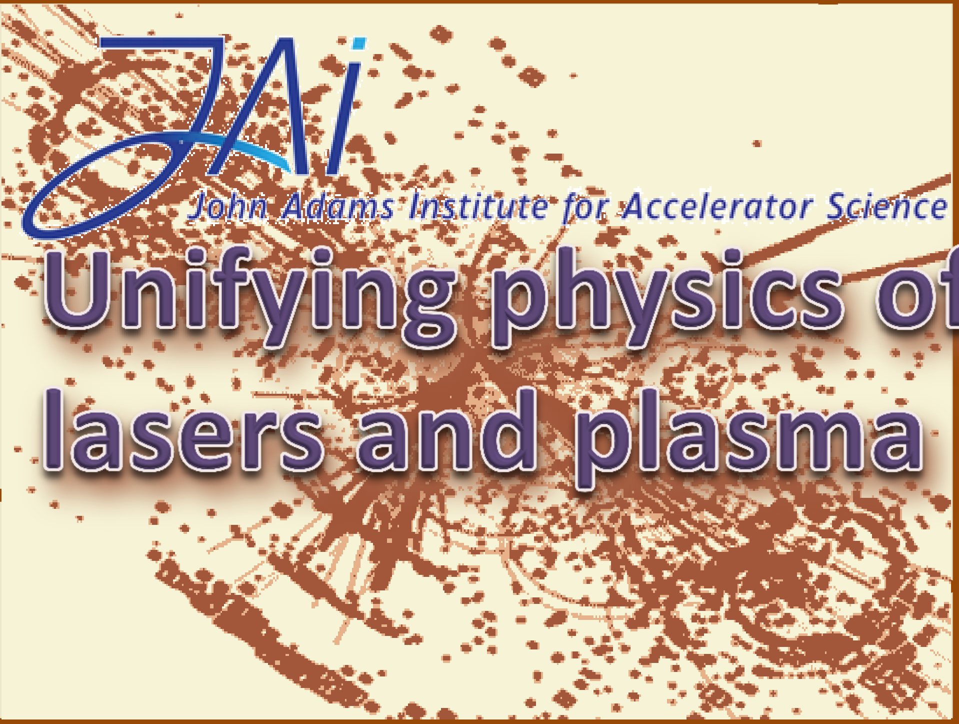
John Adams Institute for Accelerator Science

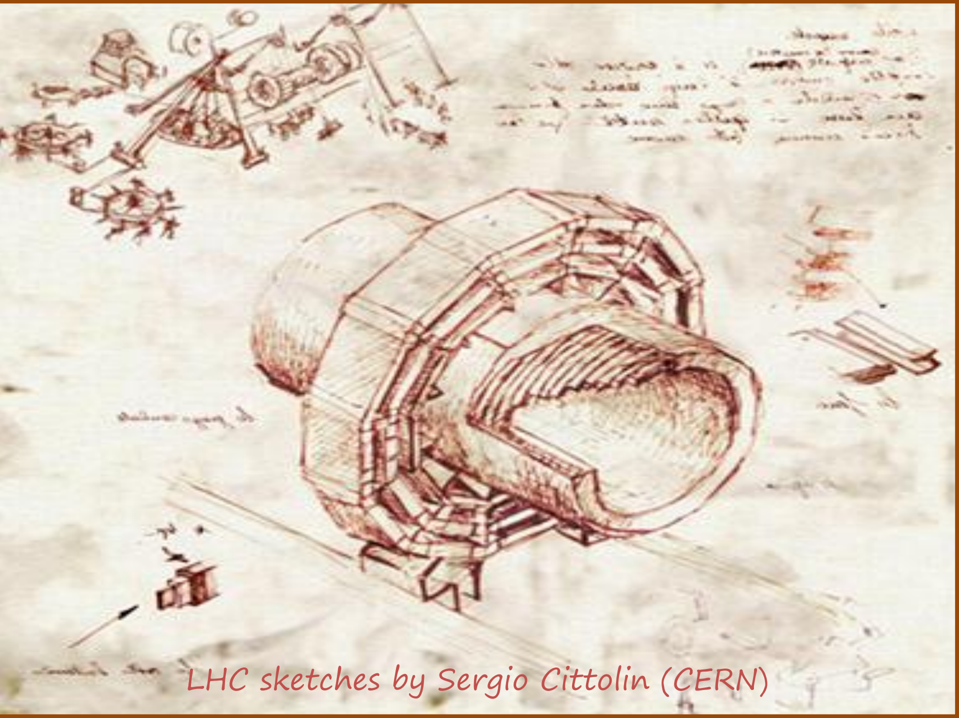
Imperial College London

Royal Holloway University of London

University of Oxford

# Unifying physics of accelerators, lasers and plasma





LHC sketches by Sergio Cittolin (CERN)

Prof. Andrei A. Seryi
John Adams Institute

## Lecture 11: Advanced beam manipulation (II) - stability

USPAS 2016

June 2016

# Scope of the lecture – stability

- Stability of beams
  - Colliders and LIGO
  - Beam-beam effects
  - BNS damping
- Damping and cooling
  - Landau damping
  - Laser cooling
  - Ionization cooling
  - Round to flat beam transfer, etc.

