ_i is the phase advance from i-th quad and exit. Obviously, $\Psi_i = \frac{\mu}{2}(N-i)$

And here β_i and β_N are beta-functions in the quads. For such regular FODO, the min and max values of beta-functions (achieved in quads) are

$$\beta_{max,min} = \frac{L}{\tan\left(\frac{\mu}{2}\right)\left[1 \mp \sin\left(\frac{\mu}{2}\right)\right]}$$

Since the energy dependence comes mostly from the phase advance (it has large factor of N) and the beta-function variation can be neglected, the second order coefficients are given by

$$t_{126}^i \approx -r_{12}^i \;(N-i)\;\tan\left(\frac{\mu}{2}\right)\frac{1}{\tan(\Psi_i)}$$

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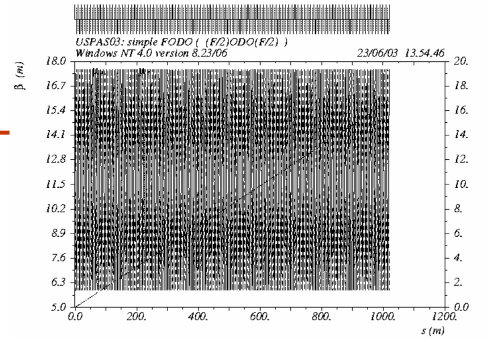
Exercise 5
create a FODO linac

In this case you will create a fodo linac in MAD for further studies of stability in MatLIAR. The necessary files are in C:\LC_WORK\ex5



The fodo beamline is defined as shown below:

```
LH  : DRIF, L = 4.900

! strength of quads (for 60 degrees per cell)
KQ  = 1.0

! length of quad
LQ  = 0.2/2

QF:QUAD,L=LQ,K1= KQ
QD:QUAD,L=LQ,K1=-KQ
BPM : MONITOR
IP  : MONITOR

FCELL: LINE=(QF,LH,QD,BPM,QD,LH,QF,BPM)
DCELL: LINE=(QD,LH,QF,BPM,QF,LH,QD,BPM)

FLCLL:LINE=(2*FCELL)

! You may change the number of cells
FODO:LINE=(50*FLCLL,IP)
```

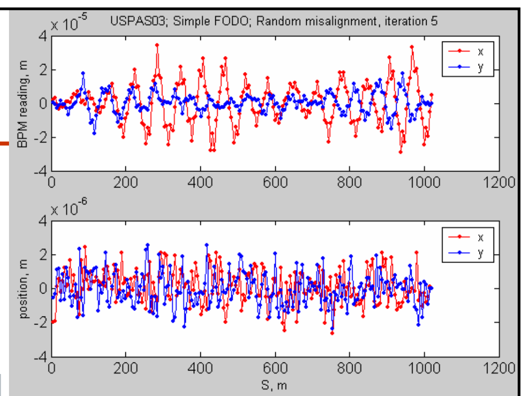
Remember that in MAD K1 is Gradient/Bρ which is in 1/m^2
So, to get the K from the previous page, multiply by quad length

Note that initial beta-functions are not specified anywhere in this file. Clever MAD decides that in this case he needs to find a solution where exit and entrance beta-functions are the same (closed solution).

When you get the FODO optics, look into fodo_simple.print to get the values for beta and alpha functions at the entrance. You will need to insert these values into the file fodo_init.liar in the Exercise 6.

Exercise 6
random misalignments of FODO linac

In this case you will use MatLIAR to simulate random misalignments of FODO linac, plot misalignments and orbits, find rms value of orbit motion at the exit, and compare with your analytical predictions. The necessary files are in C:\LC_WORK\ex6



Example of misalignments and orbits

Examples of MatLIAR calls are shown below:

```
%  Initialize MatLIAR with FODO beamline
mat_cmndliar('fodo_init.liar');
```

```
% Number of iterations to average (You may change it)
niter=5;

% RMS misalignment for quads [m]  (You may change it)
yrmsquad=1e-6;
xrmsquad=1e-6;
```

```
% Set Quad random misalignment
mat_liar('error_gauss_quad, name = ''*'','); % Name to be matched
mat_liar(['x_sigma = ',num2str(xrmsquad), ' ,' ]); % Sigma misalignment
mat_liar('x_cut   = 3,         '); % Cut for Gaussian
mat_liar(['y_sigma = ', num2str(yrmsquad) ' ,' ]); % Sigma misalignment
mat_liar('y_cut   = 3,         '); % Cut for Gaussian
mat_liar('reset = .t.        '); % reset previous misalignm.
```

Make sure to edit the file **fodo_init.liar** and put correct values of initial beta and alpha functions both in the commands **calc_twiss** and **set_initial**

```
% Track the beam:
mat_liar('  track  ');
```

```
[iss,bpmrx(:,iter),bpmry(:,iter)] = mat_liar('MAT_GET_BPMR',nbpm);% BPM reading (includes random resolution)
```

Predicting orbit motion …
escaping the complete randomness

Now you have everything to calculate **b** and **d** coefficients and find, for example, the rms of the orbit motion at the exit for the simplest case – completely random uncorrelated misalignments.

Completely random and uncorrelated means that misalignments of two neighboring points, even infinitesimally close to each other, would be completely independent.

If we would assume that such random and uncorrelated behavior occur in time also, I.e. for any infinitesimally small Dt the misalignments will be random (no "memory" in the system) then it would be obvious that such situation is physically impossible. Simply because its spectrum correspond to white noise, I.e. goes to infinite frequencies, thus having infinite energy.

We have to assume that things do not get changed infinitely fast, nor in space, neither in time. I.e., there is some correlation with previous moments of time, or with neighboring points in space.

Let's consider the random walk (drunk sailor). In this case, together with randomness, there is certain memory in this process: the sailor makes the next step relative to the position he is at the present point.

Extension of random walk model to multiple points in space and time is described by the famous ATL [B.Baklakov, et al, 1991].

N.B. Nonzero correlation (often called auto-correlation, when talking about correlation in time) would necessarily mean that spectrum decrease with frequency, saving the energy conservation law. More on this later in the lecture.

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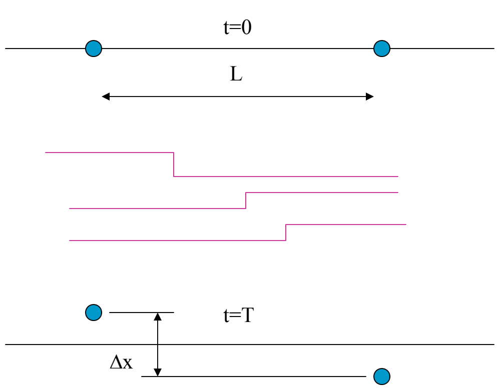
The ATL motion

According to "ATL law" (rule, model, etc.), misalignment of two points separated by a distance L after time T is given by $\Delta X^2 \sim ATL$ where **A** is a coefficient which may depend on many parameters, such as site geology, etc., if we are talking about ground motion. (The ATL-kind of motion can occur in other areas of physics as well.)



Such ATL motion would occur, for example, if step-like misalignments occur between points 1 and 2 and the number of such misalignments is proportional to elapsed time and separation between point. You then see that the average misalignment is zero, but the rms is given by the ATL rule.

Can you show this?

ATL ground measurements will be discussed later. Let's now discuss orbit motion in the linac for ATL ground motion.

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Predicting orbit motion and chromatic dilution … ATL case

So, we would like to calculate $\langle x_*^2(t) \rangle = \sum_{i=1}^{N} \sum_{j=1}^{N} b_i\, b_j\, \langle x_i(t) \cdot x_j(t) \rangle$ for ATL case.

Let's rewrite ATL motion definition. Assume that there is an inertial reference frame, where coordinates of our linac are $\mathbf{x_{abs}(t,s)}$. Let's assume that at t=0 the linac was perfectly aligned, and let's define misalignment with respect to this original positions as $x(t,s) = x_{abs}(t,s) - x_{abs}(t=0,s)$

The ATL rule can then be written as: $\langle \left(x(t,s+L) - x(t,s)\right)^2 \rangle = A \cdot t \cdot L$

Take into account that beam goes through the entrance (where s=0) without offset and write: $x_i = x(t,s_i) - x(t,0) \qquad x_j = x(t,s_j) - x(t,0)$

Then rewrite $\mathbf{x_i x_j}$ term as $x_i x_j = \frac{1}{2}\left[\left(x(t,s_i) - x(t,0)\right)^2 + \left(x(t,s_j) - x(t,0)\right)^2 - \left(x(t,s_i) - x(t,s_j)\right)^2\right]$

Now use ATL rule and get $\langle x_i x_j \rangle = \frac{1}{2} \cdot A \cdot t \cdot \left(|s_i| + |s_i| - |s_i - s_j| \right)$

Taking into account $\mathbf{S_i = (i-1)L}$ we have the final result for the rms exit orbit motion in ATL case:

$$\langle x_*^2(t) \rangle = \frac{A \cdot t \cdot L}{2} \sum_{i=1}^{N} \sum_{j=1}^{N} b_i b_j \left((i-1) + (j-1) - |i-j|\right)$$

