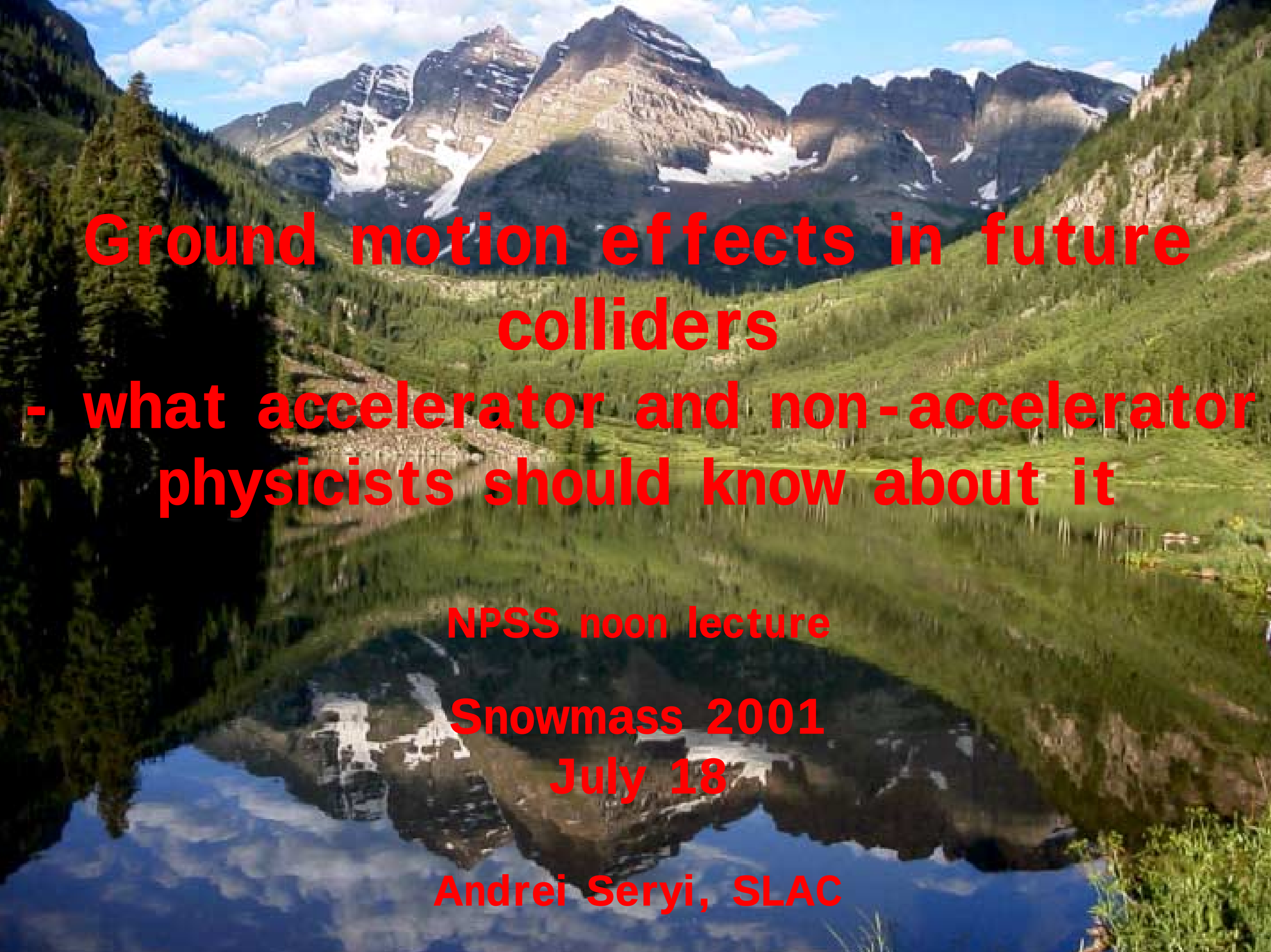


Ground motion effects in future colliders
- what accelerator and non-accelerator physicists should know about it

NPSS noon lecture

Snowmass 2001
July 18

Andrei Seryi, SLAC

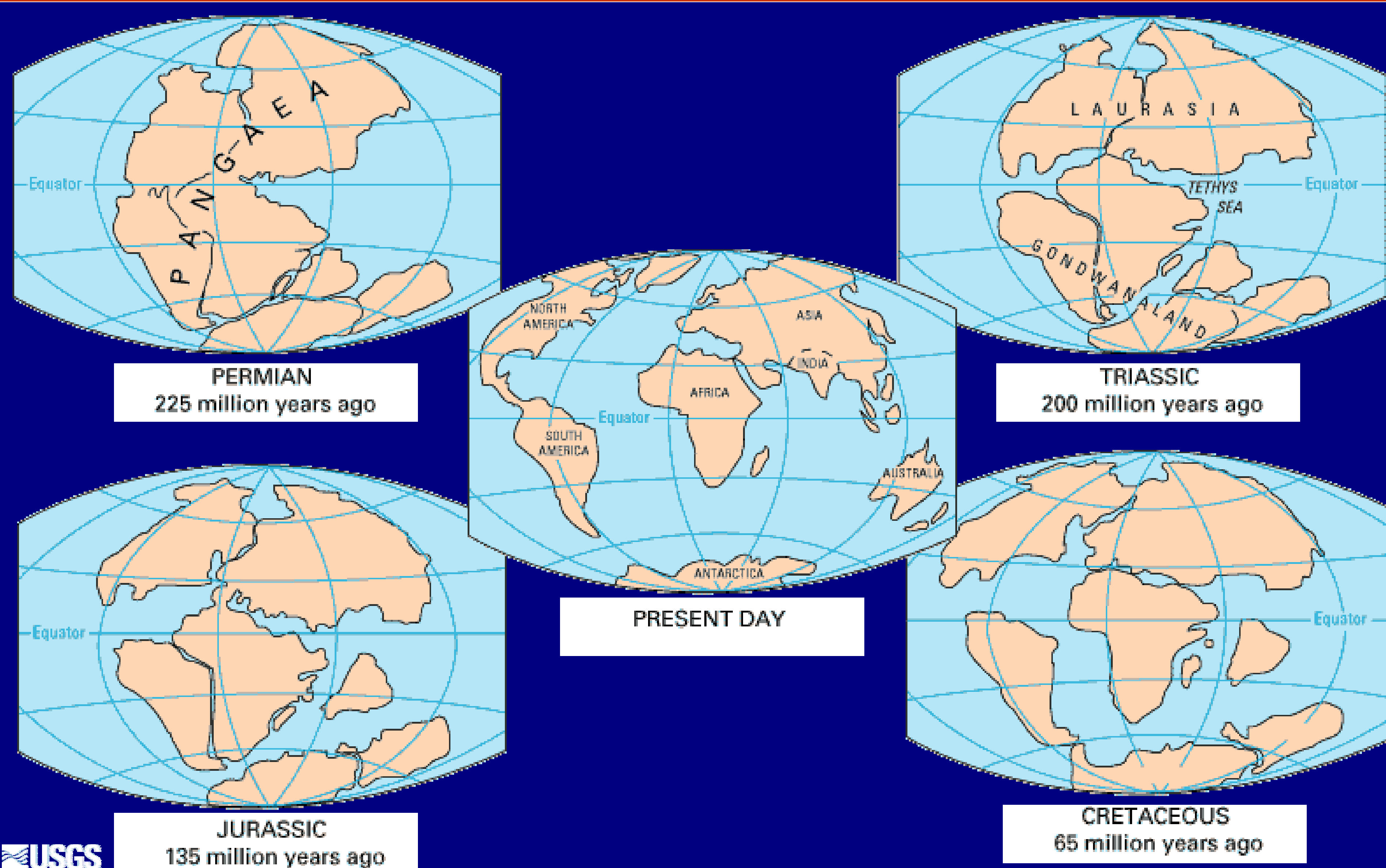
What ground motion we are talking about ?

- In some languages “Earth” and “ground” called by the same word…

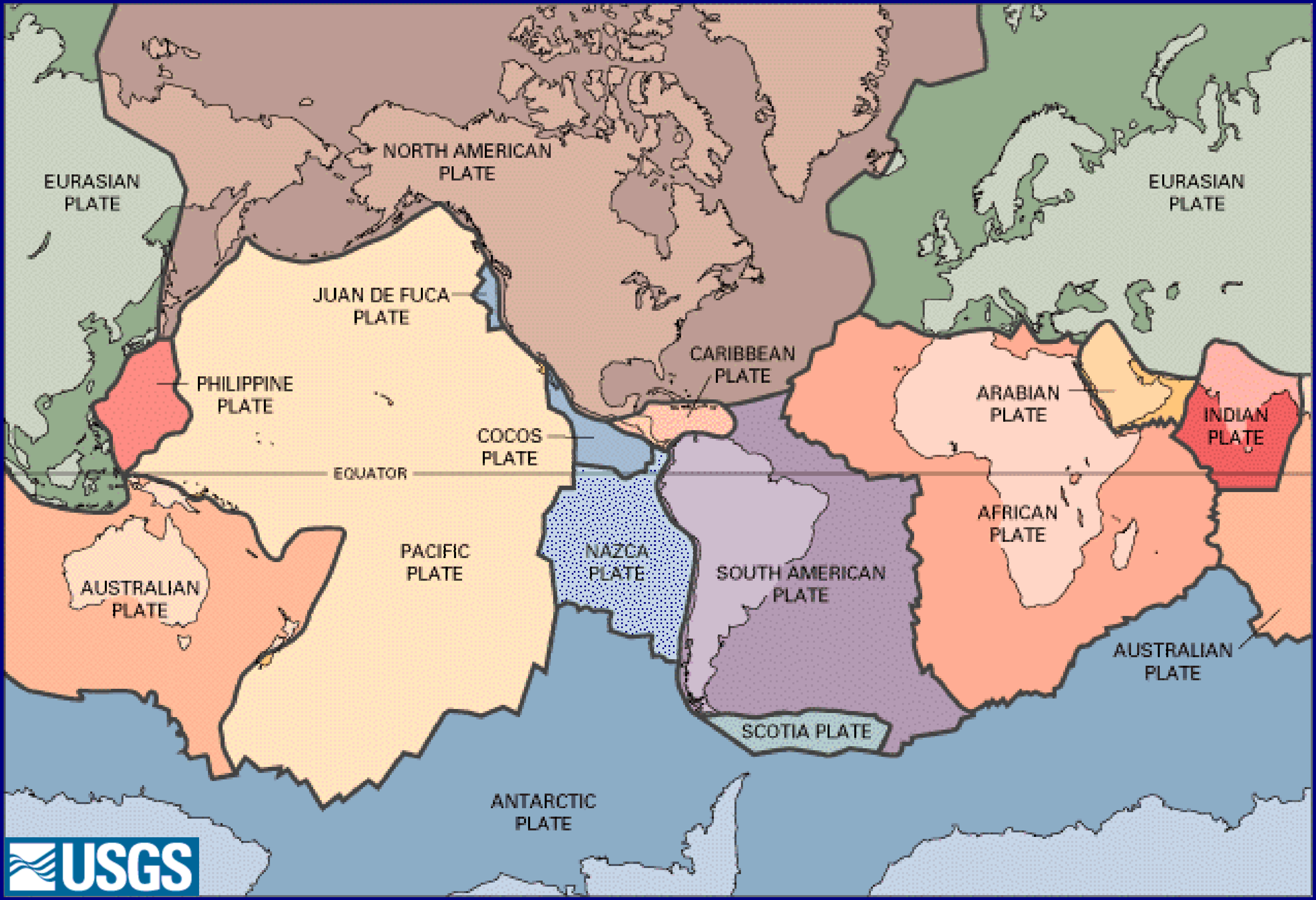
- No, we are not talking about Earth orbital motion…

NLC

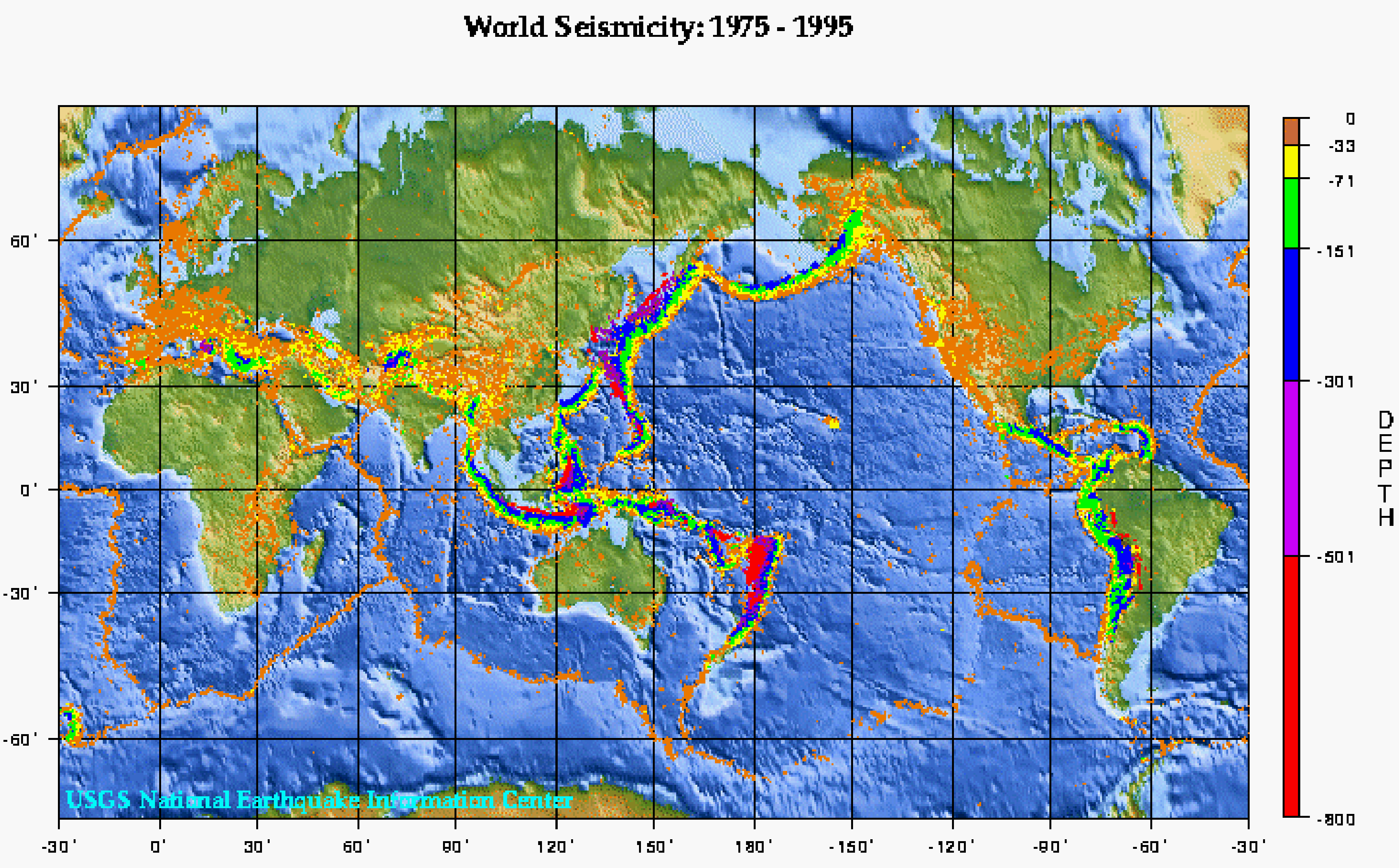
And not about continental drift...