# Two scientific instruments

**What are these two instruments?**

**What is in common?**

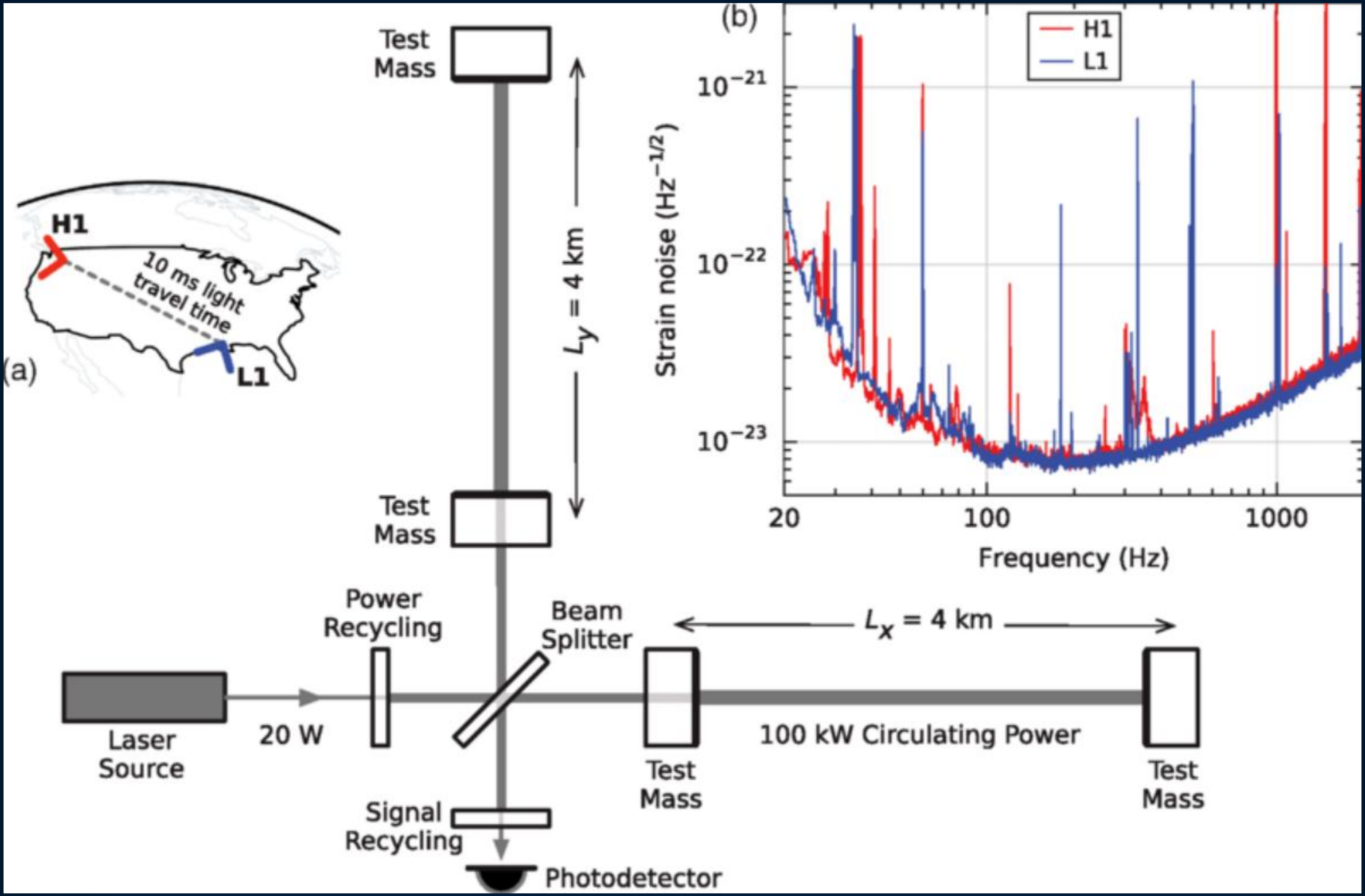
# Two scientific instruments

**LIGO, Hanford**

**SLC, Stanford**

**A lot. And also sensitivity to seismic noises.**

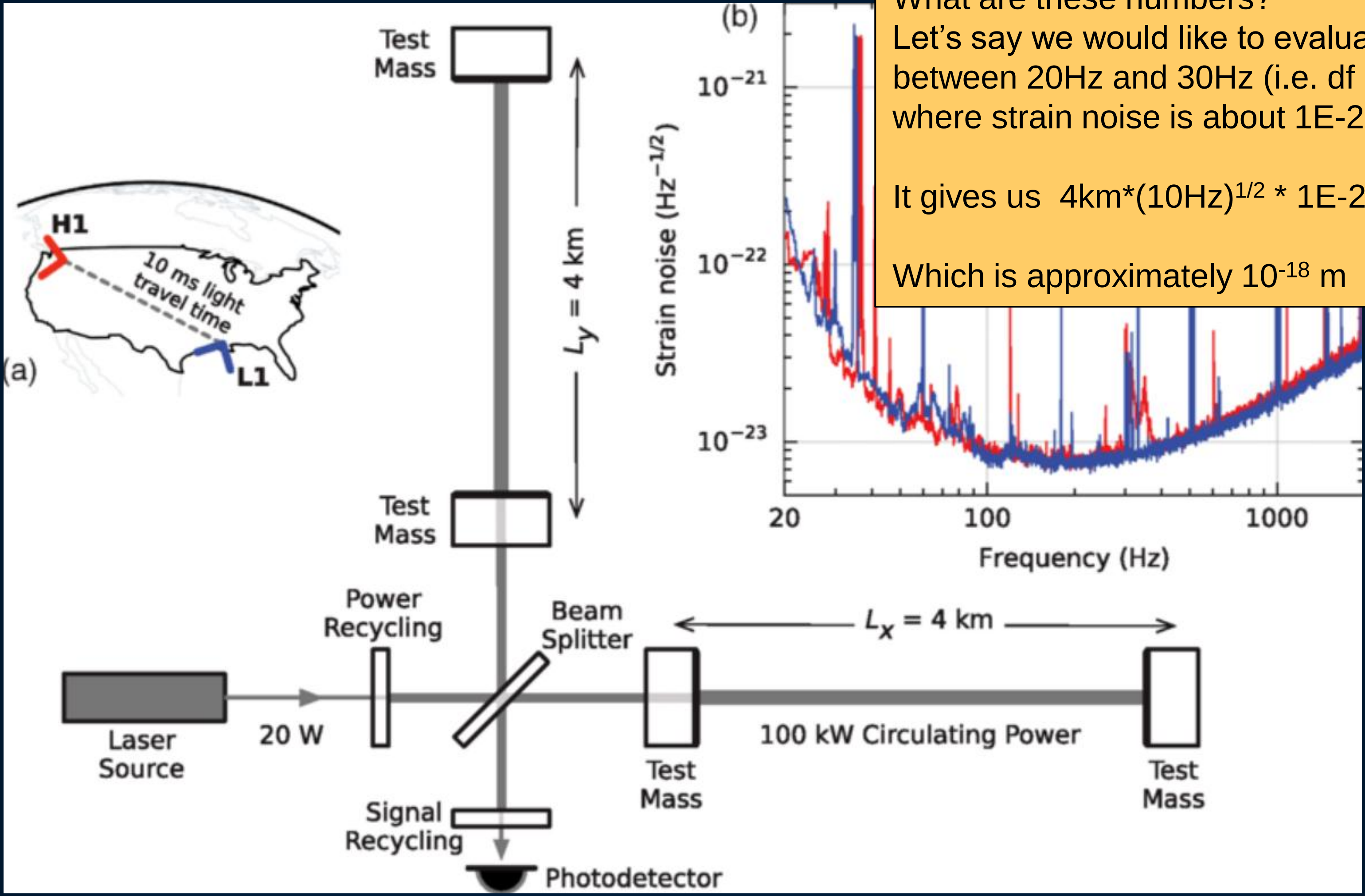
# LIGO



LIGO layout and sensitivity curve