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Exercise 6
ATL misalignments of FODO linac

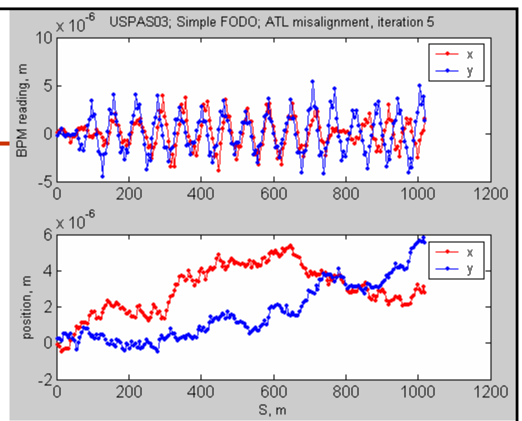
In this case you will use MatLIAR to simulate ATL misalignments of FODO linac, plot misalignments and orbits, find rms value of orbit motion at the exit, and compare with your analytical predictions. The necessary files are in C:\LC_WORK\ex6
Examples of MatLIAR calls are shown below:

```
% Coefficien A in x and y plane, [ micron^2 / (m*s)]
Ax=1e-6;
Ay=1e-6;
% Time [s]  (You may change it)
T=1e4;
```

```
for iter=1:niter

% Set ATL misalignment
mat_liar('ATLMOVE, '); %
mat_liar([' Ax = ',num2str(Ax), ' ,' ]); % Ax of ATL
mat_liar([' Ay = ',num2str(Ay), ' ,' ]); % Ay of ATL
mat_liar([' T = ',num2str(T), ' , ' ]); % Time
mat_liar(' reset = .t.        '); % reset previous misalignm.
```

```
% Compute and display standard deviation for the last BPM
last_bpm_rms_x= std ( bpmrx(nbpm,:) )
last_bpm_rms_y= std ( bpmry(nbpm,:) )
```



Example of misalignments and orbits

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Slow and fast motion, again

- We know how to evaluate effect of ATL motion
- This motion is slow
- What about fast motion?
- Its correlation?
- Measured data?

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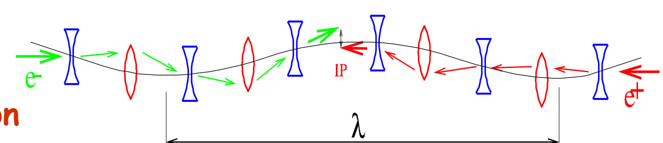
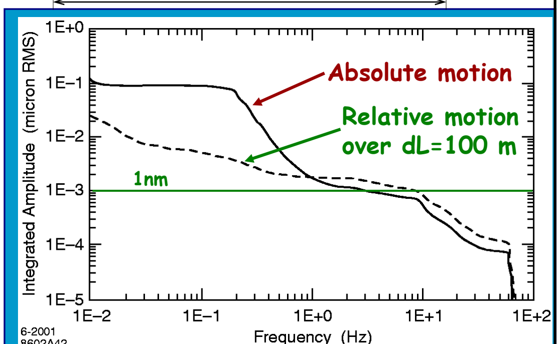
Correlation: relative motion of two elements with respect to their absolute motion

- Care about relative, not absolute motion
- Beneficial to have good correlation (longer wavelength)
- Relative motion can be much smaller than absolute





Integrated (for F>F$_o$) spectra. SLC tunnel @ SLAC

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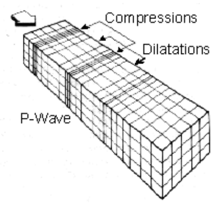
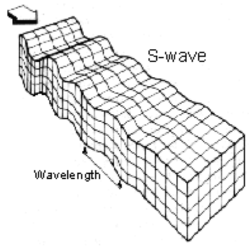
Correlation of ground motion depends on velocity of waves (and distribution of sources in space)

P-wave, (primary wave, dilatational wave, compression wave)
Longitudinal wave. Can travel trough liquid part of earth.



Velocity of propagation $\quad v_P = \sqrt{\dfrac{\lambda + 2G}{\rho}}$



S-wave, (secondary wave, distortional wave, shear wave)
Transverse wave. Can not travel trough liquid part of earth

Velocity of propagation $\quad v_S = \sqrt{\dfrac{G}{\rho}}$ $\quad$ typically $\quad v_S \approx \dfrac{v_P}{2}$

Here ρ- density, G and λ - Lame constants: $\quad G = \dfrac{E}{2(1+\nu)} \qquad \lambda = \dfrac{\nu E}{(1+\nu)(1-2\nu)}$

E-Young's modulus, ν - Poisson ratio

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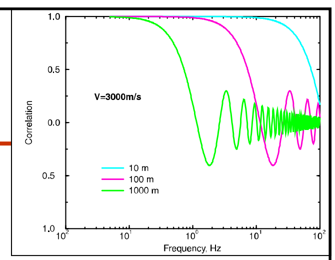
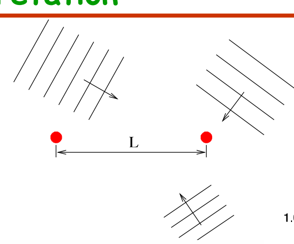
Correlation measurements and interpretation

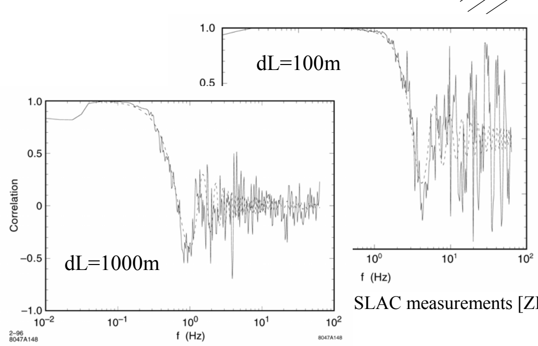


Theoretical curves

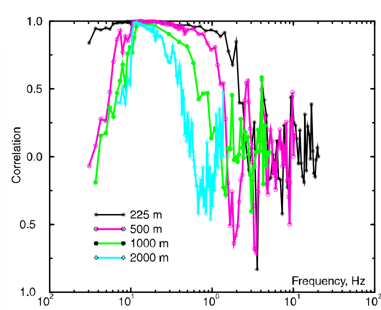
In a model of pane wave propagating on surface

correlation =
$\langle\cos(\omega\Delta L/v\ \cos(\theta))\rangle_\theta$ =
$=J_0(\omega\Delta L/v)$
where **v-** phase velocity





SLAC measurements [ZDR]



LEP measurements

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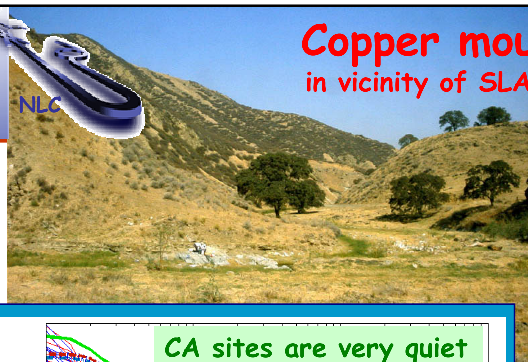
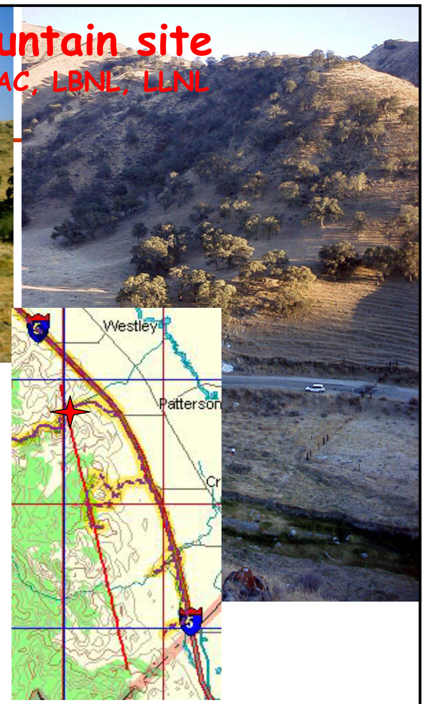
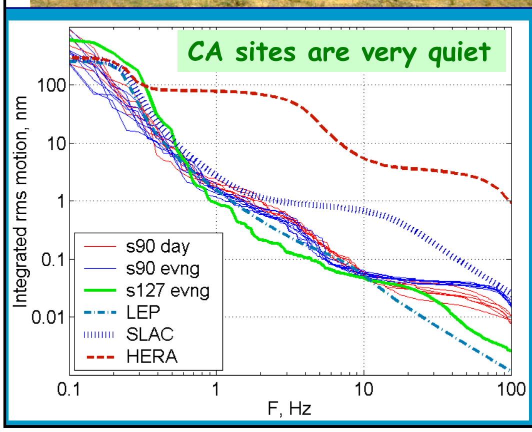
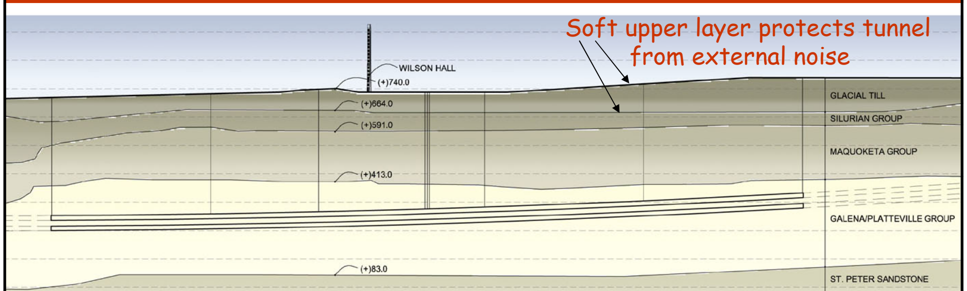
Copper mountain site
in vicinity of SLAC, LBNL, LLNL