# of tectonic plates...

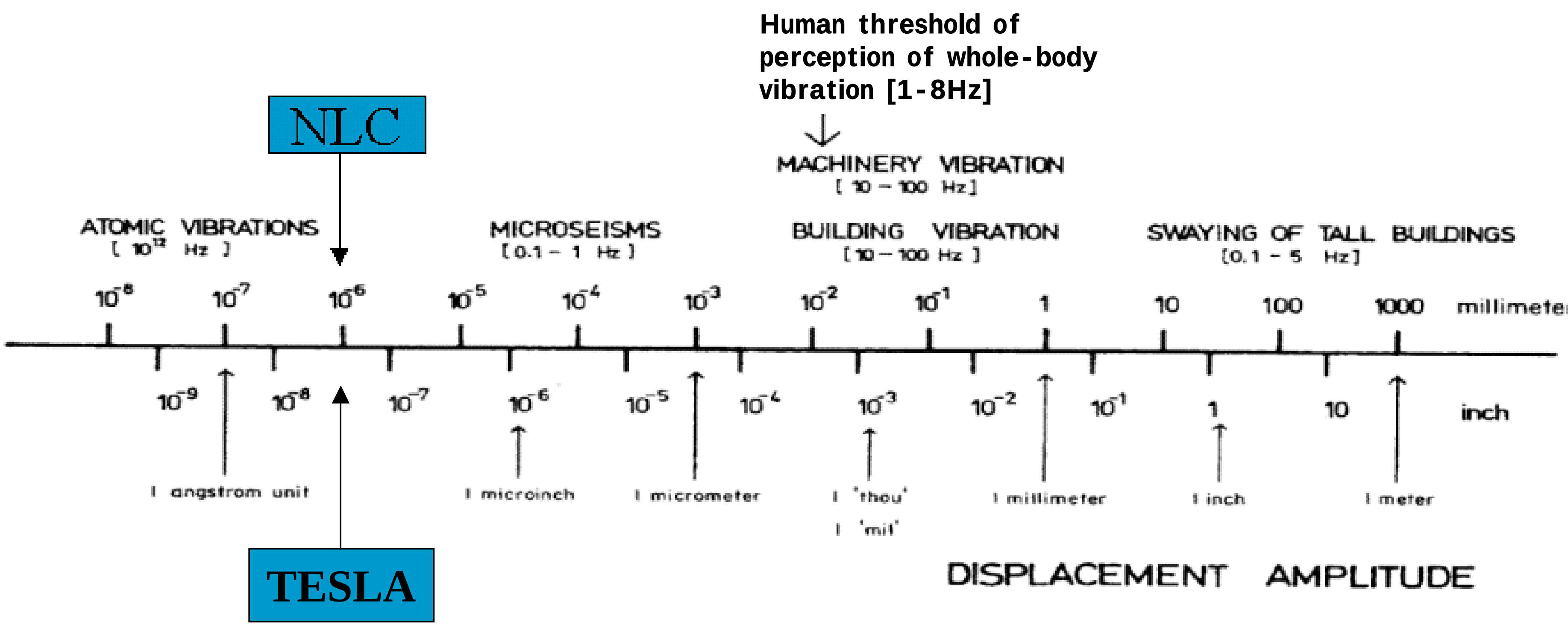


And not so much about earthquakes...



What ground motion we do care about ?

- The tiny motion which always exist and that we usually do not feel and do not care …

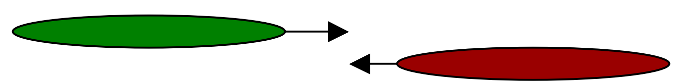


Why do we care about Ground Motion

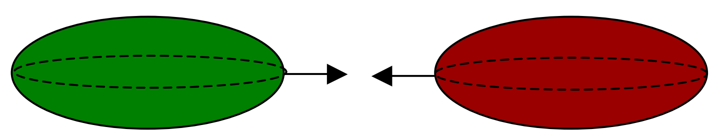
- **Linear Collider**
  - **Collide small beams (nanometers); very small beam emittance**

- **Ground Motion** and vibrations continuously **misalign** components of a collider and can result in

  - **offset at IP**

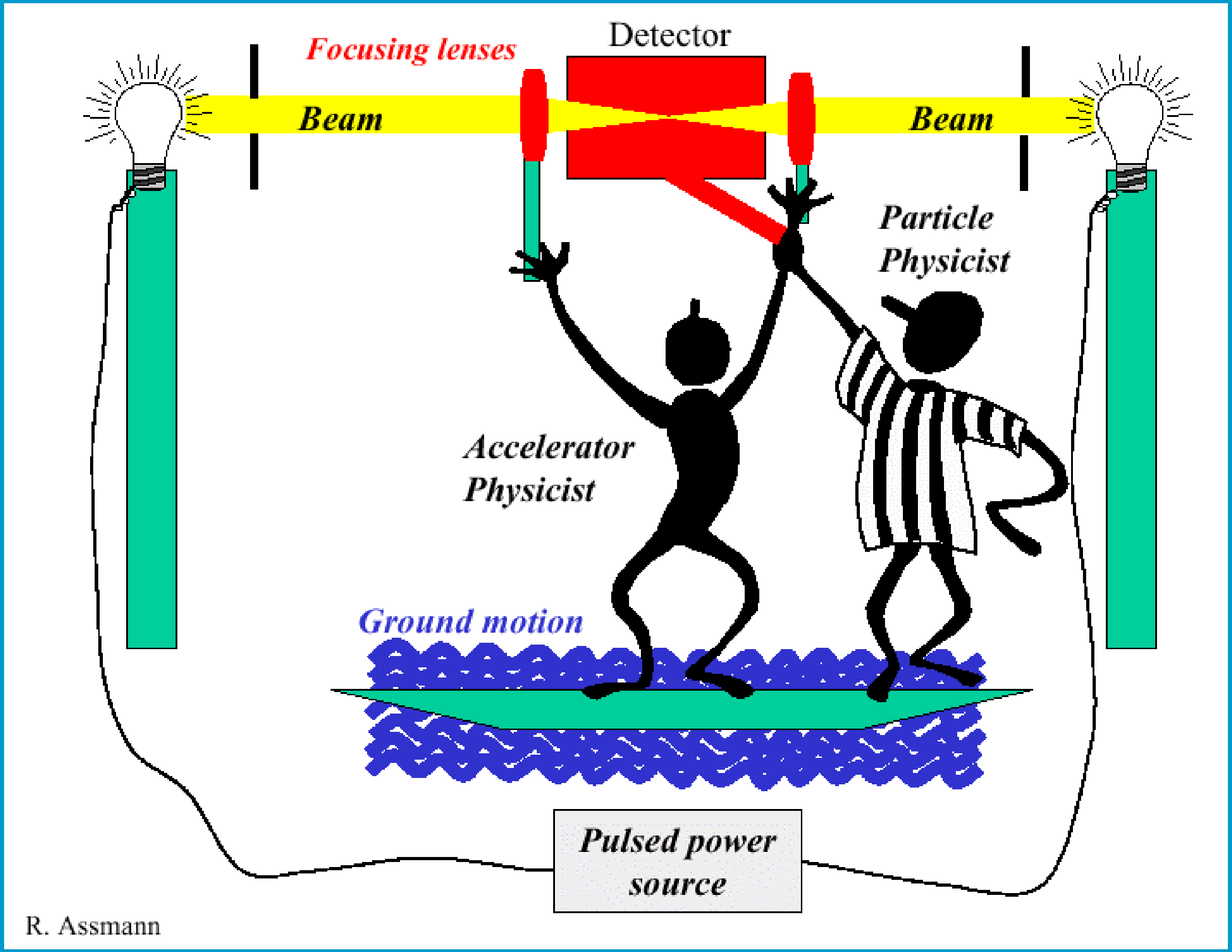


  - **emittance growth**



Ground motion may produce offset of the beams at IP...

The focusing lenses need to be on stable ground or need to be stabilized

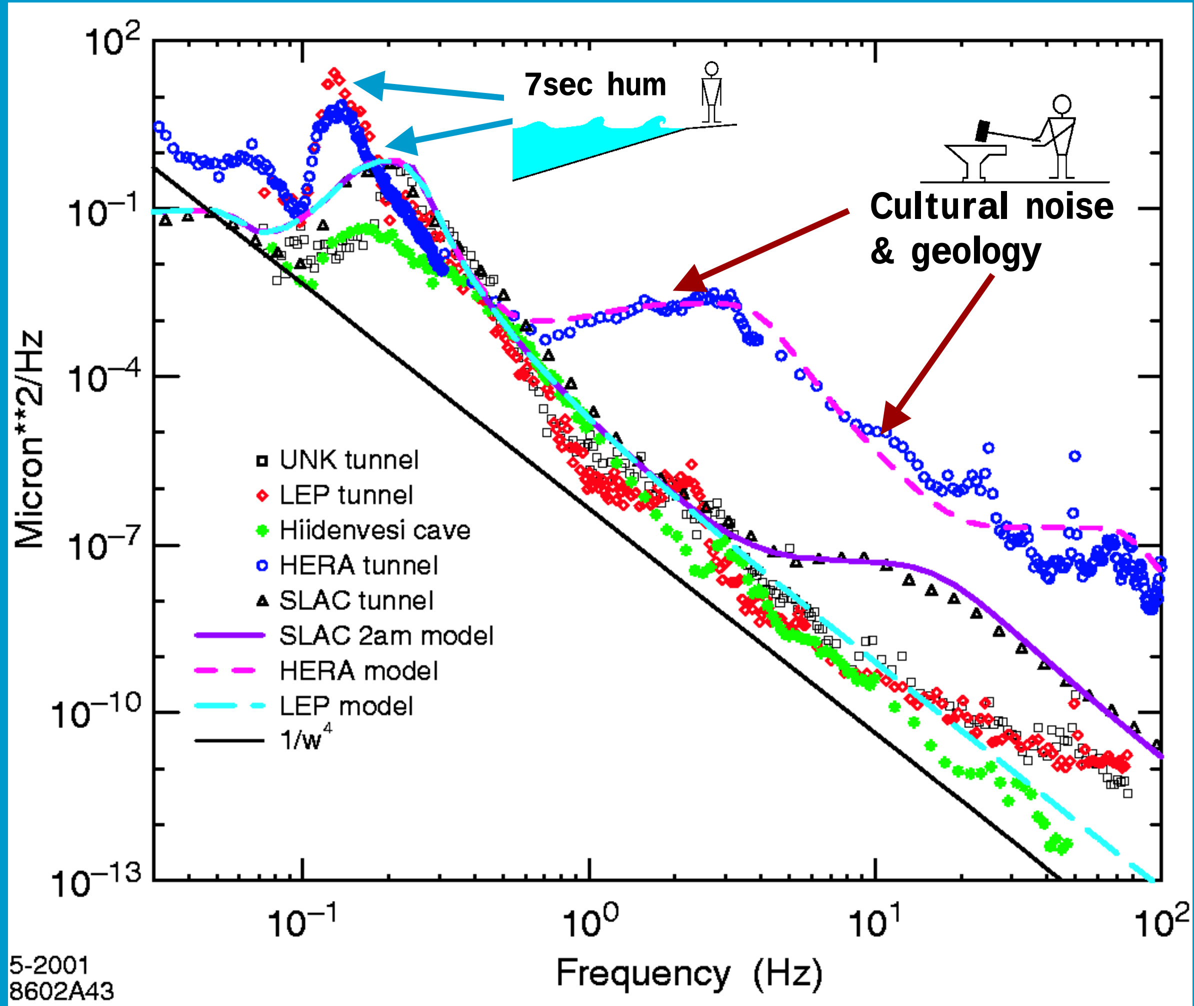


Cartoon from the talk of Ralph Assmann, CERN

Ground Motion basics
example of measured spectra

- **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



Natural ground motion is small
at high frequencies

NLC

At F>1 Hz the motion is < 1nm

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

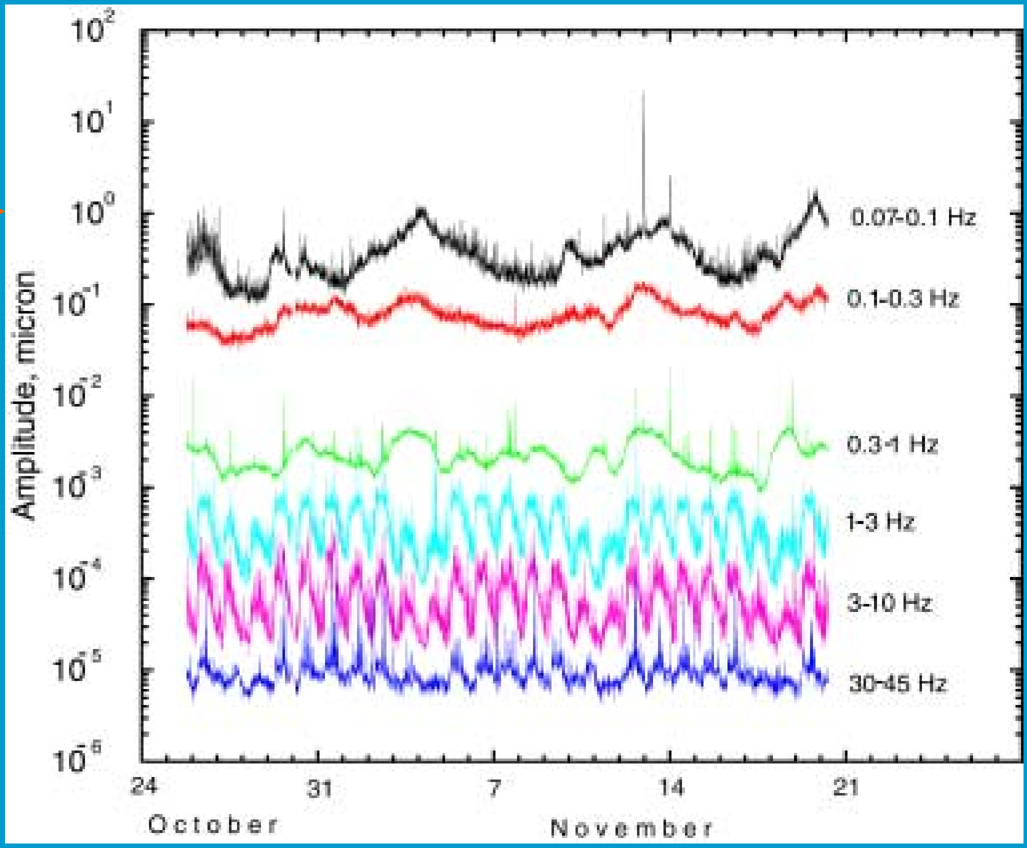
Is it OK?

What about low frequency motion?

It is much larger…

1 micron

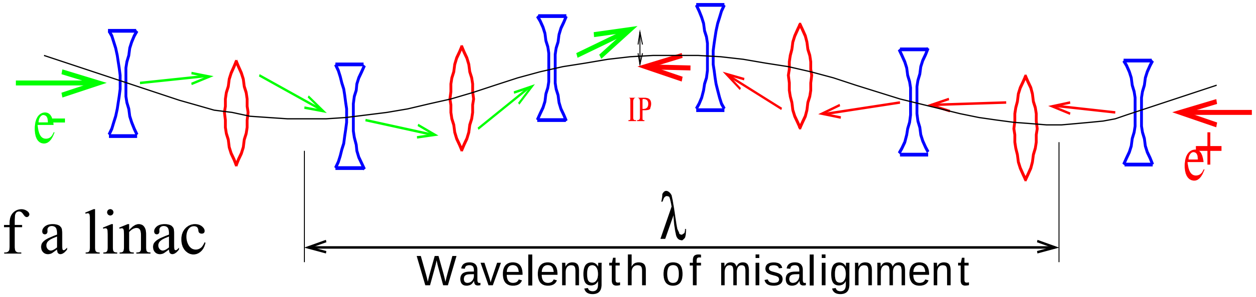
1 nm



Rms displacement in different frequency bands. Hiidenvesy cave. [V.Juravlev et al. 1994]

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

NLC

Two effects of ground motion in Linear Colliders

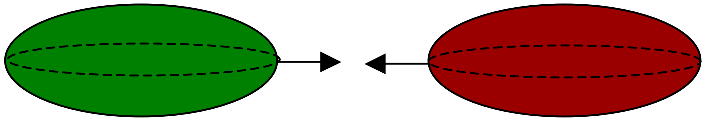
frequency

'slow motion' | **'fast motion'**

$F_c \sim F_{rep}/20$

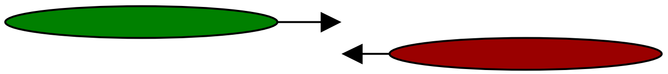
Beam offset due to **slow motion** can be compensated by feedback