Source: PRL 116, 061102 (2016)

# LIGO



What are these numbers?
Let's say we would like to evaluate noise between 20Hz and 30Hz (i.e. df = 10Hz), where strain noise is about 1E-22 $\mathrm{Hz}^{-1/2}$

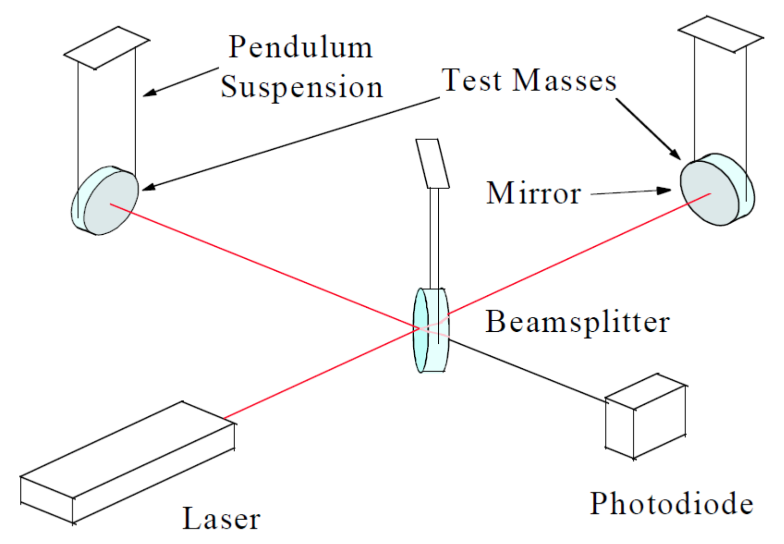
It gives us 4km*$(10\mathrm{Hz})^{1/2}$ * 1E-22 $\mathrm{Hz}^{-1/2}$