NLC representative site @ Fermilab



- Tunnel can be placed **~100m deep in geologically (almost) perfect Galena Platteville dolomite platform**
- **Top ground layer is soft – this increase isolation from external noises**

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Predicting orbit motion for arbitrary misalignments

So, we would like to calculate, for example, $\langle x_*^2(t)\rangle = \sum_{i=1}^{N}\sum_{j=1}^{N} d_i\, d_j \,\langle x_i(t)\cdot x_j(t)\rangle$ in case of arbitrary properties of misalignments

One can introduce the spatial harmonics **x(t,k)** of wave number **k=2π/λ**, with λ being he spatial period of displacements:

$$x(t,k) = \int_{-\mathcal{L}/2}^{\mathcal{L}/2} x(t,s)e^{-iks}ds$$

The displacement x(t,s) can be written using the back transformation:

$$x(t,s) = \int_{-\infty}^{\infty} x(t,k)(e^{iks}-1)\frac{dk}{2\pi}$$

which ensures that at the entrance **x(t,s=0)=0**.

Then the variance of dispersion is

$$\langle \eta_x^2(t)\rangle = \sum_i \sum_j d_i d_j \int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\langle x(t,k_1)x^*(t,k_2)\rangle(e^{ik_1 s_i}-1)(e^{-ik_2 s_j}-1)\frac{dk_1}{2\pi}\frac{dk_2}{2\pi}$$

We can rewrite it as

$$\langle \eta_x^2(t)\rangle = \sum_i \sum_j d_i d_j \int_{-\infty}^{\infty} P(t,k)(e^{iks_i}-1)(e^{-iks_j}-1)\frac{dk}{2\pi}$$

Where we defined the spatial power spectrum of displacements **x(t,s)** as

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

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Predicting orbit motion for arbitrary misalignments

So, we see that we can write the variance of dispersion (and very similar for the offset) in such a way, that the lattice properties and displacement properties are separated:

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

Here G(k) is the so-called spectral response function of the considered transport line (in terms of dispersion):

$$G(k) = g_c^2(k) + g_s^2(k)$$

where

$$g_c(k) = \sum_{i=1}^{N} d_i[\cos(ks_i)-1] \quad \text{and} \quad g_s(k) = \sum_{i=1}^{N} d_i \sin(ks_i)$$

The spectral function for the offset will be the same, but $\mathbf{d_i}$ substituted by $\mathbf{b_i}$

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2-D spectra of ground motion

Arbitrary ground motion can be fully described, for a linear collider, by a 2-D power spectrum **P(ω,k)**

If a 2-D spectrum of ground motion is given, the spatial power spectrum **P(t,k)** can be found as

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

Example of 2-D spectrum for ATL motion: $P(\omega,k) = \frac{A}{\omega^2 k^2}$ And for **P(t,k)** : $P(t,k) = \frac{A \cdot t}{k^2}$

The 2-D spectrum can be used to find variance of misalignment. Again, assume that there is an inertial reference frame, where coordinates of our linac are $\mathbf{x_{abs}(t,s)}$. And assume that at t=0 the linac was perfectly aligned, and that misalignment with respect to this original positions is $x(t,s) = x_{abs}(t,s) - x_{abs}(t=0,s)$, its variance is given by

$$\langle \left(x(t,s+L) - x(t,s)\right)^2 \rangle = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} P(\omega,k)\, 2\cdot[1-\cos(\omega t)]\, 2\cdot[1-\cos(kL)] \frac{d\omega}{2\pi}\frac{dk}{2\pi}$$

You can easily verify, for example, that for ATL spectrum it gives the ATL formula

The (directly measurable !) spectrum of relative motion is given by

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

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Behavior of spectral functions

Remember that before assuming that beams injected without offset we wrote that

$$x_*(t) = R_{11}\, x_{inj}(t) + R_{12}\, x'_{inj}(t) + \sum_{i=1}^{N} b_i\, x_i(t) \qquad \eta_x(t) = T_{116}\, x_{inj}(t) + T_{126}\, x'_{inj}(t) + \sum_{i=1}^{N} d_i\, x_i(t)$$

It is easy to show that the coefficients b (and d) follow certain rules, which can be found in the next way. By considering a rigid displacement of the whole beam line, it is easy to find the identity

$$\sum_{i=1}^{N} b_i = 1 - R_{11} \qquad \text{and} \qquad \sum_{i=1}^{N} d_i = -T_{116}$$

On the other hand, one can show by tilting the whole beamline by a constant angle that the coefficients satisfy for thin lenses the following identity:

$$\sum_{i=1}^{N} b_i s_i + R_{12} = s_{\text{exit}} \qquad \text{and} \qquad \sum_{i=1}^{N} d_i s_i + T_{126} = 0$$

These rules allow to find behavior of the spectral functions at small k:

$$g_c(k) = \sum_{i=1}^{N} d_i [\cos(k s_i) - 1]$$

$$g_s(k) = \sum_{i=1}^{N} d_i \sin(k s_i)$$

$$g_c(k \to 0) \approx O(k^2) \qquad g_s(k \to 0) \approx -k \cdot R_{12} + O(k^3)$$

You see that if R_{12} is zero, effect of long wavelength is suppressed as k^2

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Additional exercise

You created a FODO , simulated misalignments and compared rms orbit motion with analytical predictions using derivation for ATL which does not involve spectra.

You may try to calculate spectral response function for your linac and calculate the rms offset using integral of spectral function and power spectrum P(t,k).

How would you deal with this fact? : In the integrals k goes from – to + infinity. However, for FODO linac the range of valid k is bounded. For example, the maximum k is equal to π/L.

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Slow motion (minutes - years)

- **Diffusive** or **ATL** motion: $\Delta X^2 \sim ATL$
  (T – elapsed time, L – separation between two points)
  (minutes-month)
- Observed 'A' varies by ~5 orders: 10^{-9} to 10^{-4} $\mu m^2/(m \cdot s)$
  - **parameter 'A' should strongly depend on geology -- reason for the large range**
  - **Range comfortable for NLC: A <** 10^{-6} $\mu m^2/(m \cdot s)$
    Very soft boundary! Observed A at sites similar to NLC deep tunnel sites is several times or much smaller.
- **Systematic** motion: ~linear in time (month-years), similar spatial characteristics
- **In some cases can be described as ATTL** law :
  - SLAC 17 years motion suggests $\Delta X^2 = A_S T^2 L$ with
    $A_S \sim 4 \cdot 10^{-12}$ $\mu m^2/(m \cdot s^2)$ for early SLAC

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Slow but short λ ground motion

- **Diffusive or ATL motion:** $\Delta X^2 \sim A_D T L$ (minutes-month)
  (T – elapsed time, L – separation between two points)

Place	A $\mu m^2/(m \cdot s)$
HERA	$\sim 10^{-5}$
FNAL surface	$\sim$ 1-few*10^{-6}
SLAC*	$\sim 5*10^{-7}$
Aurora mine*	$\lesssim 2*10^{-7}$
Sazare mine	$\sim 10^{-8}$

~20μm displacement over 20m in one month

*** Further measurements in Aurora mine, SLAC & FNAL are ongoing**

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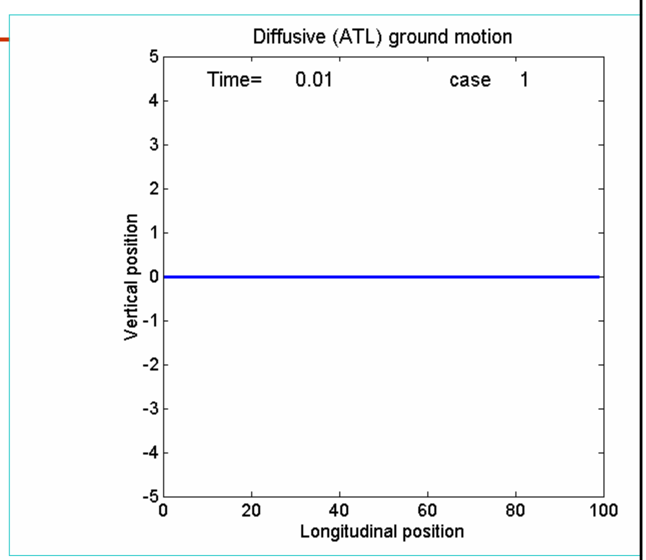
How diffusive ATL motion looks like?