May result only in beam emittance *growth*



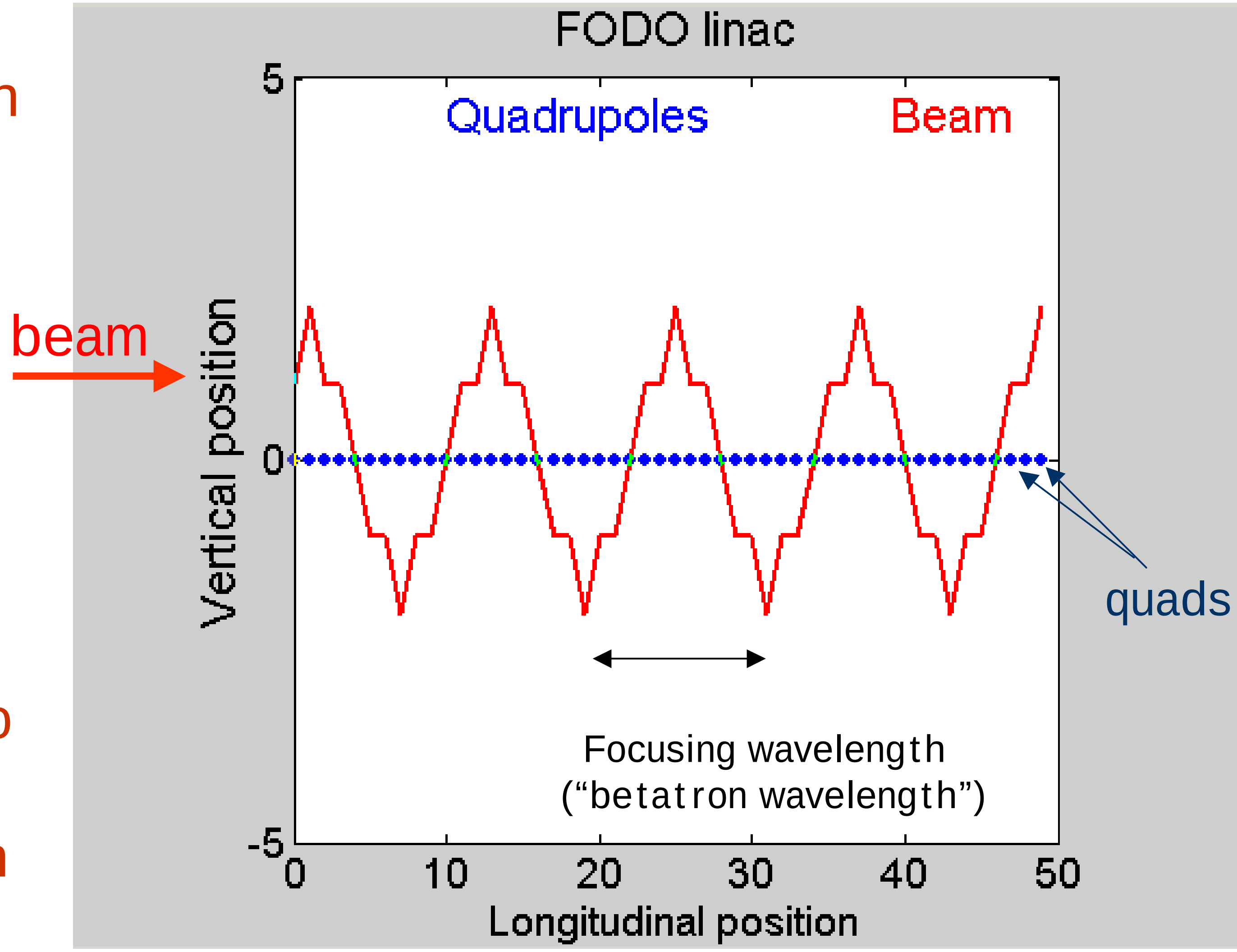
Beam offset **c**annot be corrected by a pulse-to-pulse feedback operating at the F_{rep}

Causes beam offsets at the IP



Focusing wavelength of a FODO linac

FODO linac with beam entering with an offset



Betatron wavelength is to be compared with wavelength of misalignment

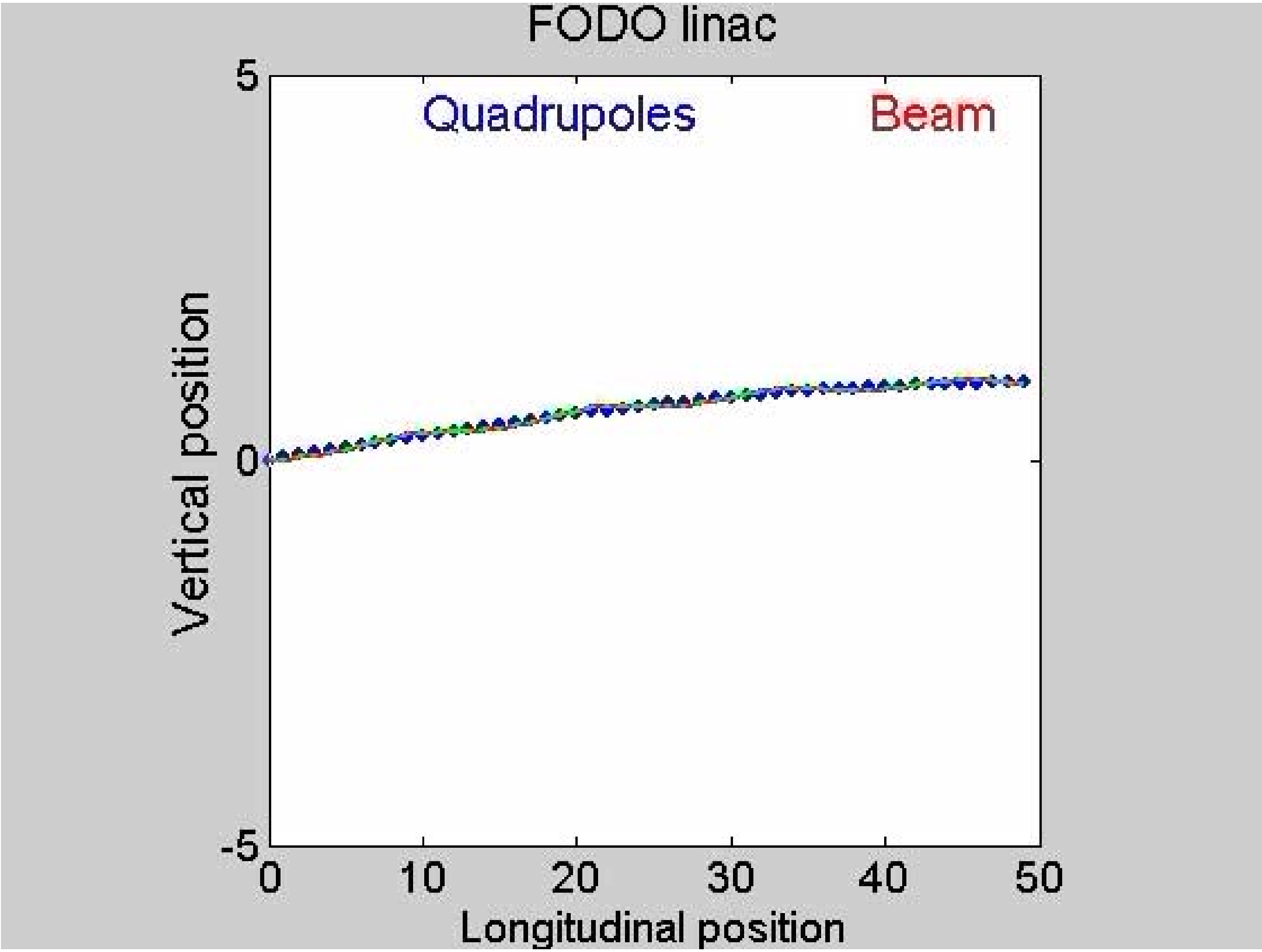
Movie of a Misaligned FODO linac

NLC

Note:

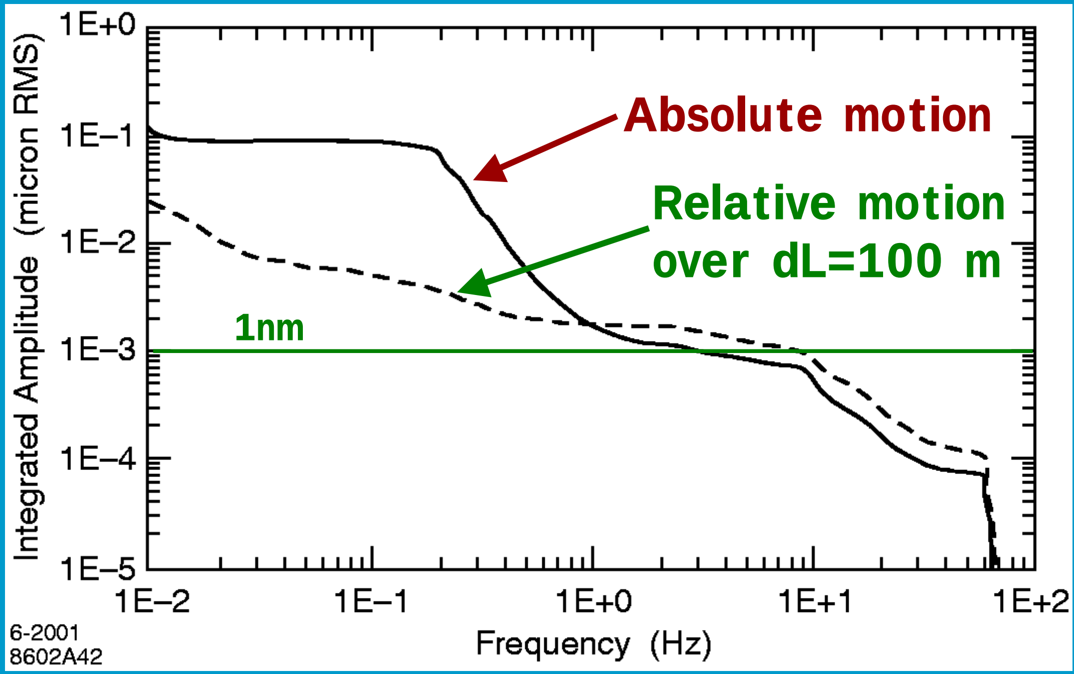
Beam follows the linac if misalignment is more smooth than betatron wavelength

Resonance if wavelength of misalignment ~ focusing wavelength



Slow motion is well correlated, i.e. its wavelength is long…

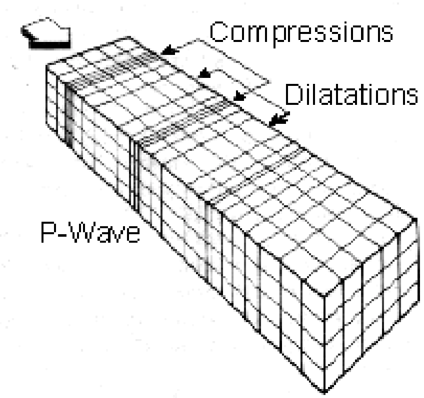
- **Effect of slow motion suppressed because**
  - It is slow and can be corrected out
  - Its wavelength is longer than betatron wavelength
- **Beneficial to have good correlation (longer wavelength)**



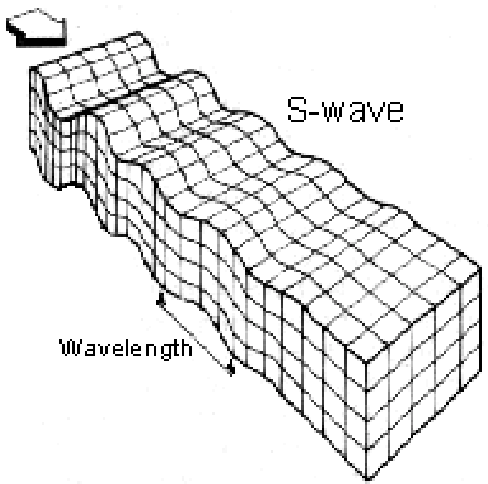
Integrated (for $F>F_o$) spectra. SLC tunnel @ SLAC

Waves in infinite homogeneous elastic media

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



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



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

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

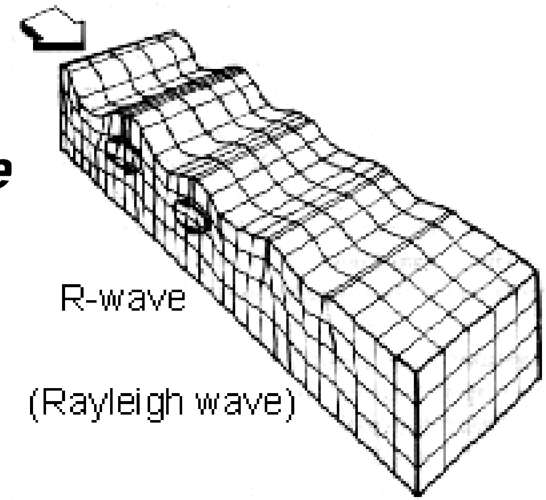
Here ρ- density, G and λ - Lame constants: $$G = \frac{E}{2(1+\nu)} \qquad \lambda = \frac{\nu E}{(1+\nu)(1-2\nu)}$$

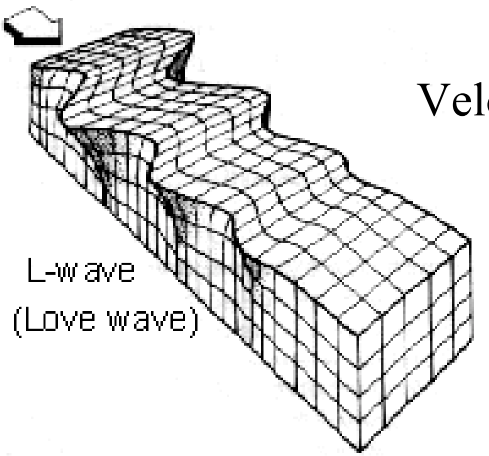
E-Young's modulus, ν - Poisson ratio

NLC

Waves in elastic half-space

In addition to p-waves and s-waves,
the half-space can also withstand the waves
that propagate and localized ***near the surface***





Velocity of propagation $v_R \approx v_S$

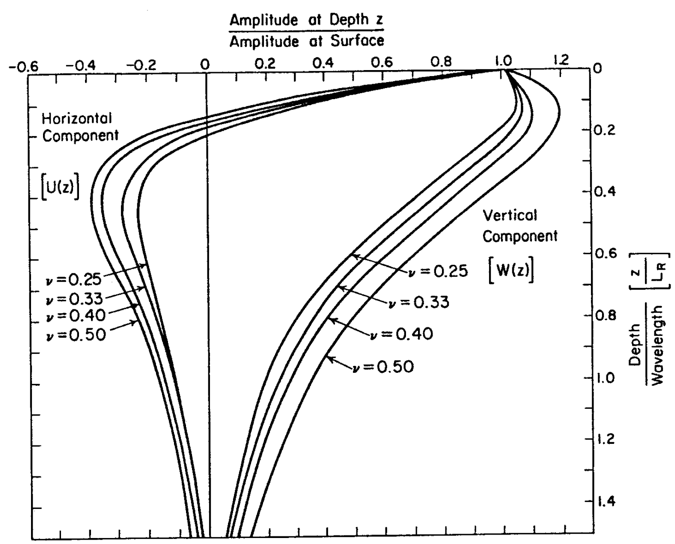


Figure 3-14. Amplitude ratio vs. dimensionless depth for Rayleigh wave.

Amplitude of Rayleigh wave decrease **exponentially** with depth

Ground motion vs geology, location, depth

- **Geology: hard rock is preferable**

  => fast motion is better correlated (as v larger and λ longer)

- **Location**:

  => avoid external <u>cultural noise</u>, especially for shallow tunnel

- **As geology and noise depend on depth, we have one more degree of freedom**

What is best way to hide from external cultural noises?

NLC

Attenuation of waves:

$$\sqrt{\frac{r_0}{r}}\exp\left(-\frac{\pi(r-r_0)}{Q\lambda}\right)\exp\left(-\frac{h}{\lambda}\right)$$

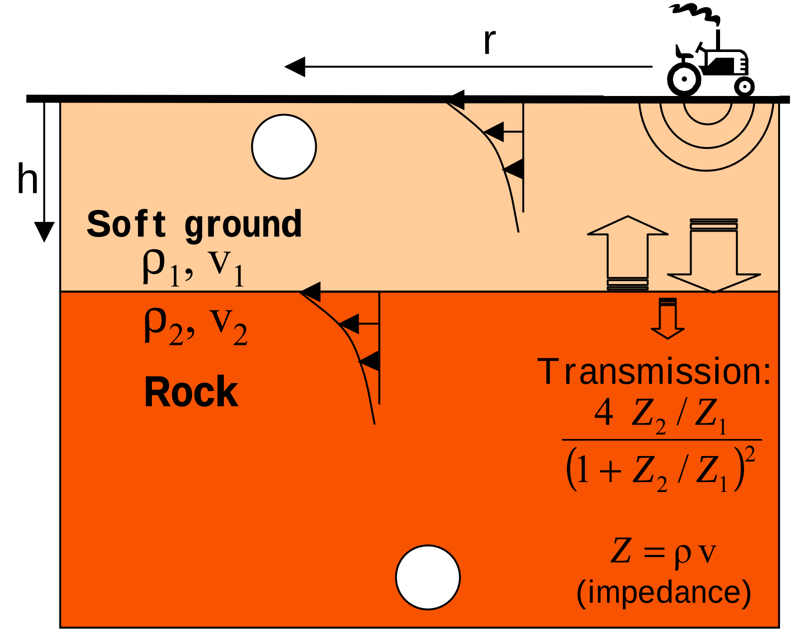
Rayleigh on-surface

geometric — dissipative

$$\frac{r_0}{r}\exp\left(-\frac{\pi(r-r_0)}{Q\lambda}\right)$$

p- or s-waves in depth

λ – wavelength; v – sound velocity; $r_0 \sim \lambda/2$; Q – can be 10 – 25 for near surface ground and up to hundreds for bedrock