Which is approximately $10^{-18}$ m

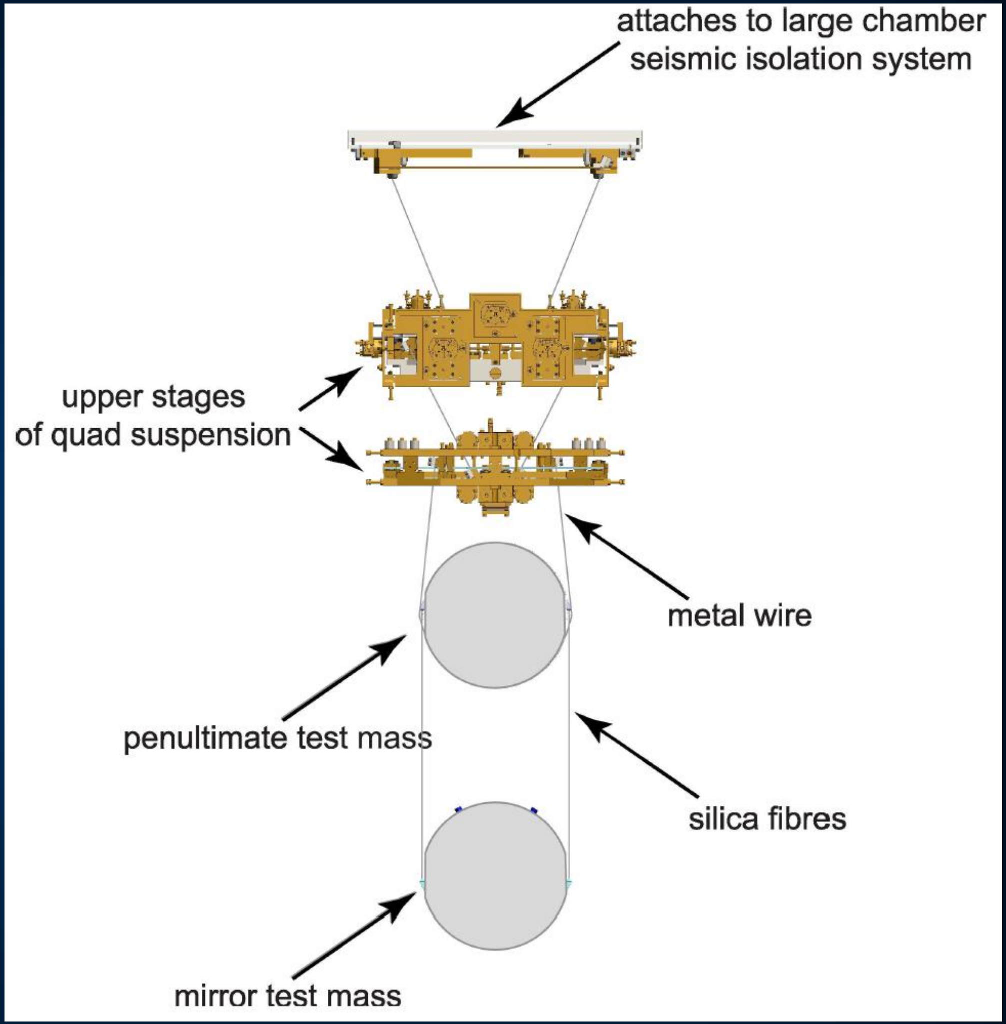
**LIGO layout and sensitivity curve**

Source: PRL 116, 061102 (2016)