- Movie of simulated ATL motion
- Note that it starts rather fast
- $X^2 \sim L$
- and it can change direction…



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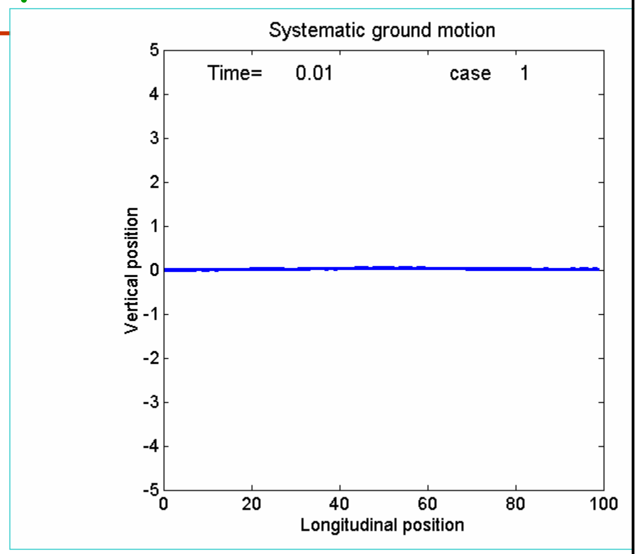
How systematic motion looks like?

- Movie of simulated systematic motion
- Note that final shape may be the same as from ATL
- And it may resemble…



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And in billion years…

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Systematic motion
SLAC linac tunnel in 1966-1983

- Year-to-year motion is dominated by systematic component
- Settlement…

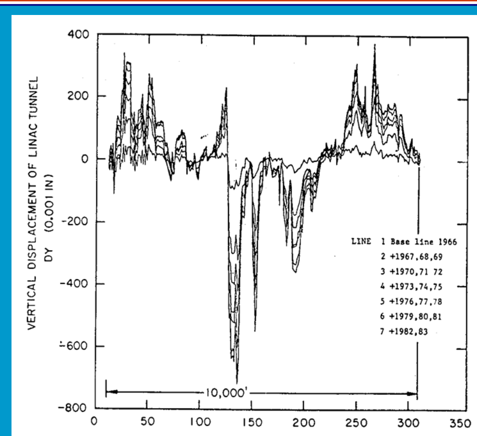

Figure 7: Displacement of the SLAC Linac Tunnel - Vertical.

Vertical displacement of SLAC linac for 17 years

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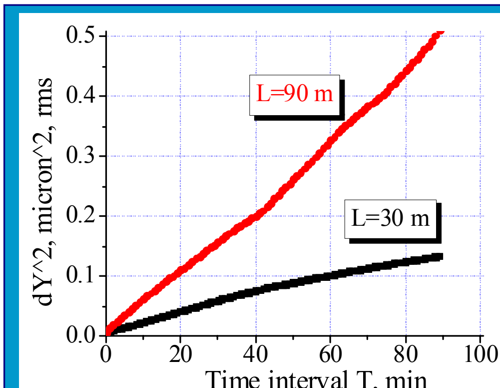
Slow motion
example: Aurora mine

- Slow motion in Aurora mine exhibit ATL behavior
- Here A~ $5*10^{-7}$ $\mu m^2/m/s$

  (similar value was observed at SLAC tunnel)



Slow motion in Aurora mine. Measured by hydrostatic level system.

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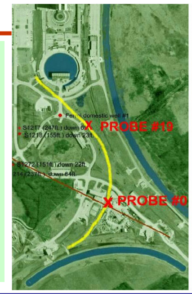
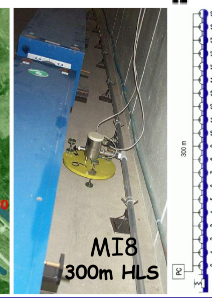
Slow motion study
(BINP-FNAL-SLAC)

NLC

Diffusion coefficients **A** [10^{-7} $\mu m^2/(m{\cdot}s)$]:
(10-100) for MI8 shallow tunnel in glacial till
(in absence of dominating cultural motion);
~3 or below in deep Aurora mine in dolomite
and in SLAC shallow tunnel in sandstone

Shallow tunnel in sedimentary/glacial geology – is a risk factor, both because of higher diffusive motion, and because of possibility of cultural slow motion.

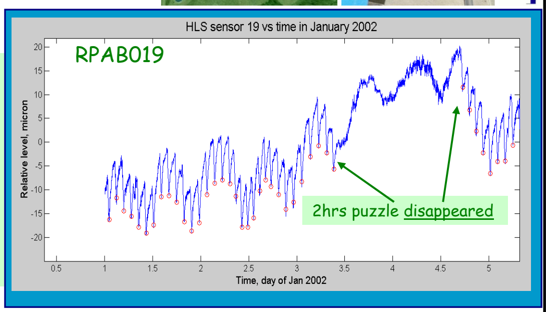




Cultural effects on slow motion:
"2hour puzzle" – 10 μm motion occurring near one of the ends of the system

Reason: domestic water well which slowly and periodically change ground water pressure and cause ground to move

Large amplitude, rather short period, bad correlation – nasty for a collider



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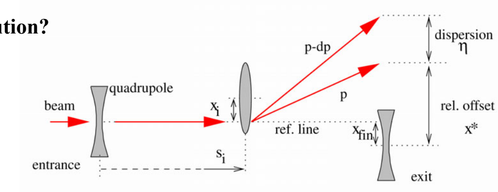
Summary, on ground motion influence on the beam

How to find trajectory offset or chromatic dilution?

Relative beam offset at exit and dispersion:

$$x^*(t) = \sum_{i=1}^{N} c_i x_i(t) - x_{fin} \qquad \eta(t) = \sum_{i=1}^{N} d_i x_i(t)$$



Linear model: $c_i = \dfrac{dx^*}{dx_i} \approx -K_i r_{12}^i \qquad d_i = \dfrac{d\eta}{dx_i} \approx K_i (r_{12}^i - t_{126}^i)$ Approximate values are for thin lens, linear order

Then, for example, the **rms beam dispersion:**

$$<\eta^2(t)> = \int_{-\infty}^{\infty} P(t,k)\, G_\eta(k) \frac{dk}{2\pi} \qquad \text{where} \qquad P(t,k) = \int_{-\infty}^{\infty} P(\omega,k)\, 2[1-\cos(\omega t)] \frac{d\omega}{2\pi}$$

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

Sum rules. E.g. $\sum d_i s_i = -T_{126}$ at small k then $G_{offset}(k) \approx k^2 R_{12}^2 \qquad G_\eta(k) \approx k^2 T_{126}^2$ unless R_{12} or $T_{126}=0$

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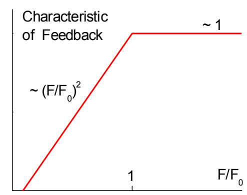
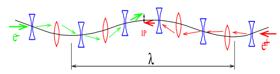
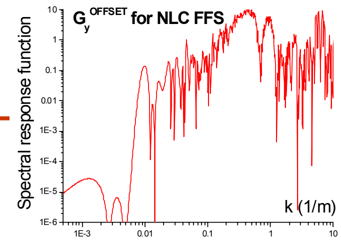
Ground motion induced beam offset at IP







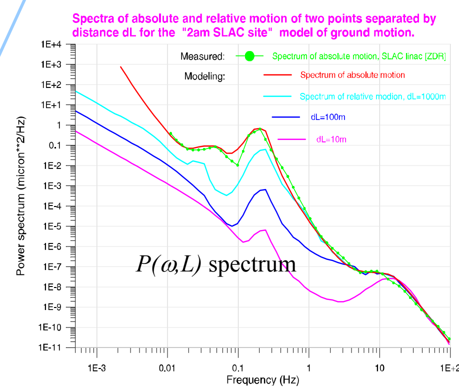
rms beam offset at IP:

$$\propto \iint P(\omega,k)\cdot G(k)\cdot F(\omega)\cdot dk\cdot d\omega$$

$G(k)$ - spectral response function

$F(\omega)$ - performance of inter-bunch feedback

$P(\omega,k)$ - 2D spectrum of ground motion



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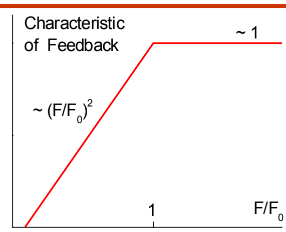
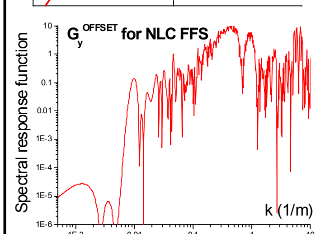
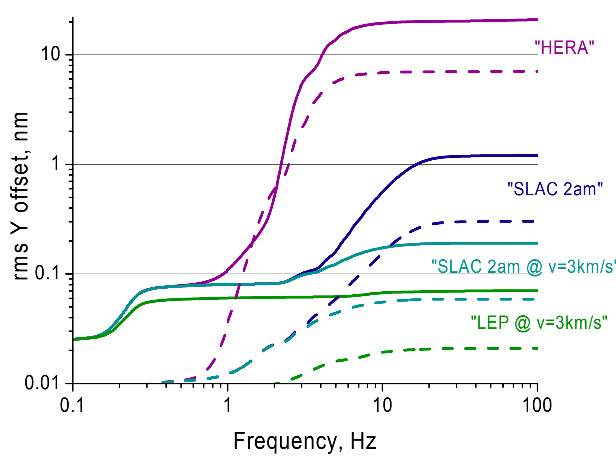
Beam offset at the IP of NLC FF for different GM models







rms beam offset at IP: $\propto \iint P(\omega,k)\cdot G(k)\cdot F(\omega)\cdot dk\cdot d\omega$