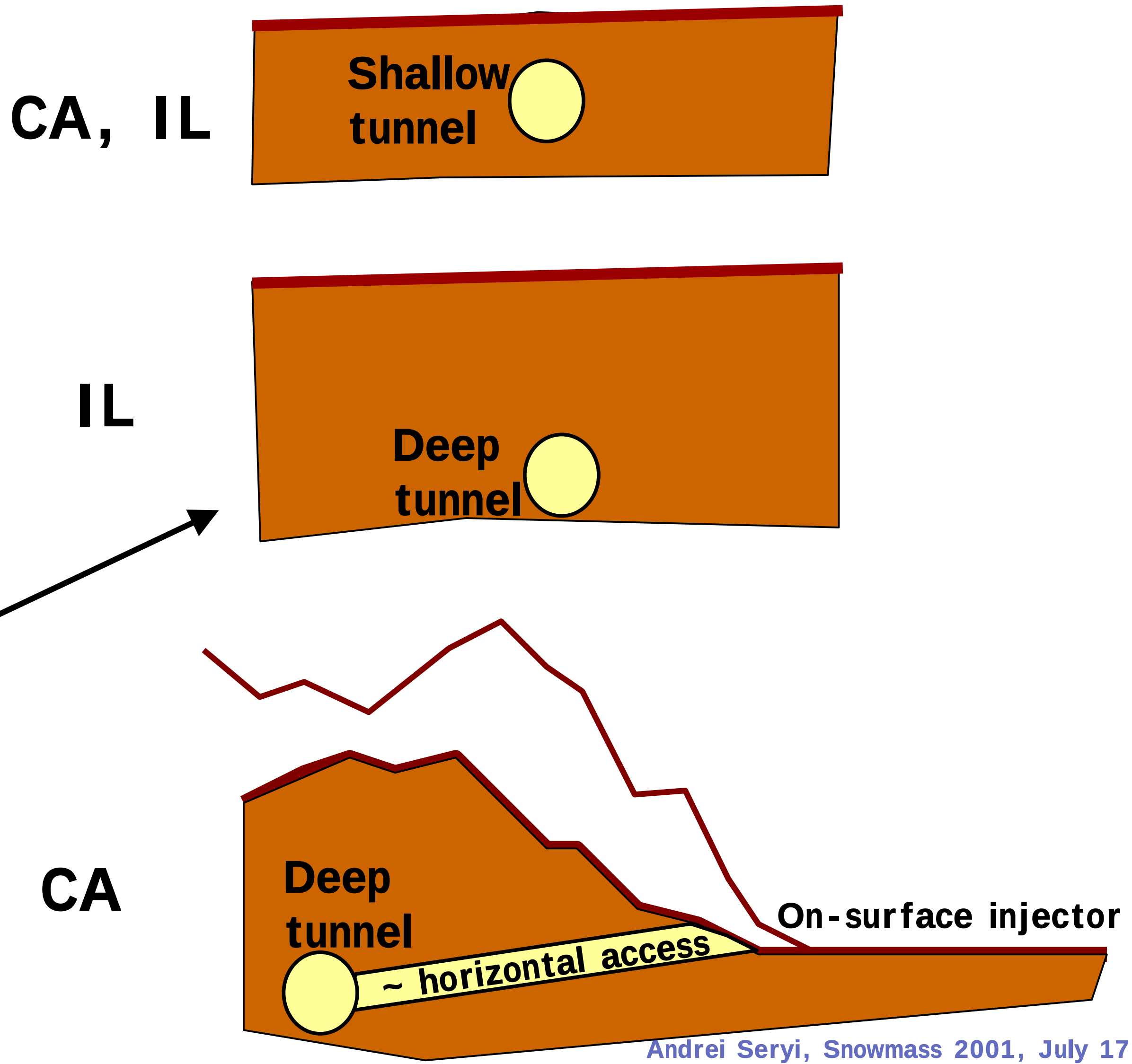
- **Attenuation of on-surface waves is slower than in-depth waves**
- **Typical layered ground structure helps prevent noise penetration to lower layers**
- **Top layers may have resonances**
- **Go deep if cannot go far from noise**

Ideally, the impedance of the top layer(s) should be << than of the lower layers

100m depth may be worth many km in r

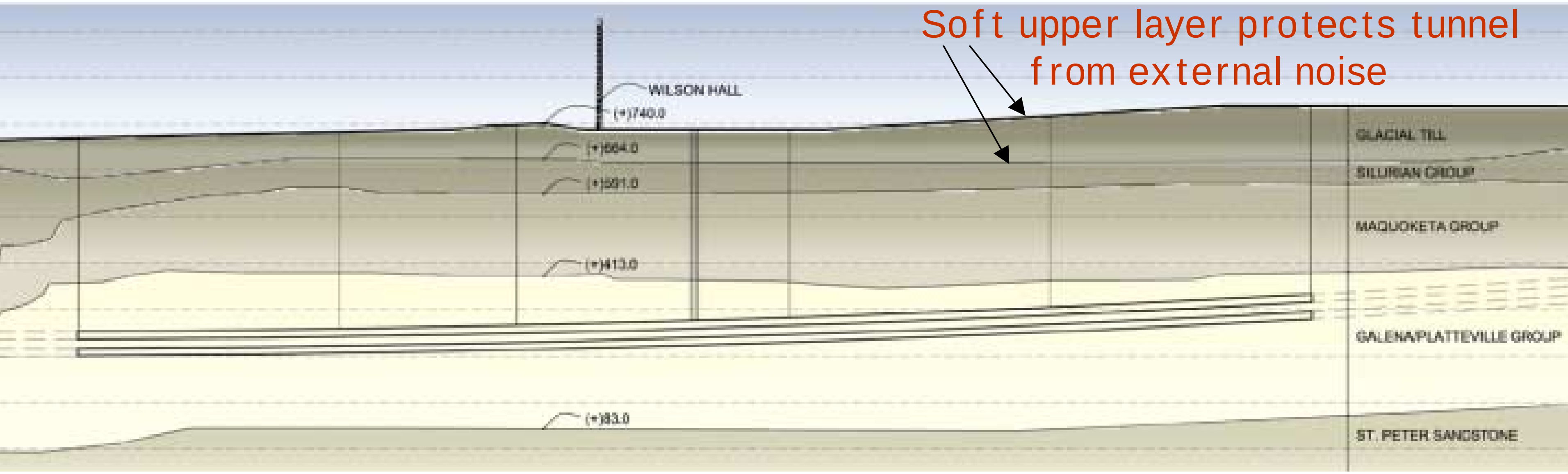
NLC sites & Ground motion

- **NLC sites considered in California and Illinois so far:**



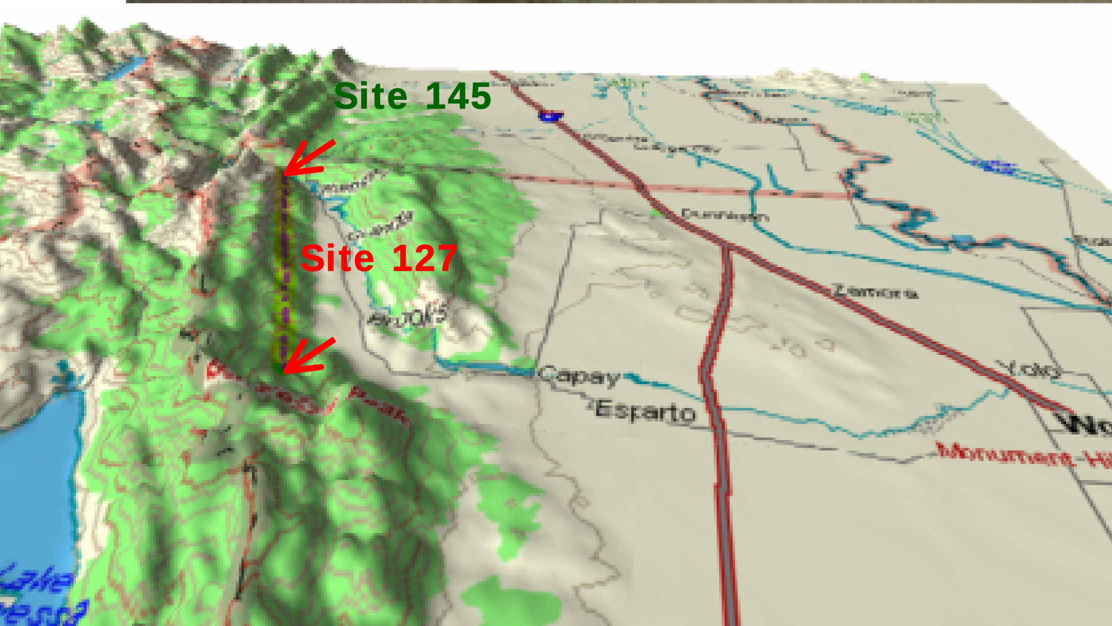
Also considered for VLHC

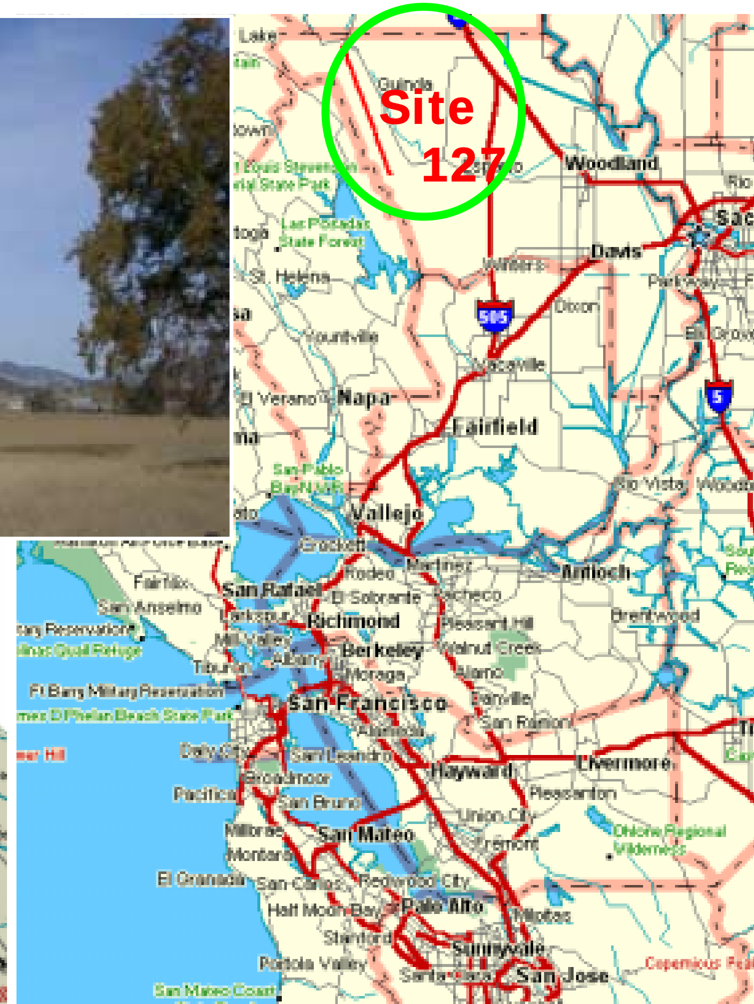
NLC deep tunnel @ Fermilab



- Tunnel is placed **~100m deep in geologically (almost) perfect Galena Platteville dolomite platform**
- **Top ground layer is soft** (NUMI geological studies : v_2/v_1 ~ 5/1 for 1st transition) – **this increase isolation from external noises**
- When choosing depth – **optimize** not only for boring conditions, but **also for vibration attenuation – each layer makes tunnel more quiet**

NLC deep tunnel CA sites 127&145





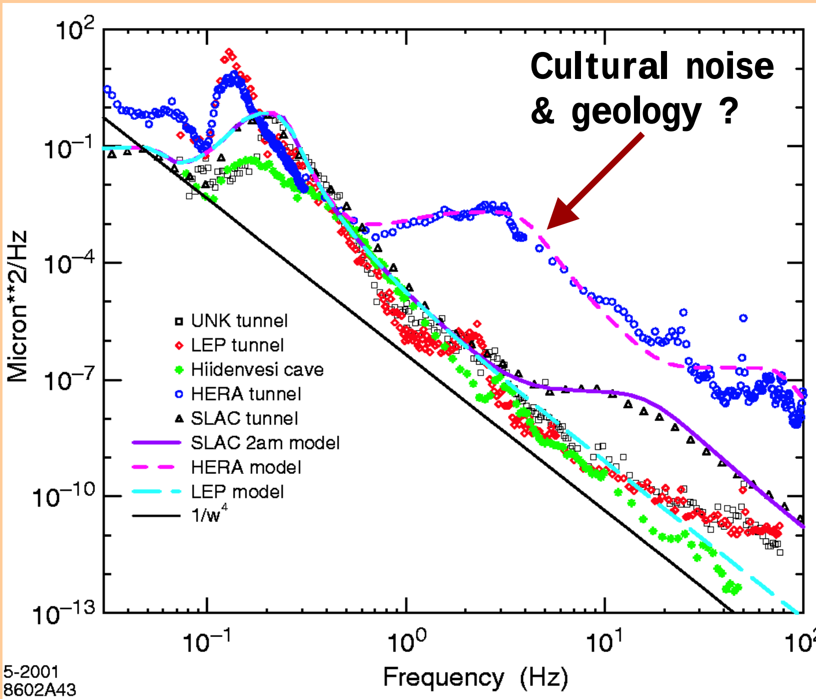
Fast Ground Motion again
geology & cultural noise

- **Deep tunnels are quiet**
  - **Care about in-tunnel noise**

- **Shallow (not deep) sites usually noisy**
  - **Because of cultural noise**
  - **Resonance of clay/sandy site itself**

- **E.g. resonance of LIGO sites:**
  - **1-5Hz Livingston LIGO site (water logged clay)**
  - **5-12Hz Hanford LIGO site (dry sand)**

(Courtesy LIGO & F.Asiri)

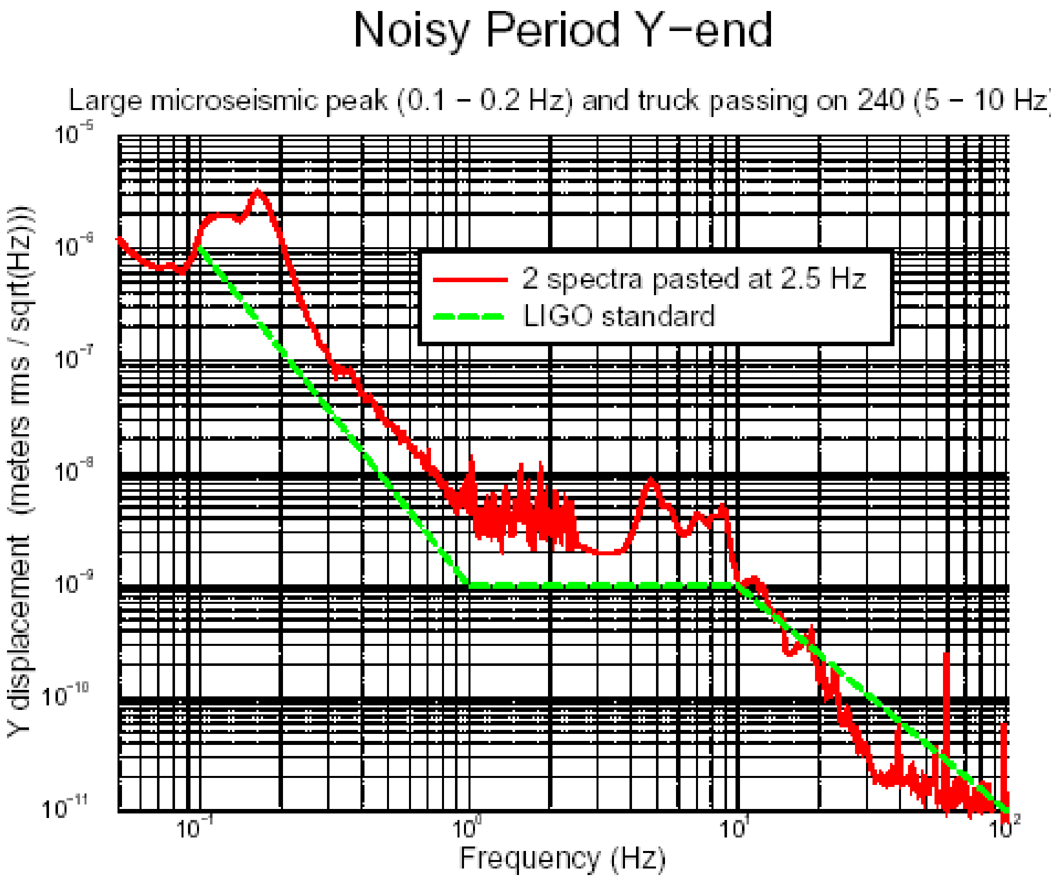


- **Resonance (?) of sandy HERA site + cultural noise may be reason for large noise at DESY**