# LIGO test mass isolation



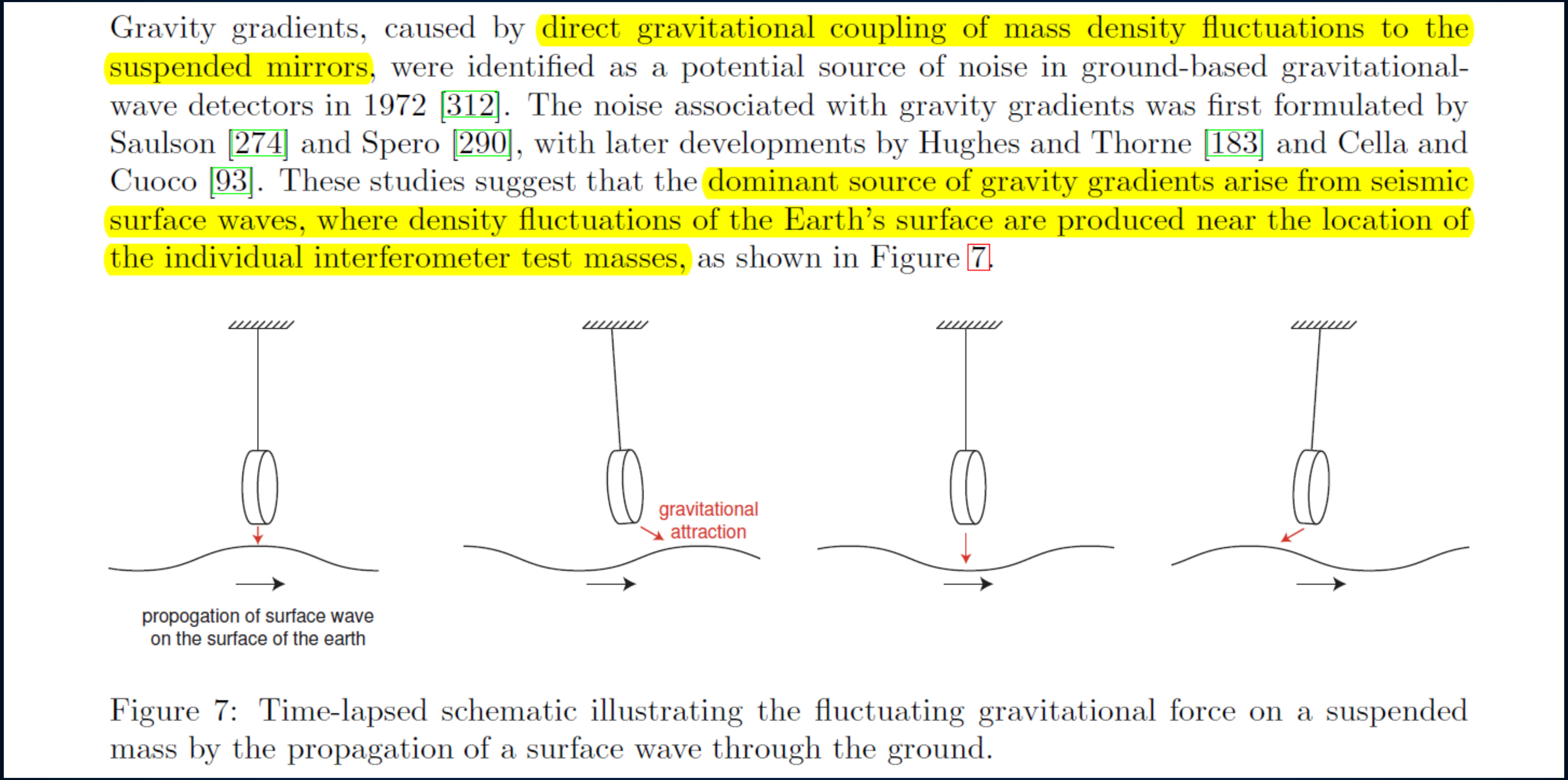
**Concept**



**Solution: nested pendulums**

Source: arXiv:1102.3355

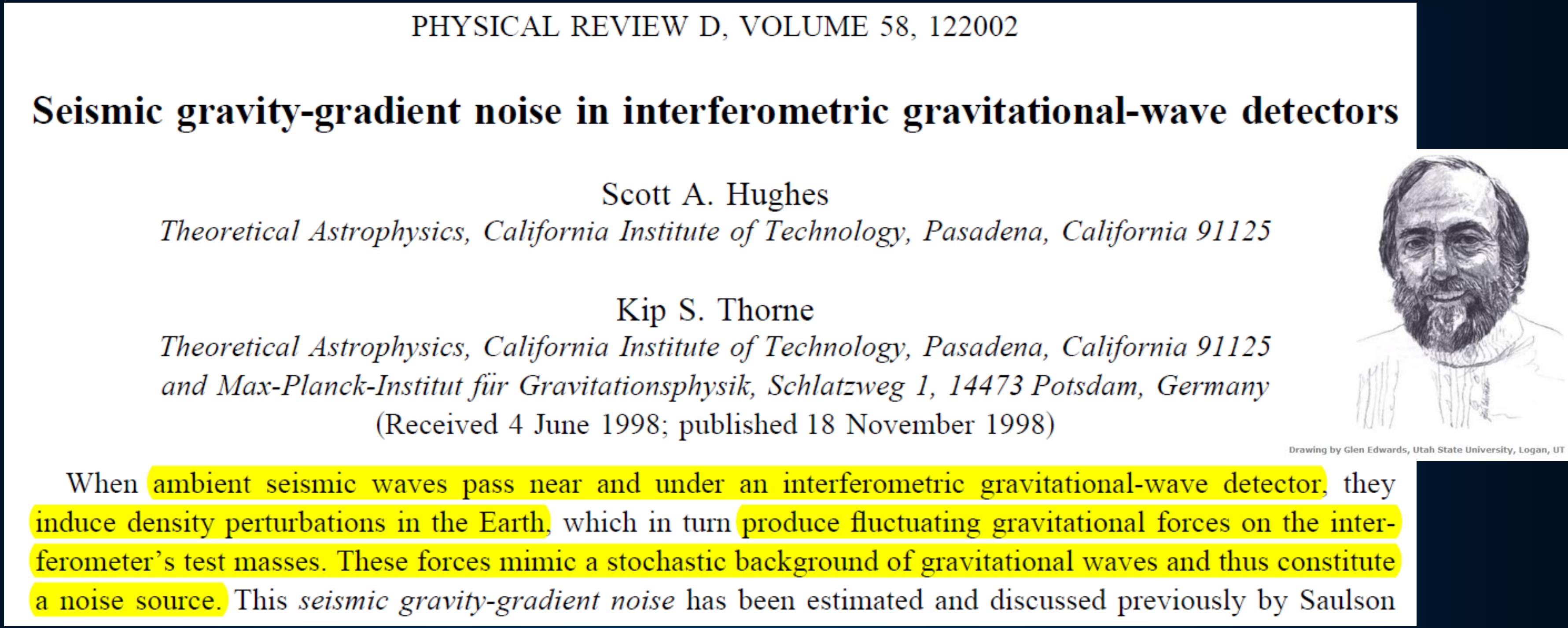
# LIGO seismic sensitivity



Gravity gradients, caused by direct gravitational coupling of mass density fluctuations to the suspended mirrors, were identified as a potential source of noise in ground-based gravitational-wave detectors in 1972 [312]. The noise associated with gravity gradients was first formulated by Saulson [274] and Spero [290], with later developments by Hughes and Thorne [183] and Cella and Cuoco [93]. These studies suggest that the dominant source of gravity gradients arise from seismic surface