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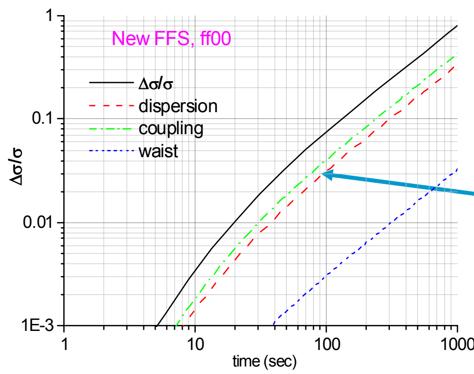
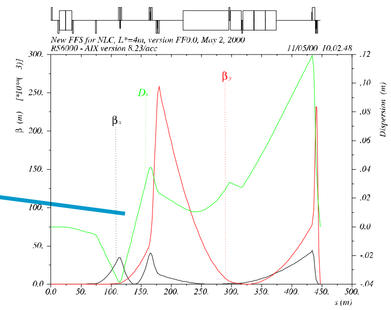
IP beam size growth due to slow misalignments





Beam energy, GeV	500
$\gamma\epsilon_x$ / $\gamma\epsilon_x$ (10^{-8} m)	400 / 6
σ_x^* / σ_y^* at IP (nm)	197 / 2.7
Energy spread σ_E (10^{-3})	3

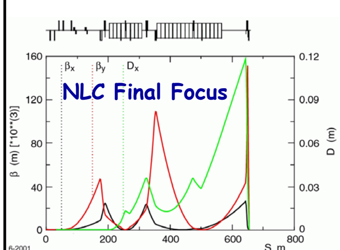
Beam size growth vs time. Evaluated using FFADA **No beamsize feedback**. Ground motion model with

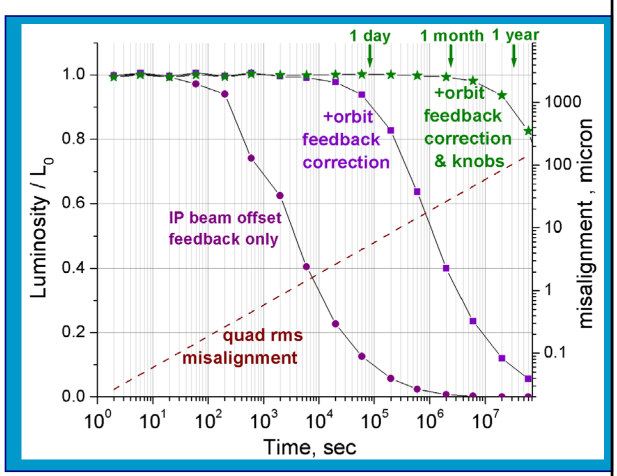
$$A = 5 \cdot 10^{-7} \frac{\mu m^2}{m \cdot s}$$

Orbit feedbacks drastically reduce this growth!

Simulations of feedbacks and Final Focus knobs

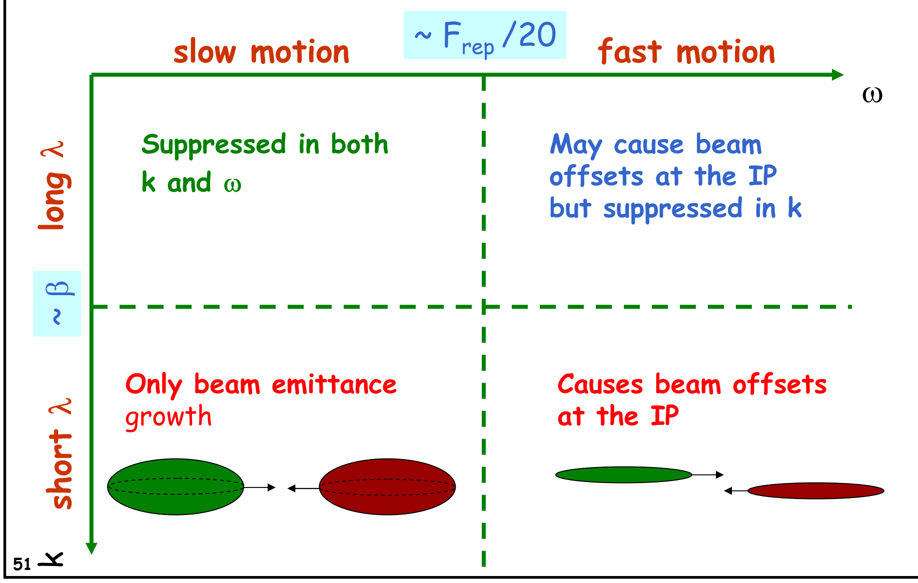
IP feedback, orbit feedback and dithering knobs suppress luminosity loss caused by ground motion





- Ground motion with $A=5*10^{-7}$ $\mu m^2/m/s$
- Simulated with MONCHOU

Two effects of ground motion in Linear Colliders, again



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Verification of NLC performance with ground motion and vibration

- Performance of NLC in terms of ground motion, procedure
  - Develop ground motion models (3 to account for different conditions)
  - Use non-ideal machines for these studies (essential especially for realistic calculations of beam-beam)
    - I.e. machines with errors which has been corrected to about nominal initial luminosity
  - Apply ground motion (A,B,C) + FD vibration to all machines
  - Apply proper IP feedback, fast IP feedback, FD stabilization
  - Find performance (delivered luminosity)

  - Determine requirements for stability
  - Experimentally verify that stability of the components can be maintained, taking into account all possible noise sources (ground motion, vibration due to cooling water, due to RF pulse, etc.)

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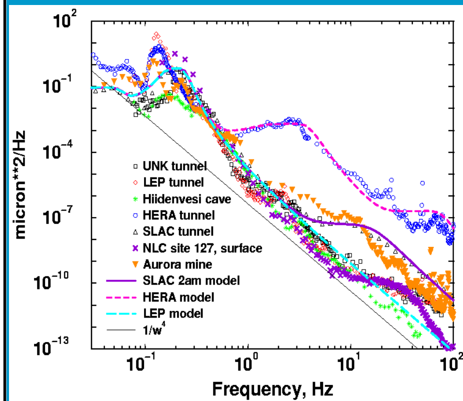
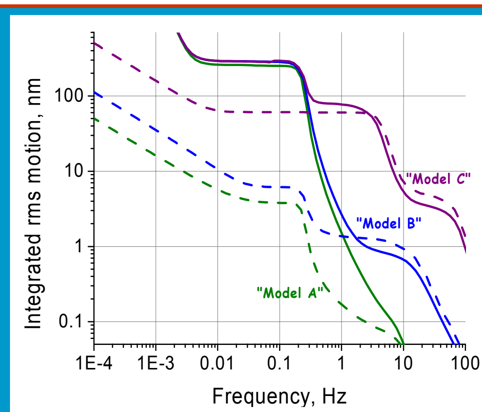
Ground motion models
example of spectra



Data from different locations
1989 - 2001



Absolute and relative (dL=50m, dashed lines) integrated spectra

Based on data, build modeling P(ω,k) spectrum of ground motion which includes:

- Elastic waves; Slow ATL motion; Systematic motion; Cultural noises

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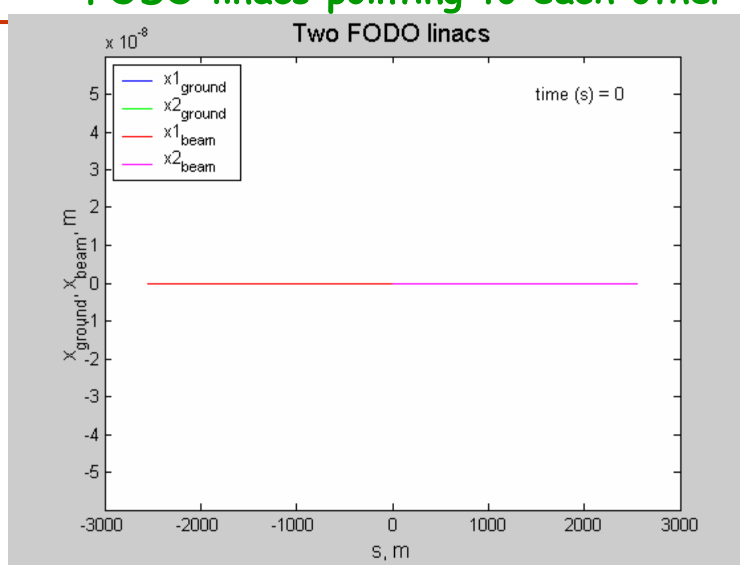
Example: effect of ground motion on two FODO linacs pointing to each other