- **Relative motion ~ 100nm, F>1Hz**

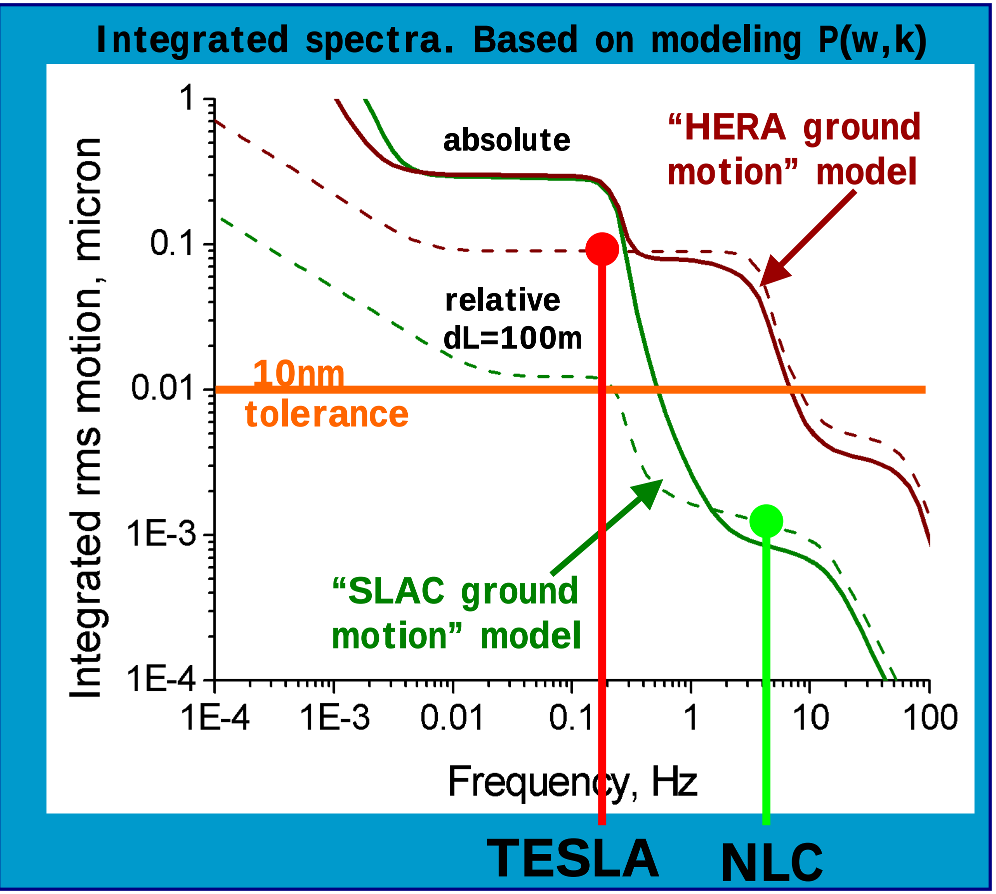
Resonance of shallow sites

- **Resonance of LIGO sites:**
  - **1-5Hz Livingston LIGO site (water logged clay)**
  - **5-12Hz Hanford LIGO site (dry sand)**



(Courtesy LIGO & F.Asiri)

Fast Ground Motion in NLC and TESLA



For linac quadrupoles, tolerance roughly 10nm for both (-> $0.25\sigma_y$ NLC ; $0.1\sigma_y$ TESLA)

Rep.Rate of bunch trains:

120Hz @ NLC -> F_C ~ 6 Hz

5Hz @ TESLA -> F_C ~ 0.2 Hz

NLC is OK at quiet site

For TESLA, motion above tolerance even at ~quiet site

But hopefully TESLA can rely on fast correction within bunch train (rep.rate of bunches 3 MHz F_C -> 100kHz)

Differences of approach to collision stability

- **TESLA**
  - Cannot rely on quiet site
  - Rely on fast correction within bunch train

Both require good girders
(low amplification by cryostat)

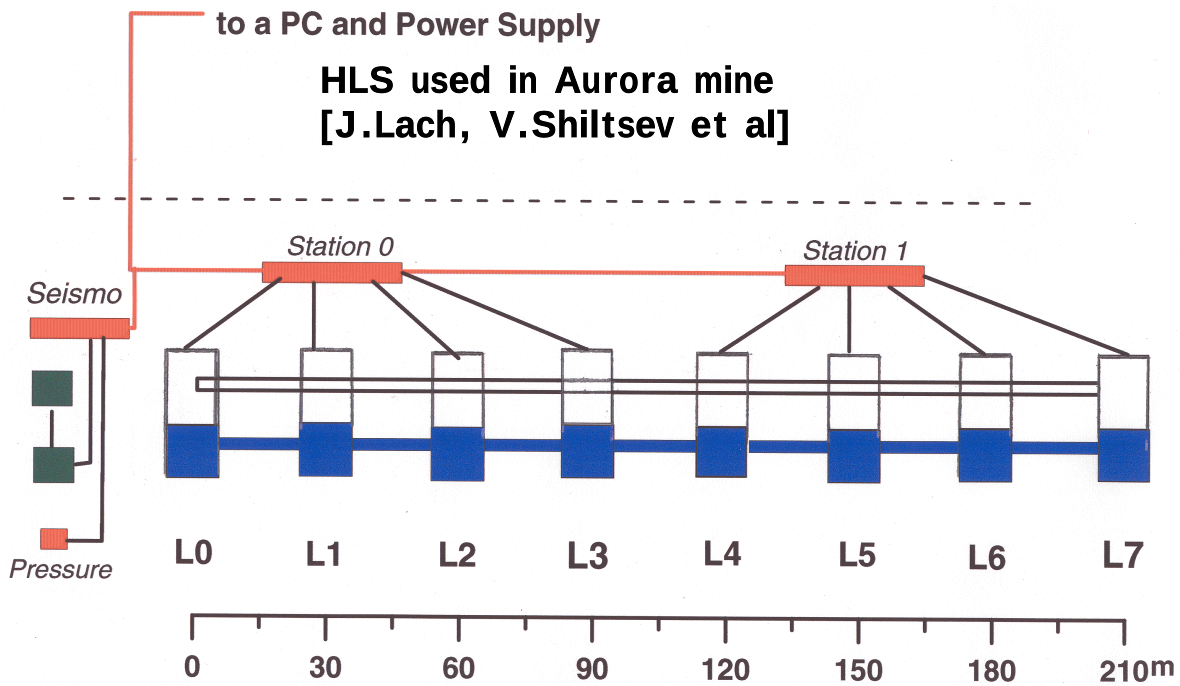
- **NLC**
  - Rely on quiet site
  - Actively stabilize final doublets
  - In addition, use fast correction within bunch train
    (more difficult because of 1.4ns bunch separation)

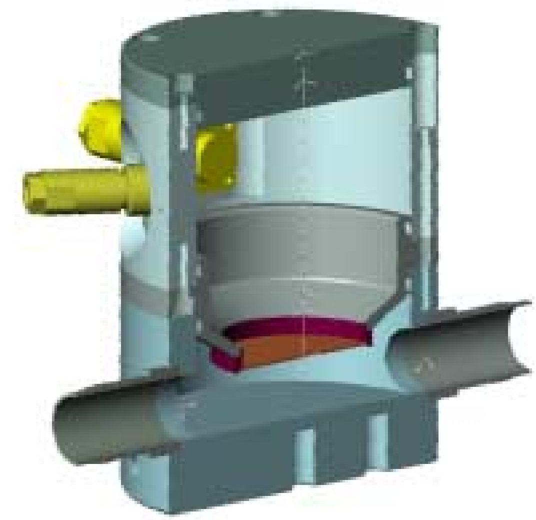
Slow motion (minutes - years)

- **Diffusive** or **ATL** motion: $\Delta X^2 \sim ATL$ **[Baklakov et al.]**
  (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**

- **Systematic** motion [R.Pitthan] : ~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

How one would measure slow motion?
Example: Hydrostatic level system



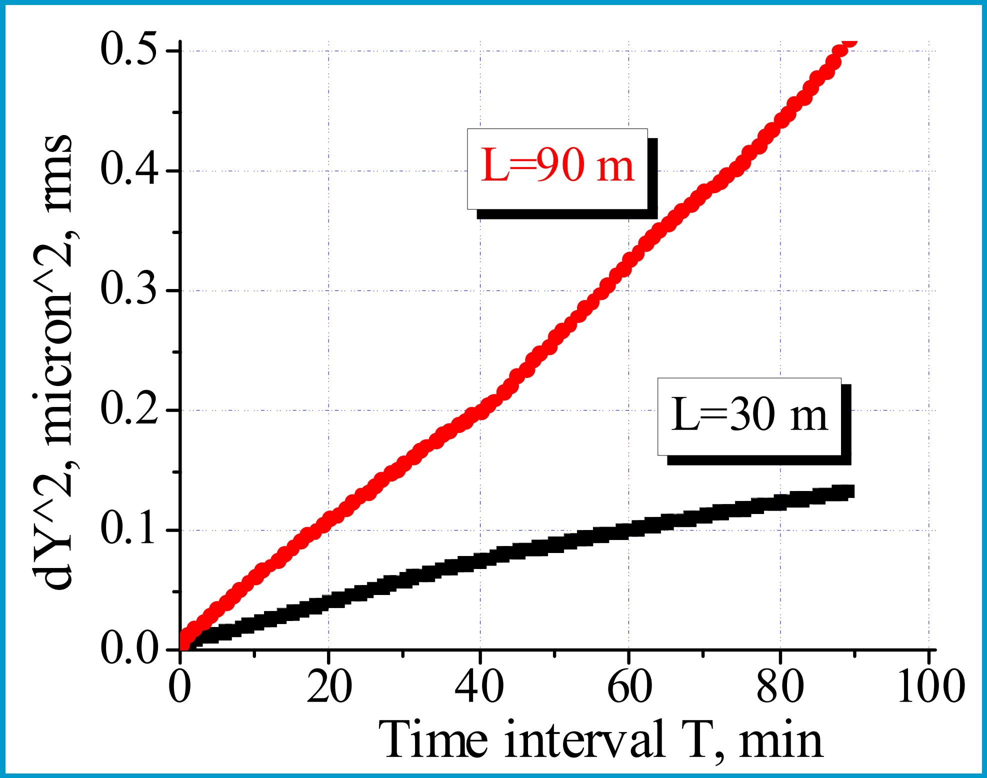


Single tube version

New HLS developed at Budker INP that will be used in further studies

Slow motion
example: Aurora mine

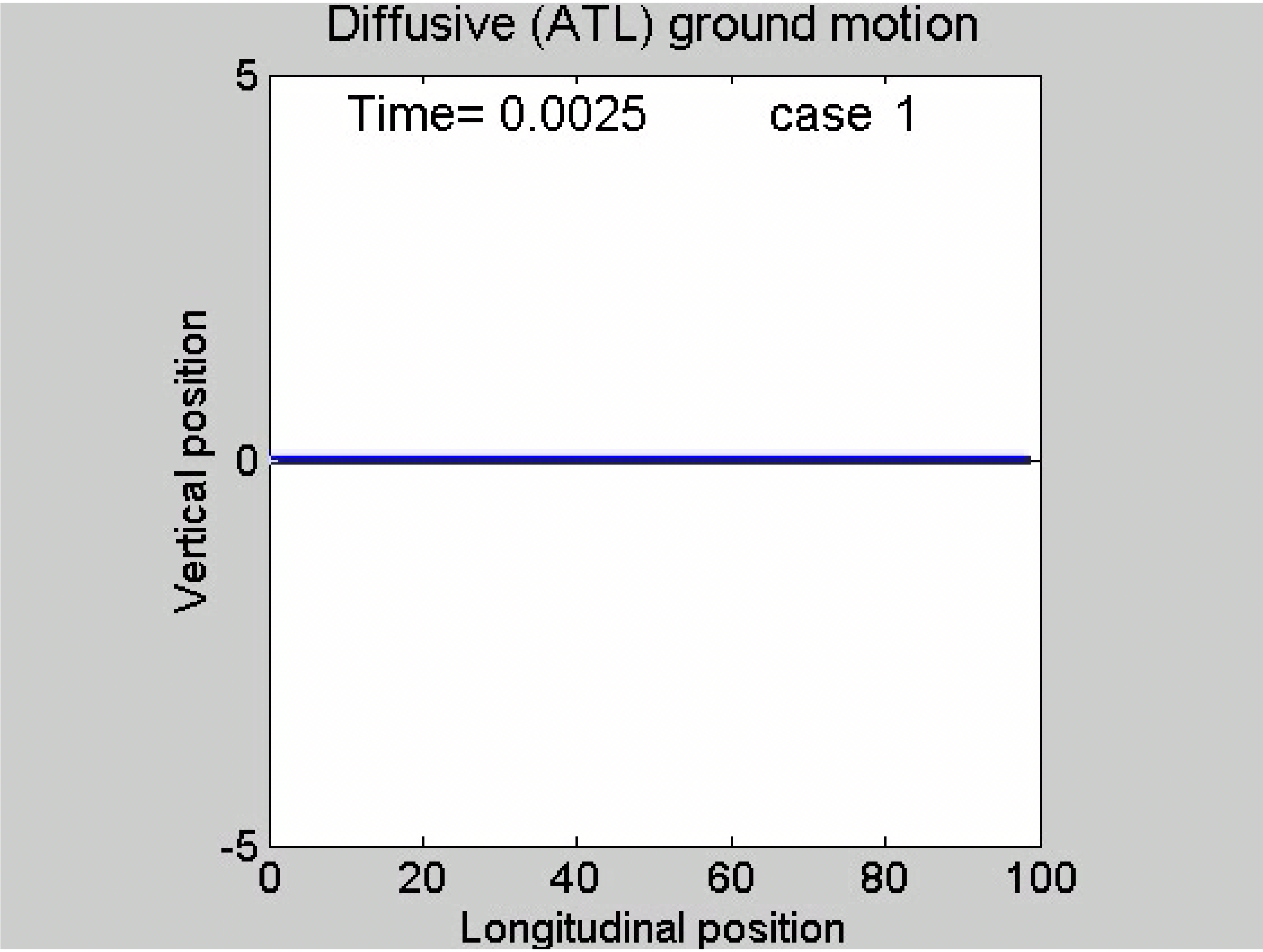
- **Slow motion in Aurora mine exhibit ATL behavior**
- **Here A~ $5*10^{-7}$ $\mu m^2/m/s$**



Slow motion in Aurora mine [J.Lach, V.Shiltsev et al] . Measured by hydrostatic level system.

Diffusive or ATL motion

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



Systematic motion
SLAC linac tunnel in 1966-1983

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

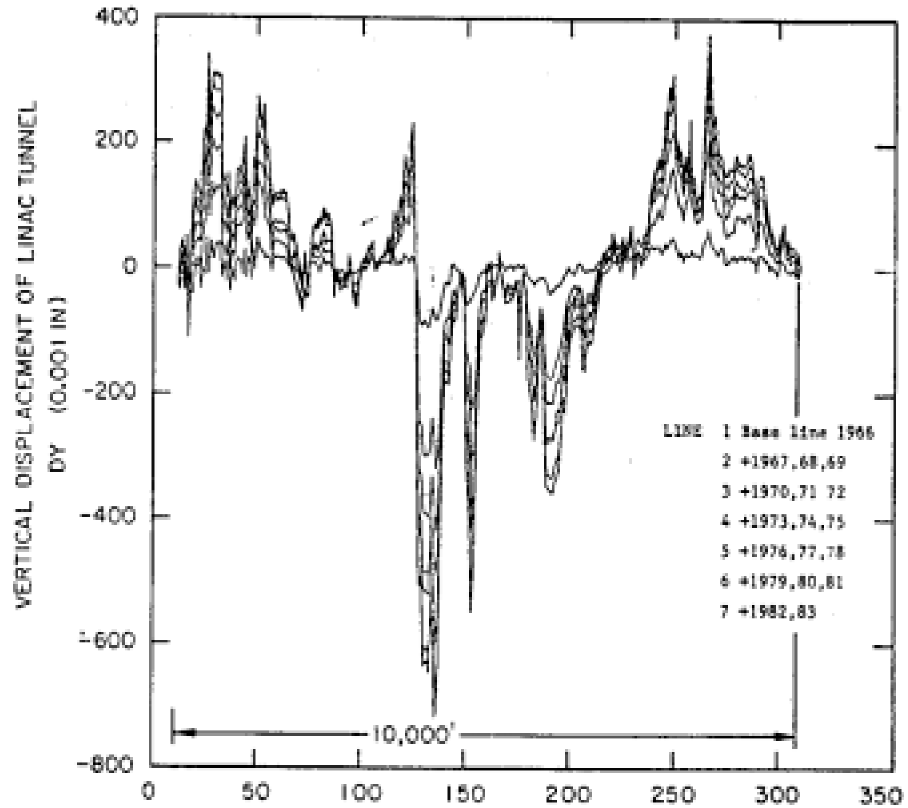


Figure 7: Displacement of the SLAC Linac Tunnel - Vertical.