waves, where density fluctuations of the Earth's surface are produced near the location of the individual interferometer test masses, as shown in Figure 7.

Figure 7: Time-lapsed schematic illustrating the fluctuating gravitational force on a suspended mass by the propagation of a surface wave through the ground.

Source: arXiv:1102.3355



PHYSICAL REVIEW D, VOLUME 58, 122002

# Seismic gravity-gradient noise in interferometric gravitational-wave detectors

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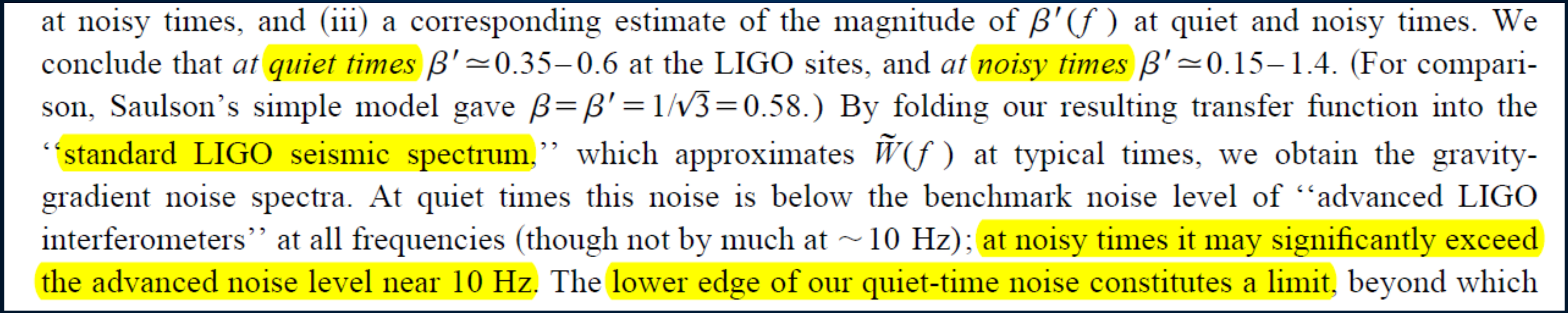
(Received 4 June 1998; published 18 November 1998)

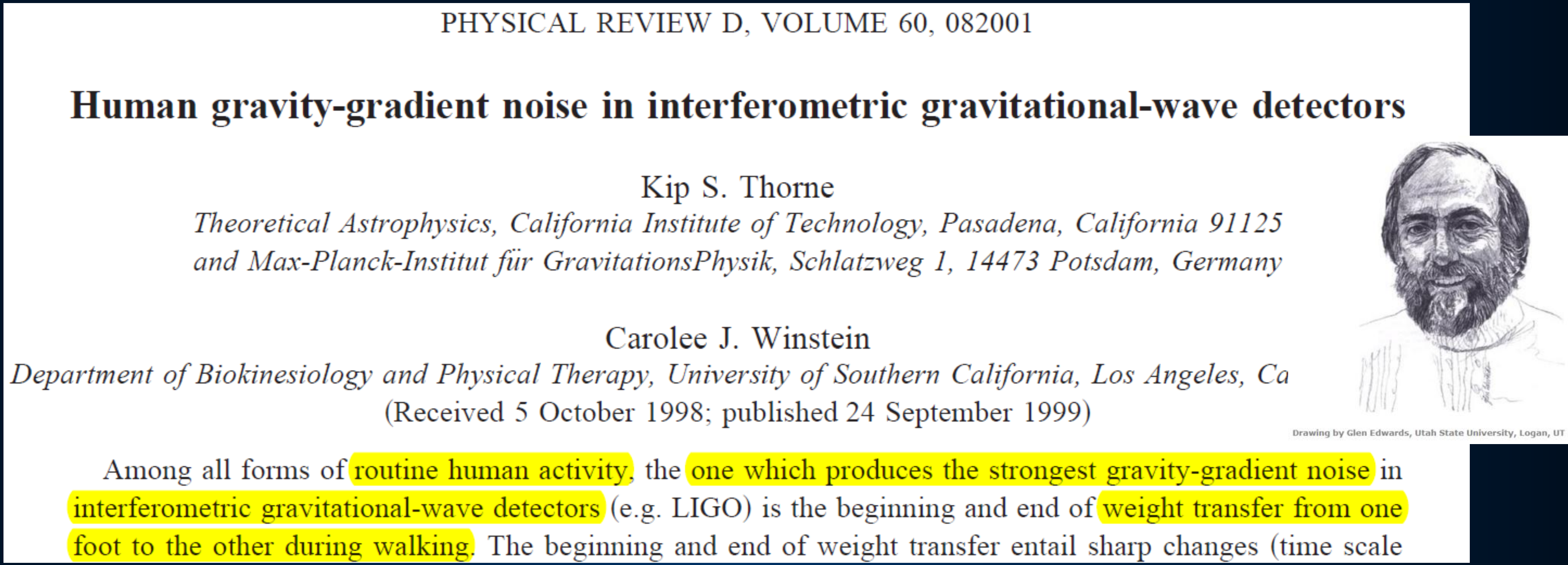
Drawing by Glen Edwards, Utah State University, Logan, UT