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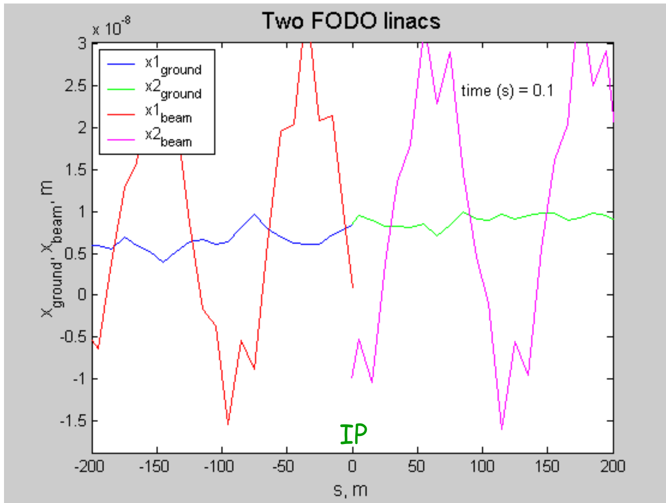
Example of Mat-LIAR modeling

Important that correlation between e+ and e- beamlines is preserved



Note that ground is continuous, but beams have separation at the IP

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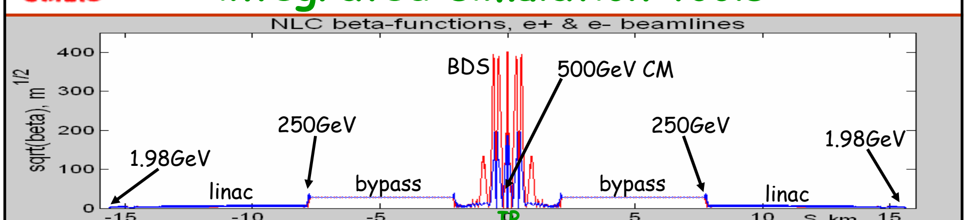
DR => IP <= DR integrated simulation tools

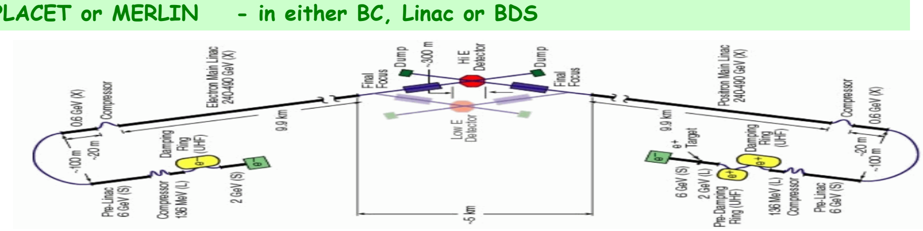
ILC-TRC



DIMAD – in Bunch Compressor and Beam Delivery System (high order optics, accurate particle tracking)
LIAR – in Linac (wakes, fast tracking of macroparticles)
} MATLAB driven

GUINEAPIG – beam-beam collisions at IP

PLACET or MERLIN – in either BC, Linac or BDS



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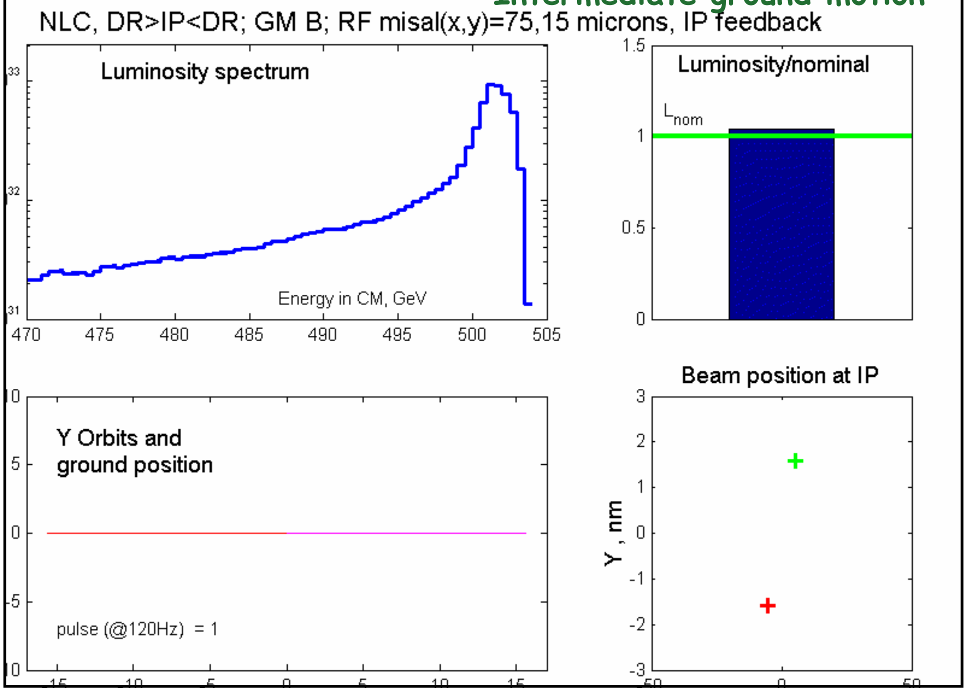
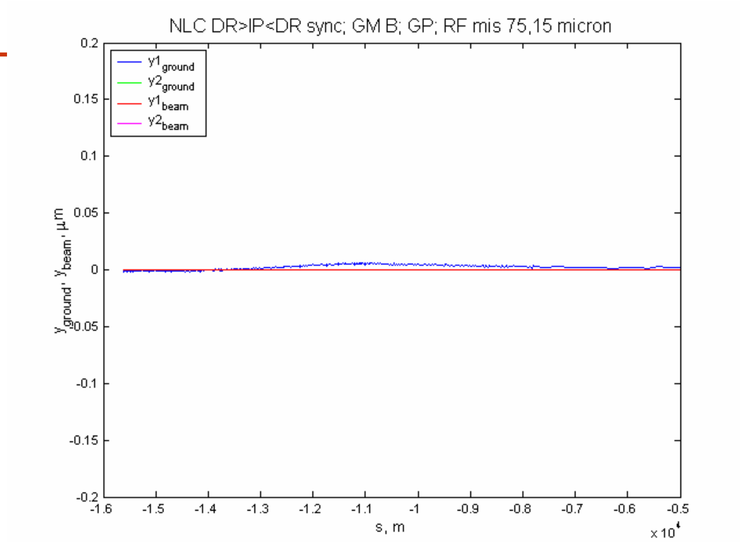
Intermediate ground motion