Vertical displacement of SLAC linac for 17 years

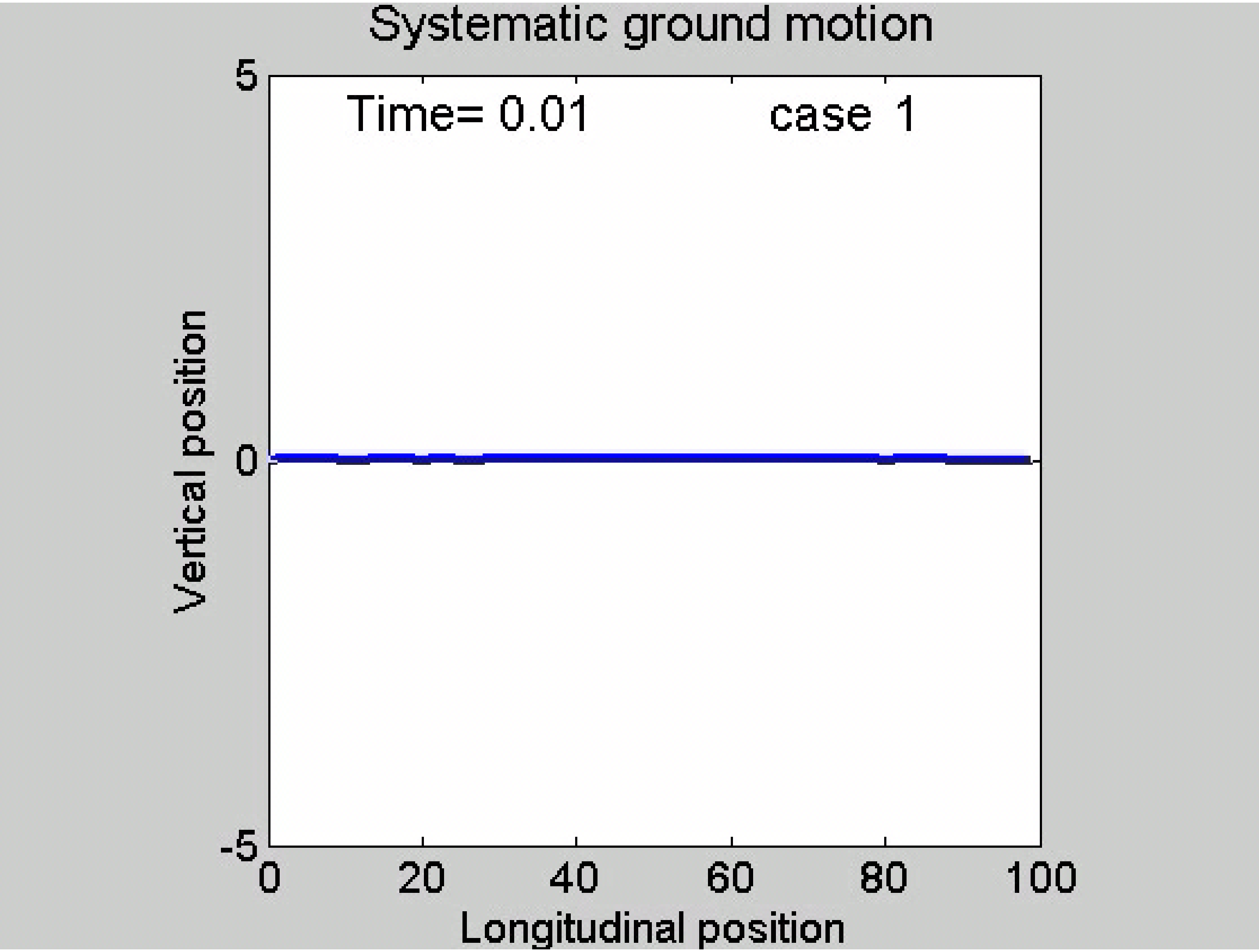
[G.Fischer, M.Mayond 1988]

Systematic motion

- Movie of simulated systematic motion

- Note that final shape may be the same as from ATL

- And it may resemble…



NLC

And in billion years...

Topography of many natural surfaces exhibits $\Delta X^2 \sim A\ L$ behavior

...

$$G(\omega) = 2\pi k/\omega^2 = (k/2\pi)\lambda^2$$
$$\text{or } G(1/\lambda) = k\lambda^2 \qquad (2)$$

in agreement with experiment (Figure 2.).

We call k the 'topothesy' of the surface (τοποθεσια, a description of a place or region[17]). Its value uniquely defines the statistical geometry of the random components of an isotropic surface for any given range of wavelengths. The topothesy has units of length. It seems able to characterise successfully and completely, examples of surface structures of a wide range of sizes (Fig. 2) drawn from throughout the physical universe.

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Nature Vol. 271 2 February 1978

Surface topography as a nonstationary random process

TOPOGRAPHY is often considered as a narrow bandwidth of features covering the form or shape of the surface. After detailed study of many measurements we consider that as well as the possibility of a dominant range of features there is always an underlying random structure where undulations in surface height continue over as broad a bandwidth as the surface size will allow. We consider this a result of many physical effects each confined to a specific waveband but no band being dominant. We invoke the central limit theorem and show through Gaussian statistics that the variance of the height distribution of such a structure is linearly related to the length of sample involved. In another form, the power spectral density, this relationship is shown to agree well with measurements of structures taken over many scales of size, and from throughout the physical universe. ...

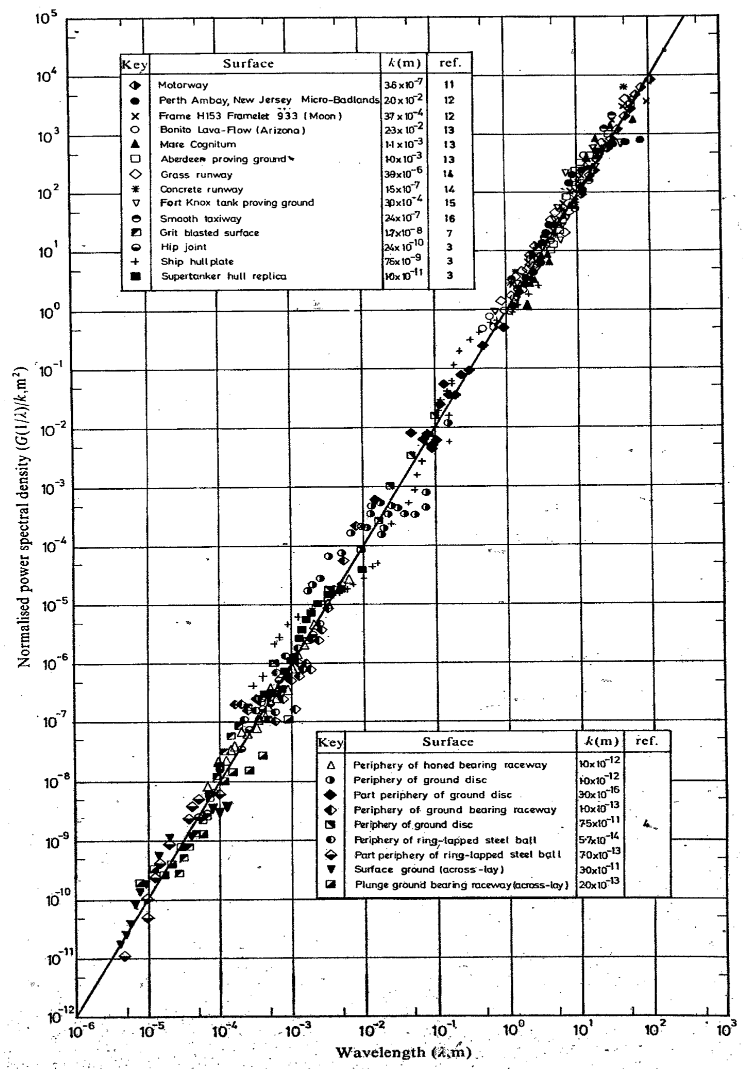
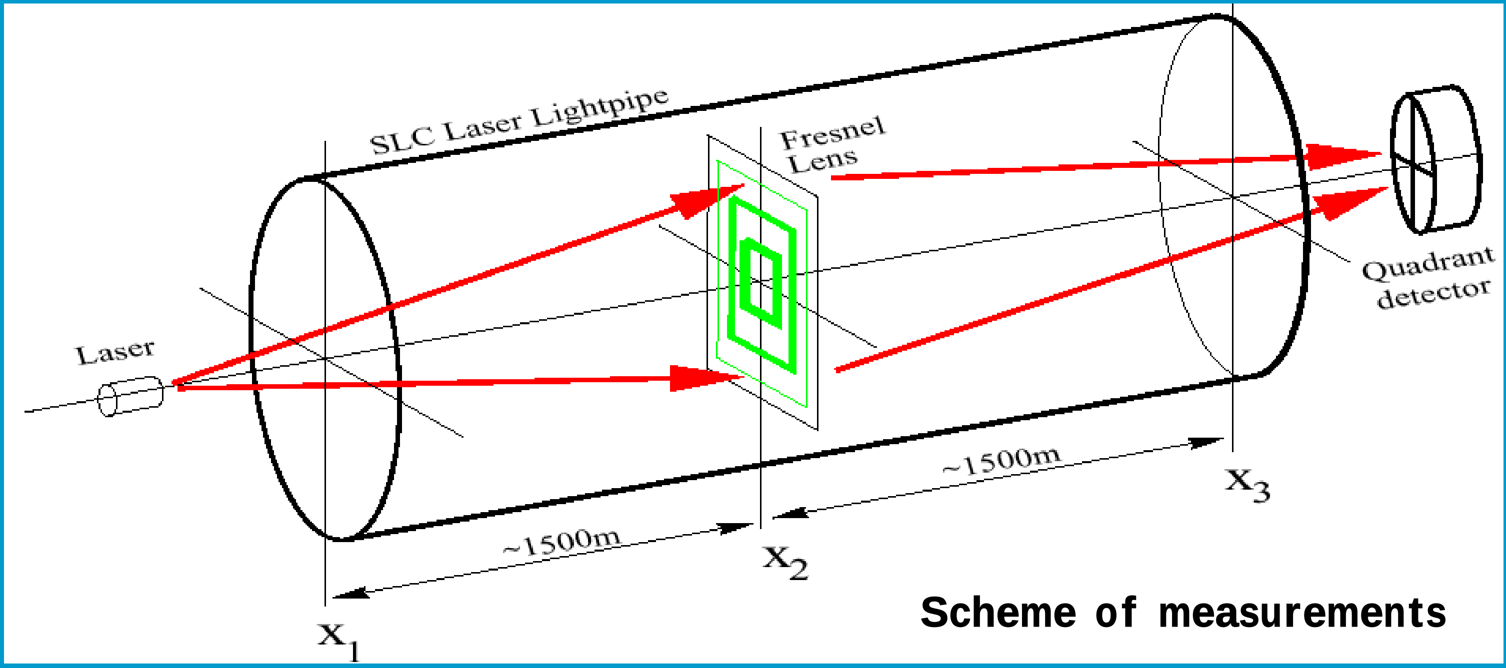


Fig. 2 Variation of normalised power spectral density ($G(1/\lambda/k$, m²) with wavelength (λ, m). The graph shows that many different surface topographies existing in the physical universe have a similar form of power spectrum. Note that the spectra available cover almost eight decades of surface wavelength and throughout this range the r.m.s. power increases, to a good approximation, as the square of the wavelength (solid line, equation (2)).

SLAC tunnel drift studies



Scheme of measurements

Signals from the quadrant photo detector were combined to determine X and Y relative motion of the tunnel center with respect to its ends

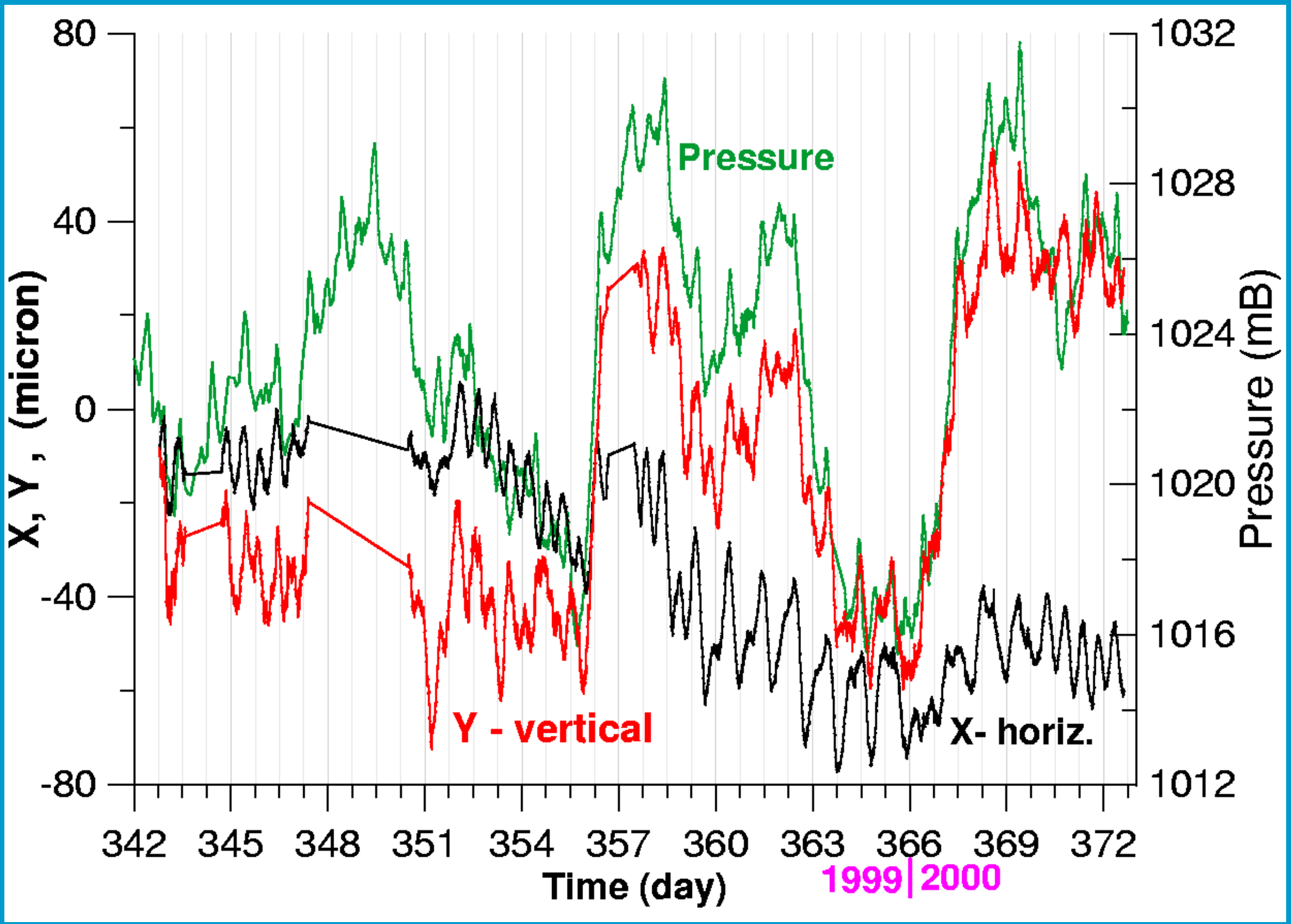
Slow transverse relative drift of SLC tunnel

NLC

SLC tunnel deformation is correlated with atmospheric pressure

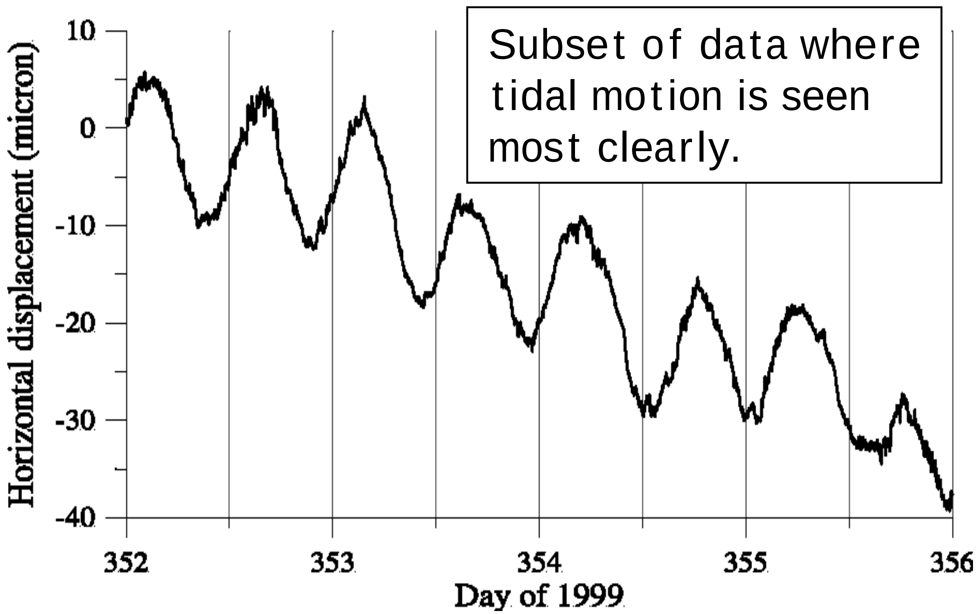
Reason:
landscape and ground property vary along the linac

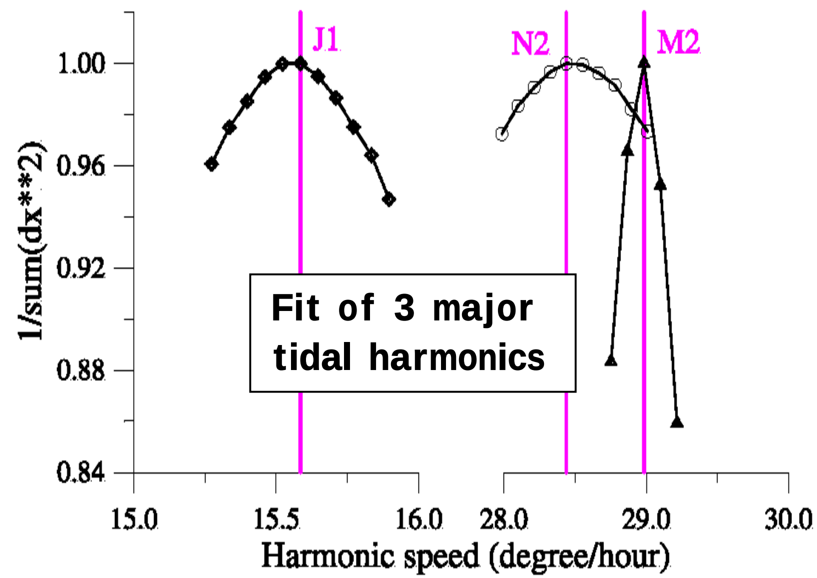
Motion shows diffusive or ATL character



Transverse displacement of the 3 km SLAC linac tunnel (center w. respect to ends) and atmospheric pressure.