When ambient seismic waves pass near and under an interferometric gravitational-wave detector, they induce density perturbations in the Earth, which in turn produce fluctuating gravitational forces on the interferometer's test masses. These forces mimic a stochastic background of gravitational waves and thus constitute a noise source. This *seismic gravity-gradient noise* has been estimated and discussed previously by Saulson



at noisy times, and (iii) a corresponding estimate of the magnitude of $\beta'(f)$ at quiet and noisy times. We conclude that *at quiet times* $\beta' \simeq 0.35-0.6$ at the LIGO sites, and *at noisy times* $\beta' \simeq 0.15-1.4$. (For comparison, Saulson's simple model gave $\beta=\beta'=1/\sqrt{3}=0.58$.) By folding our resulting transfer function into the "standard LIGO seismic spectrum," which approximates $\tilde{W}(f)$ at typical times, we obtain the gravity-gradient noise spectra. At quiet times this noise is below the benchmark noise level of "advanced LIGO interferometers" at all frequencies (though not by much at ~10 Hz); at noisy times it may significantly exceed the advanced noise level near 10 Hz. The lower edge of our quiet-time noise constitutes a limit, beyond which

Source for portrait: Caltech web



PHYSICAL REVIEW D, VOLUME 60, 082001

# Human gravity-gradient noise in interferometric gravitational-wave detectors

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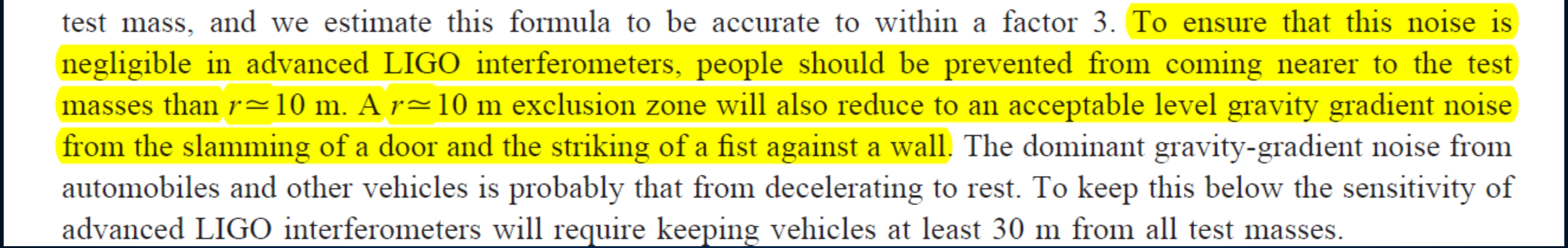
(Received 5 October 1998; published 24 September 1999)

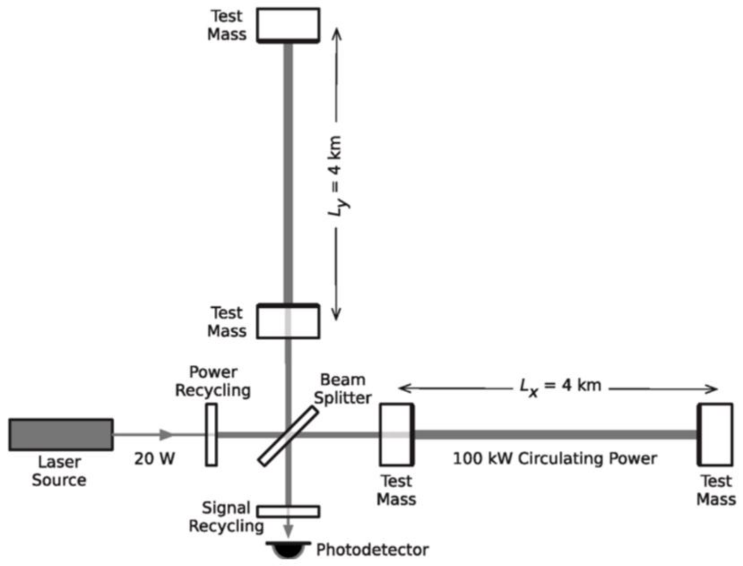
Drawing by Glen Edwards, Utah State University, Logan, UT