Zoom into beginning of e- linac …



Transition from linac to transfer line

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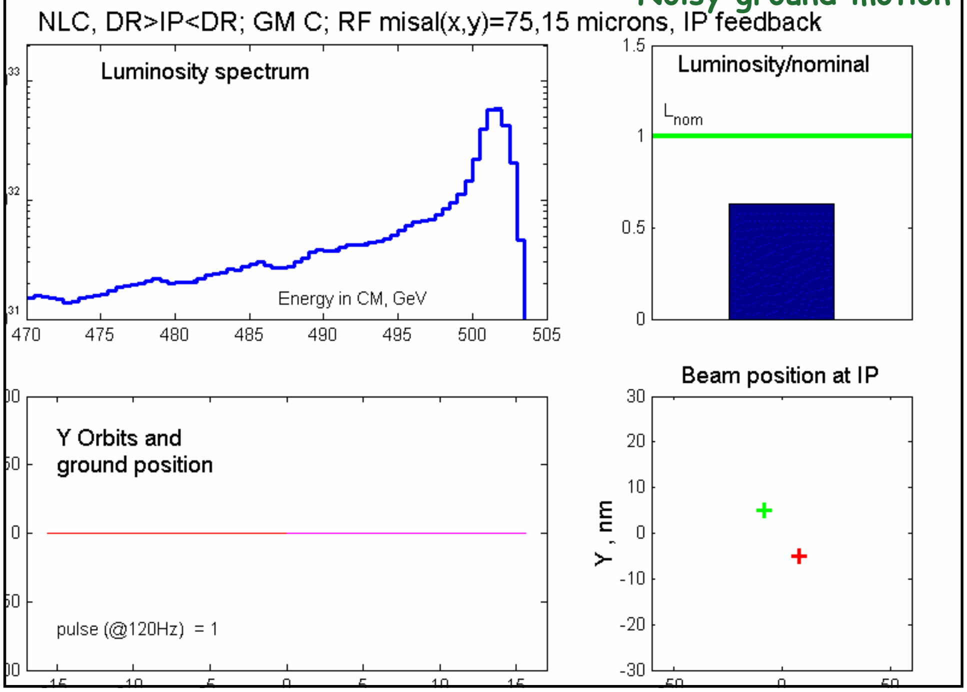
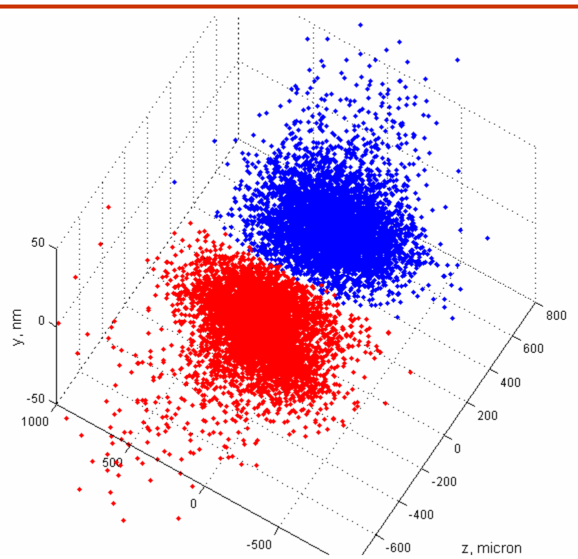
Noisy ground motion



Beam-beam collisions calculated by Guinea-Pig [Daniel Schulte]



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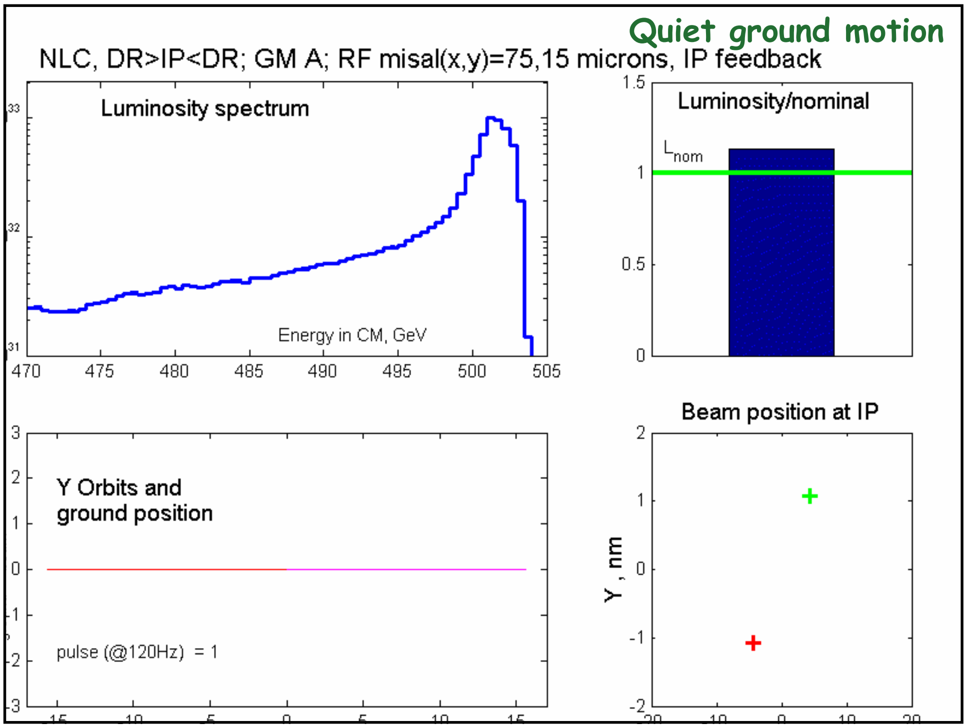

IP beam-beam feedback

Colliding with offset e+ and e- beams deflect each other

Deflection is measured by BPMs

Feedback correct next pulses to zero deflection
(it uses state space, Kalman filters, etc. to do it optimally)

The previous page shows that feedback needs to keep nonzero offset to minimize deflection
reason: asymmetry of incoming beams
(RF structures misalignments=> wakes=> emittance growth)

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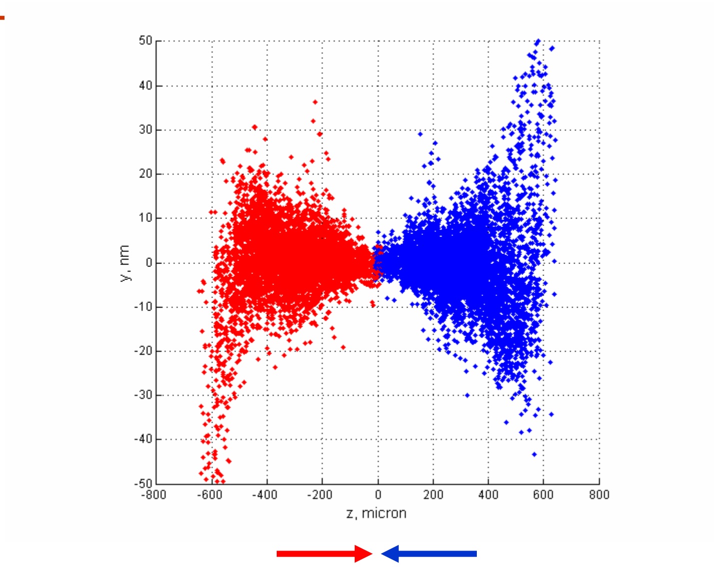
Pulse #100, Z-Y



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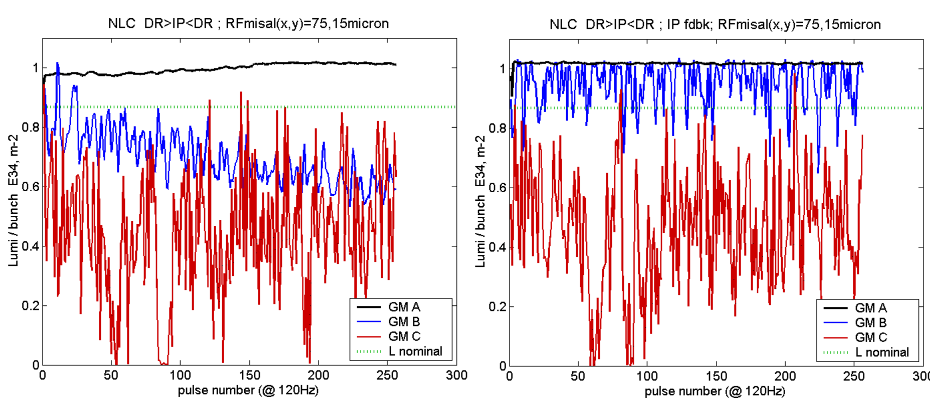
With and without IP feedback, examples



Example for one particular seed
(seed is the same for the left and right plots)

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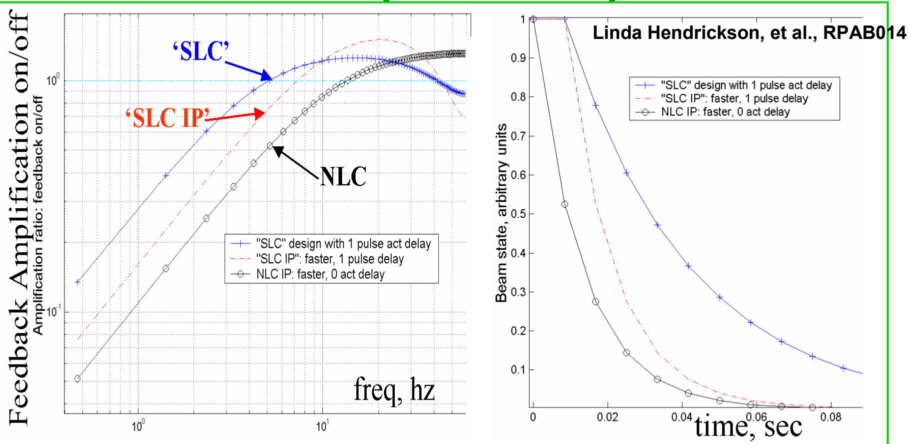
IP beam-beam feedback
(train-to-train)