Tidal motion of the SLAC linac tunnel

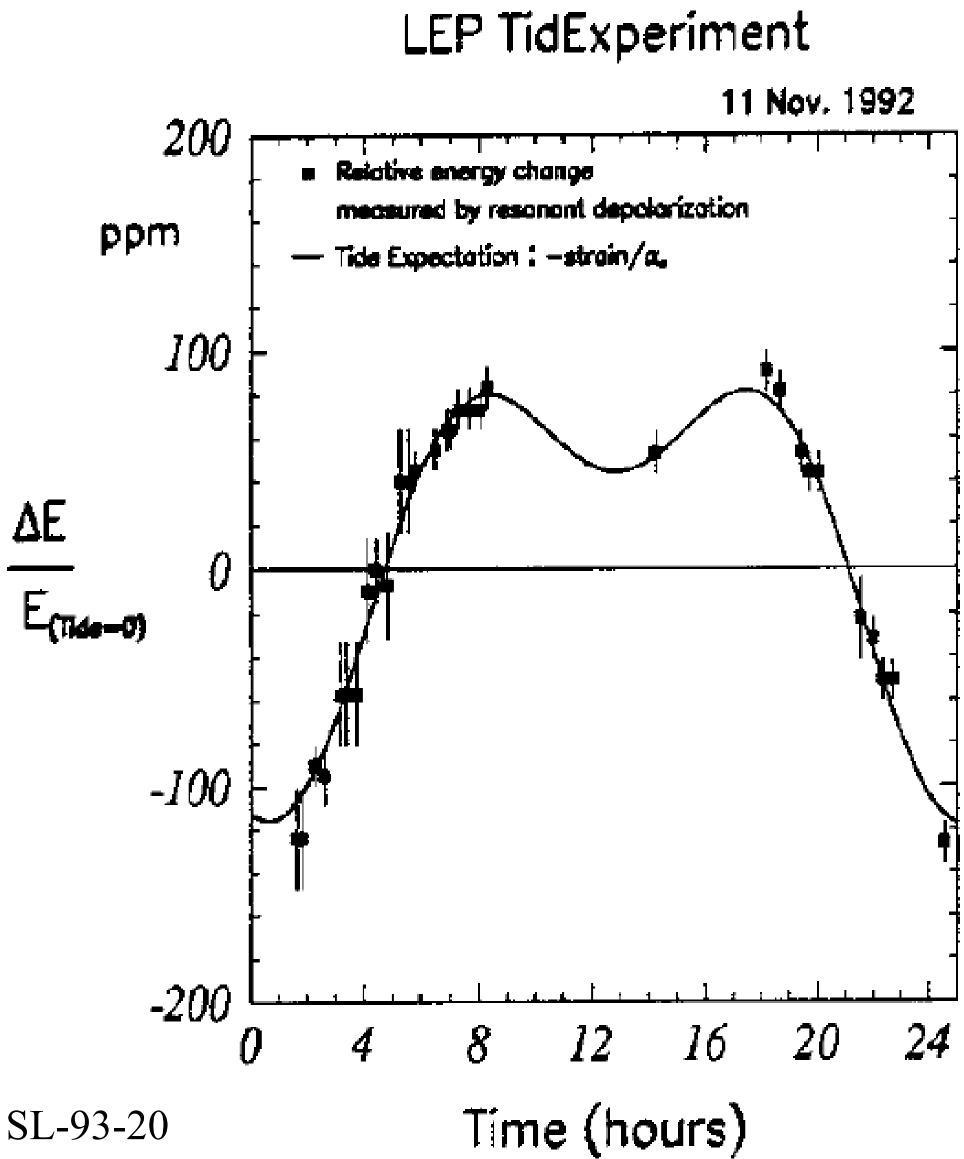




- Second order effect (curvature change)
- Observed tidal motion ~100 times larger than expected for oceanless Earth
- Enhanced by tidal motion of ocean water that produce additional loading in vicinity (~500km) of the shoreline
- Tidal motion is slow, predictable, it has long wavelength and is not a serious problem for a collider

Tidal motion observed by LEP

- Change of LEP energy due to change of LEP circumference
- First order effect (stretching)
- Surface move +-0.25m
- Change of LEP circumference ~1mm



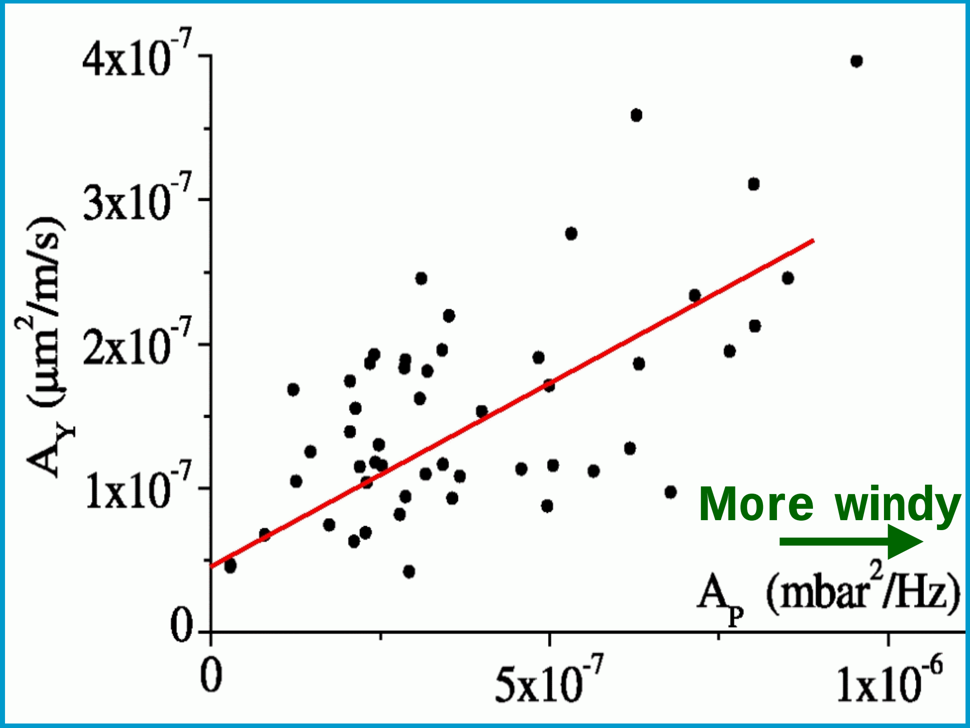
L.Arnaudon, et al. CERN SL-93-20

Atmosphere causes "A" of ATL to vary in shallow tunnel

NLC

- **Parameter A_D of ATL correlates** with amplitude of **atmospheric pressure variation**

- For **deep tunnel** the **atmospheric contribution** to A_D should **vanish**



"A" vs amplitude of atmospheric pressure spectrum A_p (which behaves as A_p/ω^2)

'Slow' Ground motion at NLC and TESLA

NLC

- **Diffusive or ATL motion: $\Delta X^2 \sim A_D T L$**
- **Produce misalignments and result in emittance growth**
- **TESLA : Low wakes -> smaller σ_E and $\Delta\varepsilon$ ($\sim \sigma^2_E$)**

Place	**A** $\mu m^2/(m \cdot s)$
HERA R.Brinkmann,et al.	$\sim 10^{-5}$
FNAL surface V.Shiltsev,et al.	$(1\text{-}10)*10^{-6}$
SLAC*	$\sim 5*10^{-7}$
Aurora mine* V.Shiltsev,et al.	$(2\text{-}20)*10^{-7}$
Sazare mine S.Takeda,et al.	$\sim 5*10^{-8}$

TESLA: Undisruptive realignment ~every month — OK for TESLA

NLC: Undisruptive realignment ~every 5hrs — OK for NLC

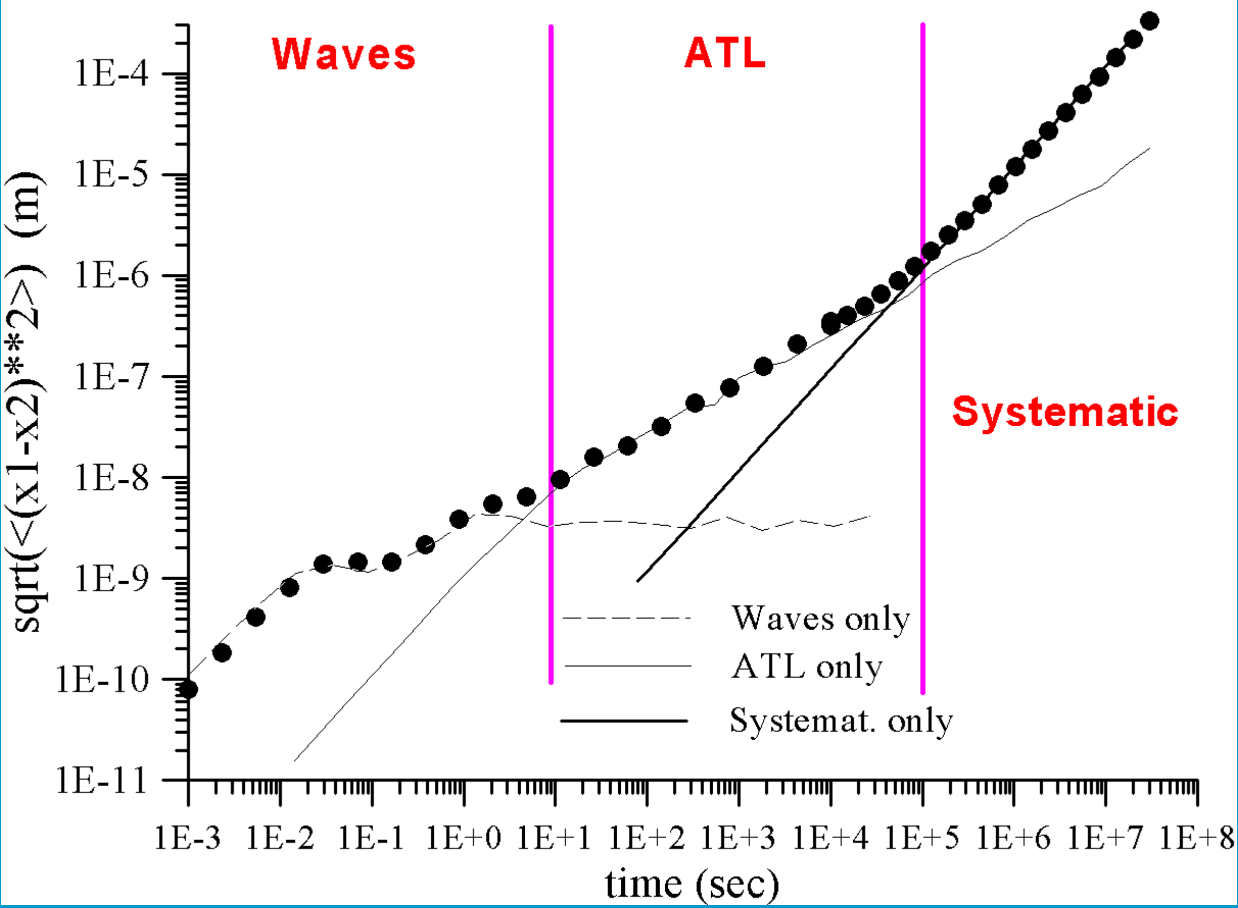
NLC: Undisruptive realignment ~every 2 days

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

Undisruptive = can collide while realigning

Three types of motion in one model

- A ground motion model based on P(ω,k) spectrum can be build



<x^2> for SLAC site ground motion model for ΔL=30m versus ΔT

Slow motion questions and recommendations

NLC

- Reasons for slow motion
  - Atmosphere, underground water, dissipation of high frequency motion. What else?

- Dependence on geology, tunneling
  - **Geology: good hard rock is preferable**
    => slow motion has lower amplitude
    => collider stability time is larger
  - **Tunneling**:
    => TBM preferable; avoid blasting

One need to firmly connect to ground by good girders

- FFTB quad
  Only 2nm difference to ground
  (on movers, with water flow)

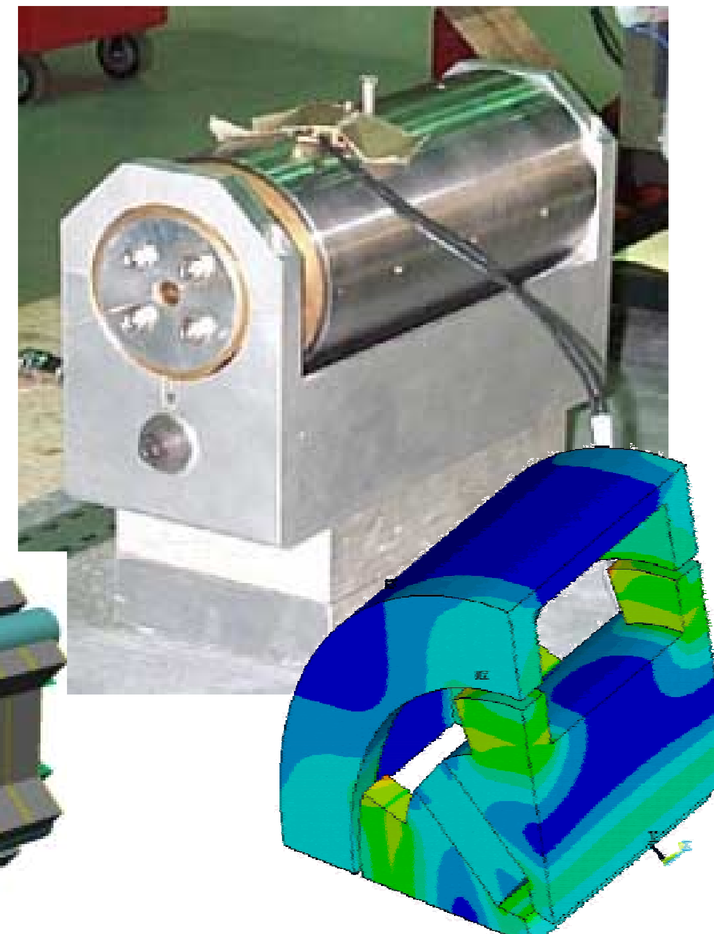
- **Further improvements: lower water flow, lower girder, permanent quad**

Linac quads need to be quiet & near vibration free

- Low water flow EM quads
- NLC **P**ermanent **M**agnet linac quad prototype

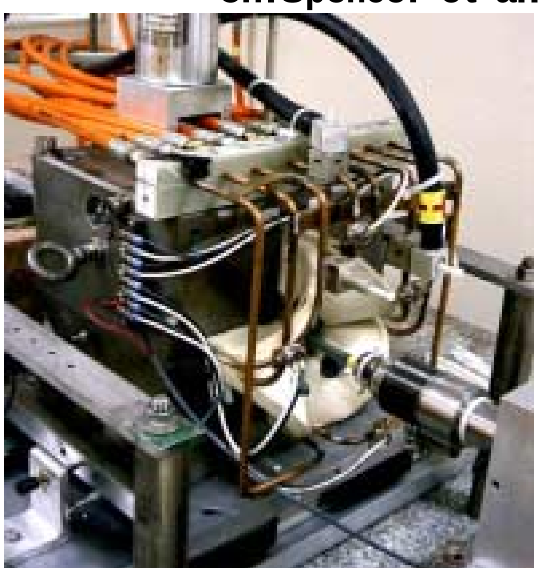
NLC PM sliding shunt quad

J.Volk et al., FNAL

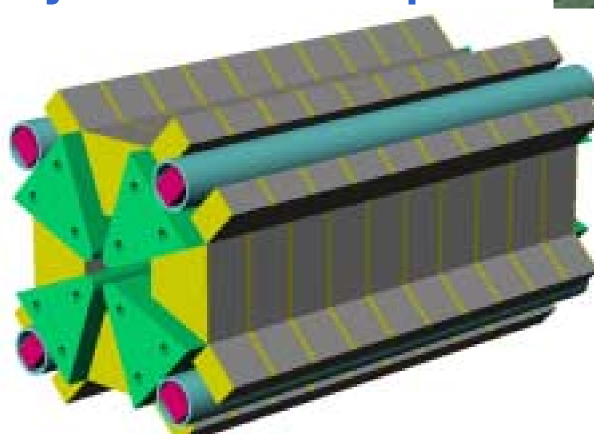


NLC linac EM quad

Ch.Spencer et al.