NLC design of IP feedback is improved w.r.to feedback used in SLC

Realistic model if beam-beam feedback was used in TRC simulations

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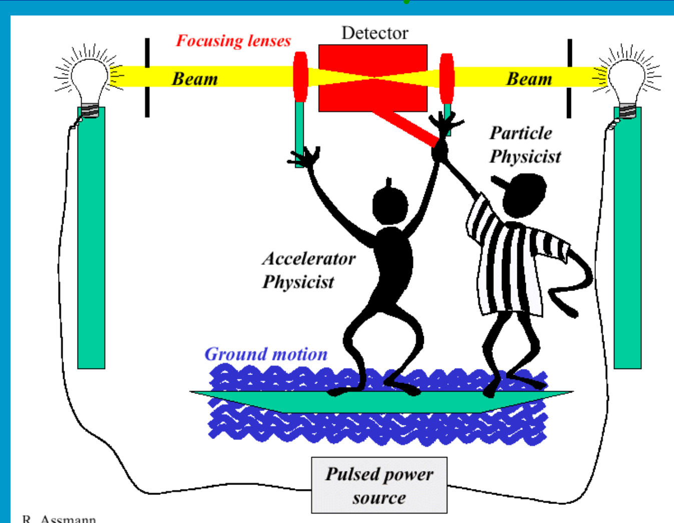
Detector complicates reaching FD stability



Cartoon from Ralph Assmann (CERN)

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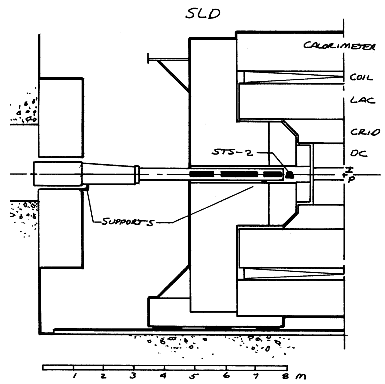
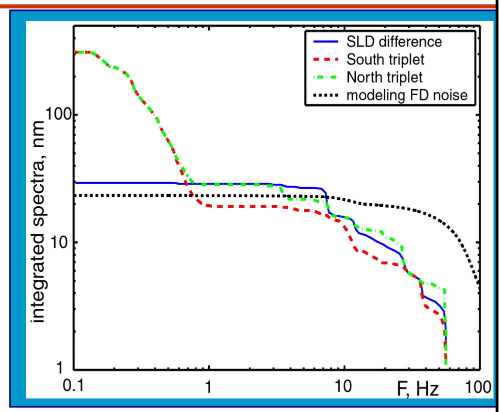
Detector is a noisy ground !





Measured ~30nm relative motion between South and North final triplets of SLC final focus. The NLC detector will be designed to be more quiet. But in modeling we pessimistically assume the amplitude as observed at SLD

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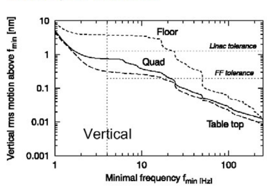
CLIC stability study

Quadrupole vibration:



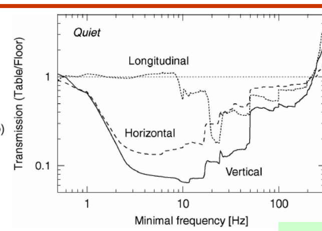
On magnet top:

X: (0.4 ± 0.1) nm

Y: (0.9 ± 0.1) nm
(0.3 nm on table top)

Z: (3.2 ± 0.4) nm

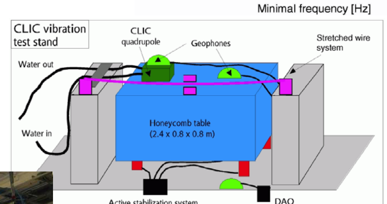
without cooling water.



With nominal flow of cooling water:

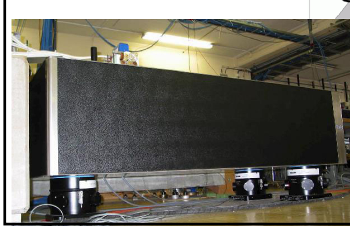
Y: (1.3 ± 0.2) nm

Tight vertical linac tolerance demonstrated!

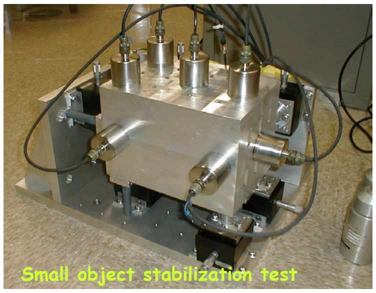


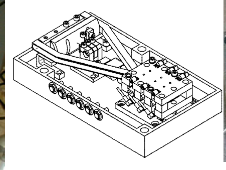
Using commercial STAICIS 2000 (TMC) achieved 1nm stability of a CLIC quadrupole

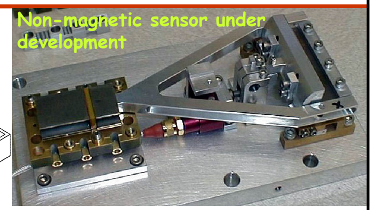
Nonmagnetic sensors, detector friendly design, would be needed in real system



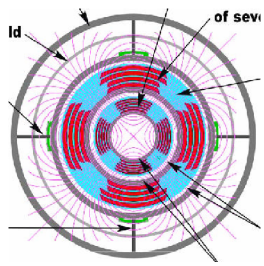
R&D on FD Stabilization







NLC and CLIC groups have active R&D on active stabilization of Final Doublet



BNL SC compact final quad

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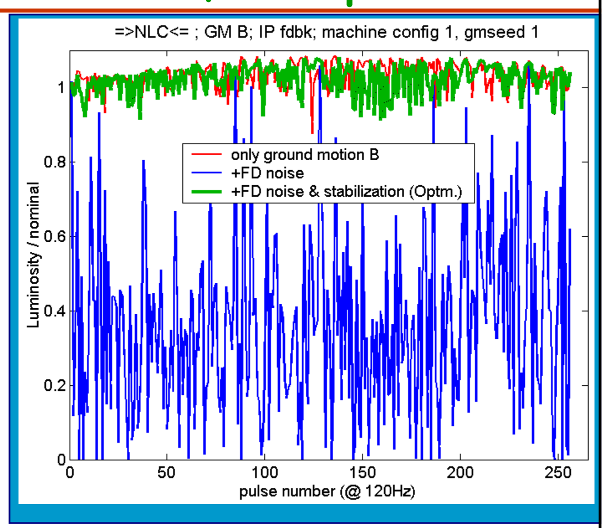
NLC with and without FD stabilization, example

- Assume pessimistic, SLD-like FD vibration
- Then luminosity drops significantly (to ~1/3)
- If FD is actively stabilized or corrected, luminosity is restored



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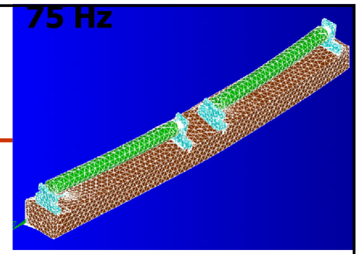
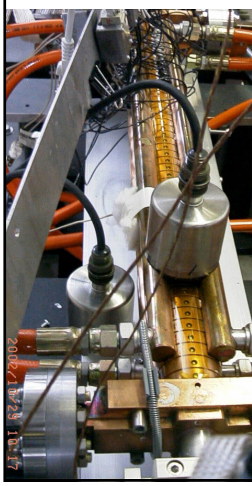
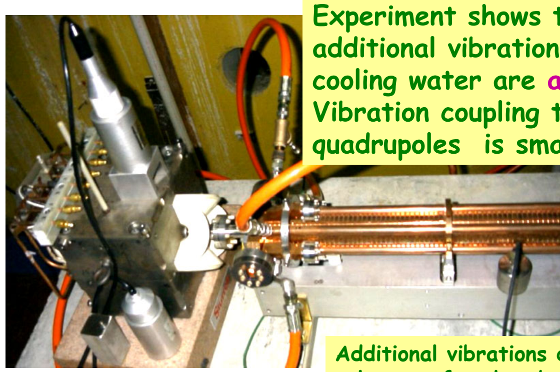
Linac stability study at SLAC and FNAL







Experiment shows that additional vibrations due to cooling water are acceptable. Vibration coupling to quadrupoles is small

Additional vibrations due to RF pulse was found to be negligible

We would like the NLC stability to be within the model B and believe it is achievable

Stability R&D w.r.to near- and in-tunnel sources

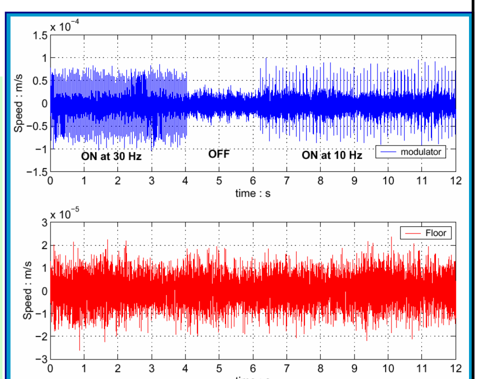
NLC

Vibration transfer from surface to tunnel
- done at SLAC in 2002

Vibration transfer along the tunnel and between tunnels
- done in May in LA metro

Klystron modulator noises
~ no vibration transmitted to the floor!

Measurements => modeling => vibrations isolations specs



Vibration on the modulator (top) and on the floor

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Join ! There will be interesting work for everyone !

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