NLC linac corner adjustment PM quad



Conventional Facilities in&near tunnel noise need to be minimized

NLC

- **Need to minimize CF noises**
- **Unusual practice for accelerators, but**
- **Inexpensive solutions exist**
- **Successfully used in LIGO**
- **Can be applied to NLC**

Chiller equipment at the LIGO Hanford site

4Hz spring isolator

Courtesy: LIGO

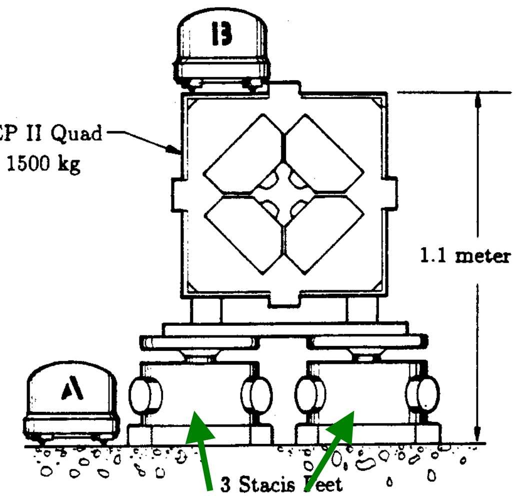
LIGO = Laser Interferometer Gravitational-wave Observatory)

NLC

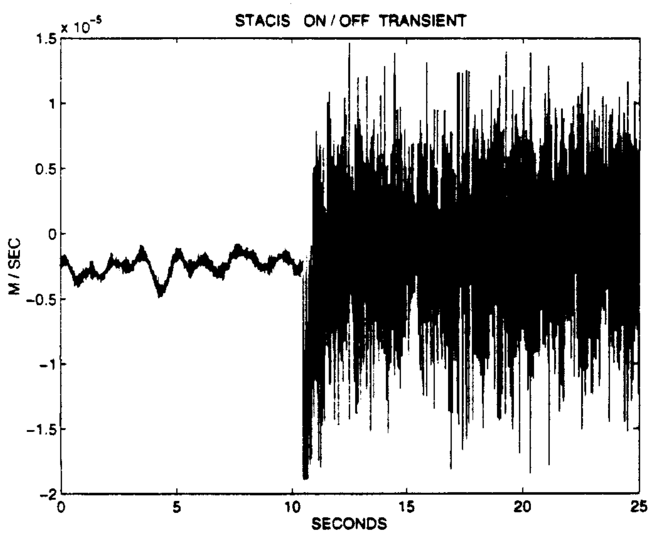
Stability of Final Doublet need to be provided by active methods

- **FD feedback position stabilization and/or feedforward magnetic center correction**

- **1996 – tests of STACIS**
- **Achieved:**
  40nm -> **2nm for** f>2Hz
  (in noisy room)



TMC STACIS
Active Piezoelectric
Vibration Control System



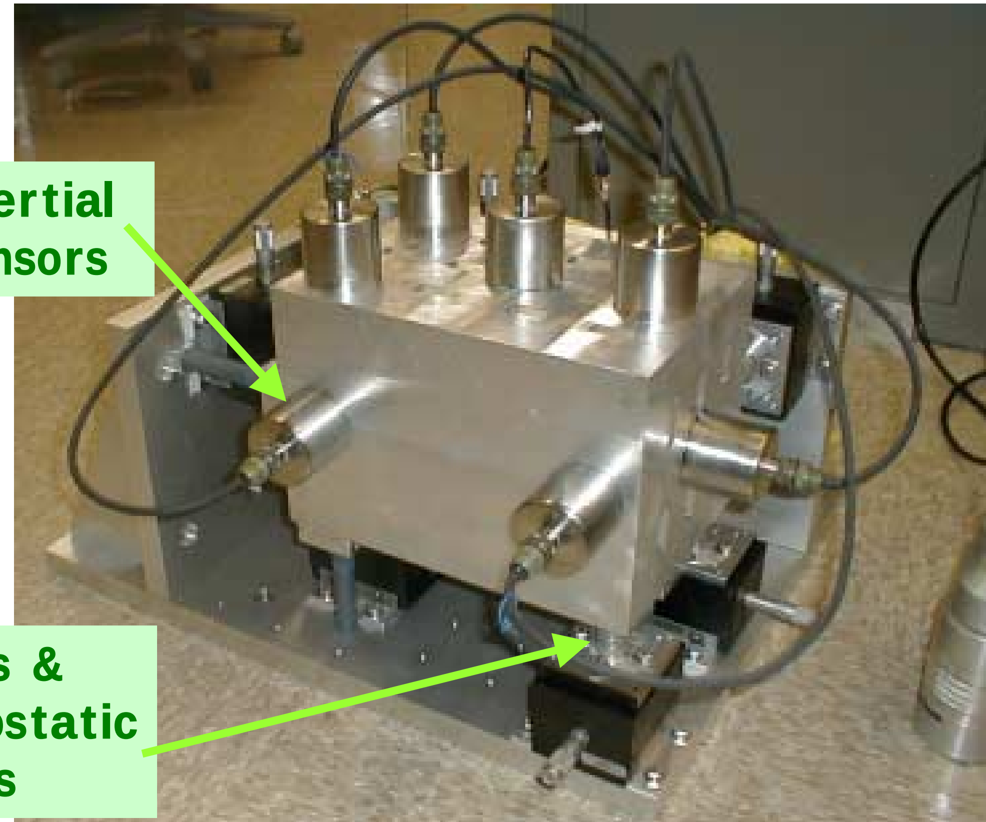
G.Bowden, et al. 96

- **2000-2001- develop digital feedback stabilization; compact; will optimize for 2 long FD; high magnetic field compatible**

Inertial digital feedback is one of ways to keep Final Doublets steady

NLC

- Inertial stabilization in 6D at SLAC for NLC

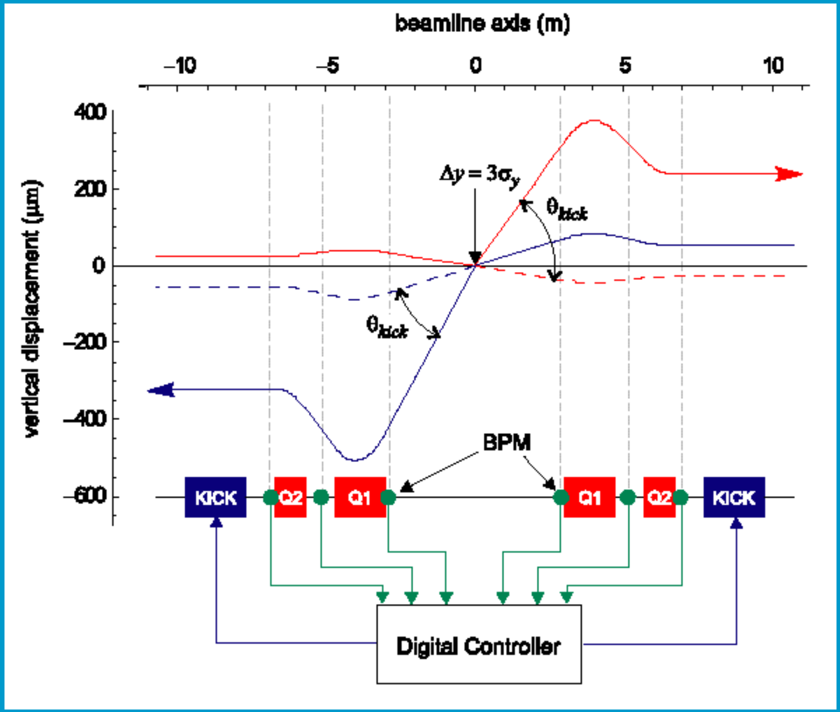


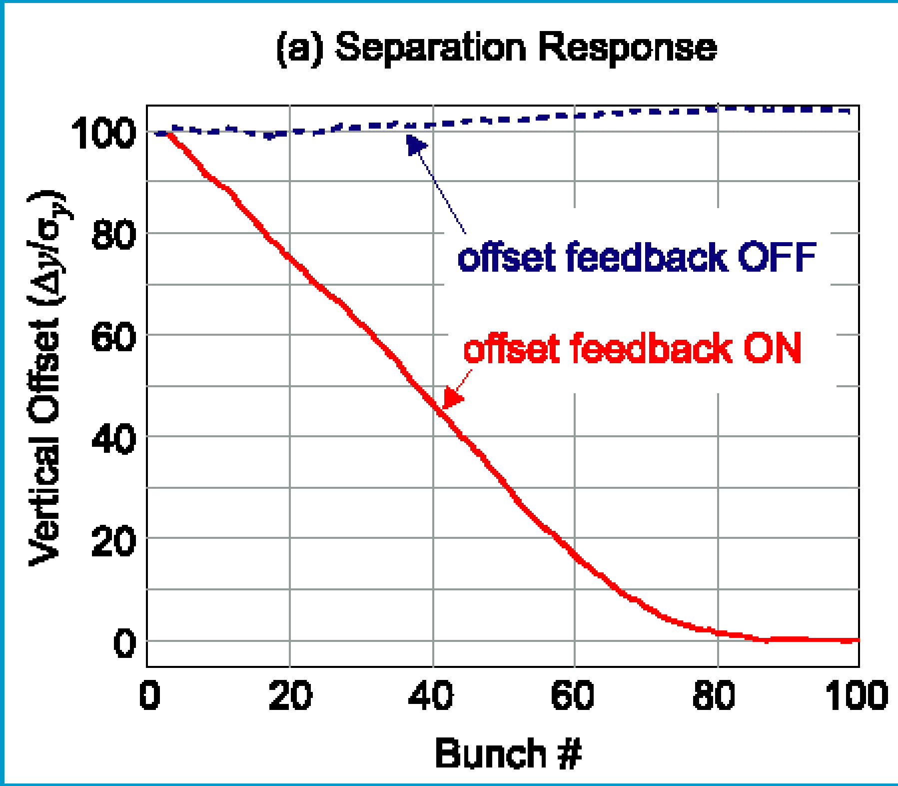
J.Frisch et al

- June 2001 – start of stabilization work
- Achieved ~10 times reduction, work to improve
- Next step: stabilize large realistic FD model

IP collision stability

- TESLA needs fast IP feedback to provide collision stability
- Large bunch separation (300ns) simplifies its implementation

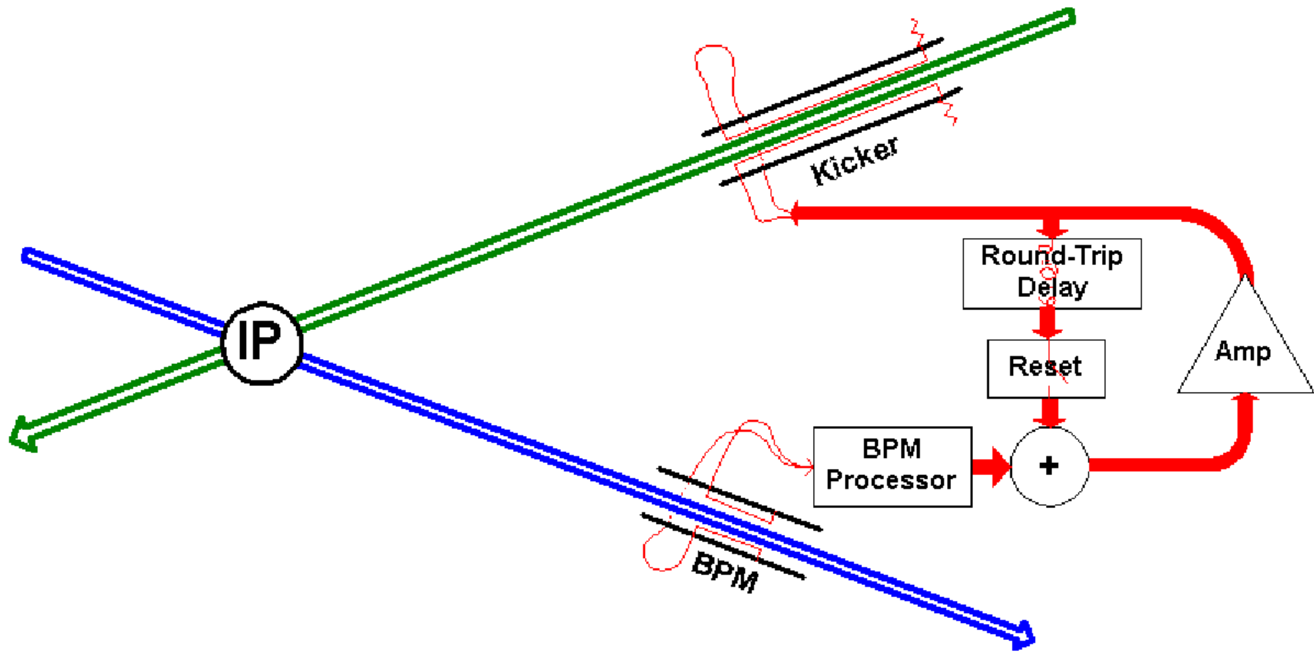




Pictures from TESLA TDR

Very Fast intratrain feedback for additional collision stability of NLC

- This is not a required, but additional NLC system
- It decreases sensitivity to beam jitter and ground motion



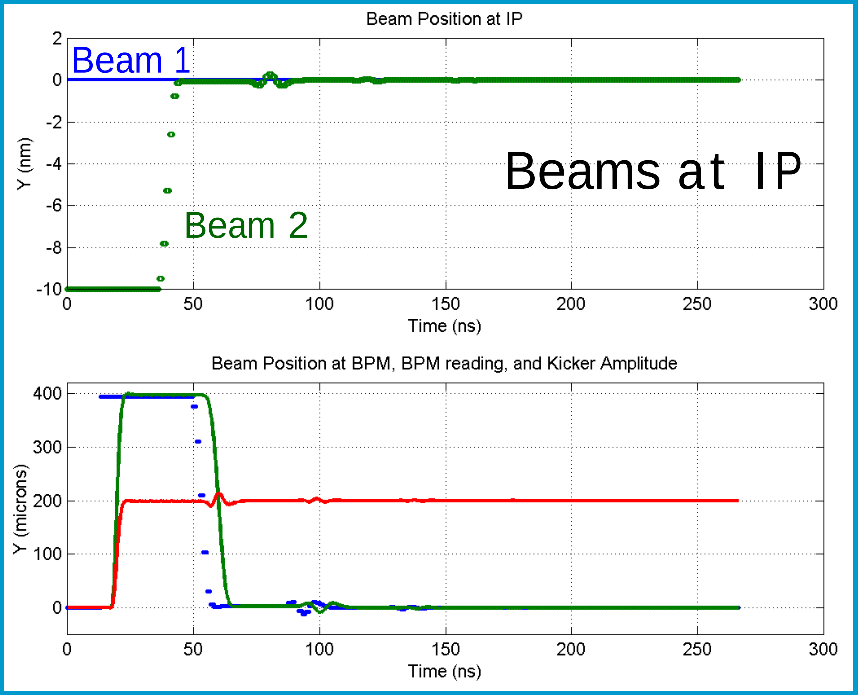
Oxford Univ., SLAC

S.Smith, SLAC,
LCC-0056, March 2001

NLC Very Fast intratrain feedback

- Due to round trip delay compensator the convergence is very fast
- NLC stability will be provided by other systems, but
- Even if all other system fail, can recover almost full luminosity
  (80-50% for 5-50 σ beam jitter)
- Angle feedback is not yet included in considerations
- Now in lab, later beam tests

Capture transient for 10nm initial beam offset. Full NLC bunch train is shown



S.Smith, LCC-0056, March 2001

Summary

- Ground motion and vibration are important for any future collider, in particular LC
- Have measurements data from around the world; develop models of motion
- A lot of experience on beam-based feedbacks from SLC – basis for confidence
- Active suppression system being developed
- Learning from other fields (e.g. LIGO)
- It would require patience, but the problems appear solvable