Among all forms of routine human activity, the one which produces the strongest gravity-gradient noise in interferometric gravitational-wave detectors (e.g. LIGO) is the beginning and end of weight transfer from one foot to the other during walking. The beginning and end of weight transfer entail sharp changes (time scale



test mass, and we estimate this formula to be accurate to within a factor 3. To ensure that this noise is negligible in advanced LIGO interferometers, people should be prevented from coming nearer to the test masses than $r \simeq 10$ m. A $r \simeq 10$ m exclusion zone will also reduce to an acceptable level gravity gradient noise from the slamming of a door and the striking of a fist against a wall. The dominant gravity-gradient noise from automobiles and other vehicles is probably that from decelerating to rest. To keep this below the sensitivity of advanced LIGO interferometers will require keeping vehicles at least 30 m from all test masses.

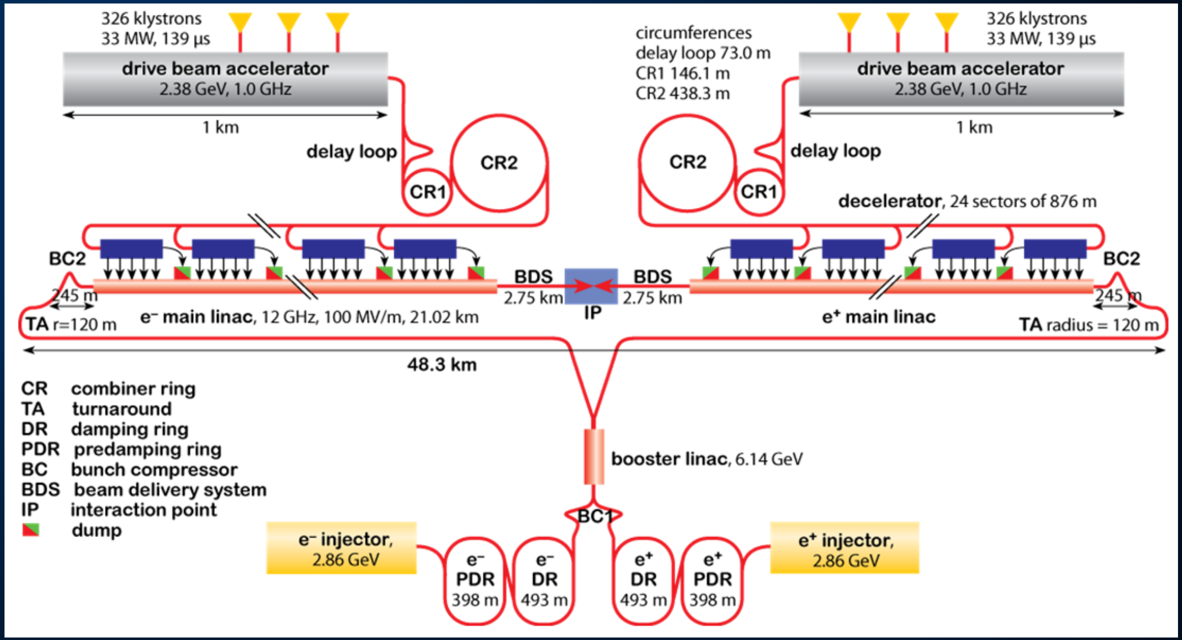
Source for portrait: Caltech web



# These two instruments

**LIGO: keep two objects placed 4km apart stable* to about 1e-9 nm**

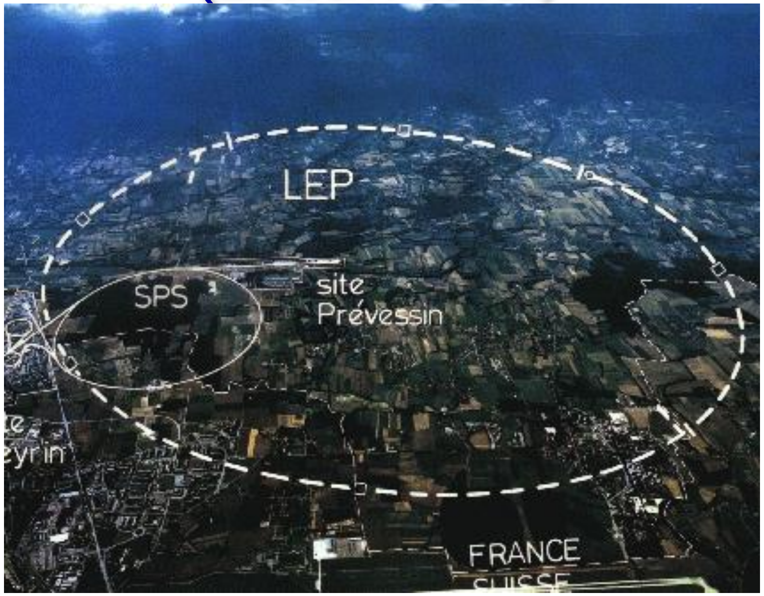
**CLIC – Compact Linear Collider: keep 100,000 objects distributed over 50km stable* to about 10 nm**



*) approximately, and in certain frequency range

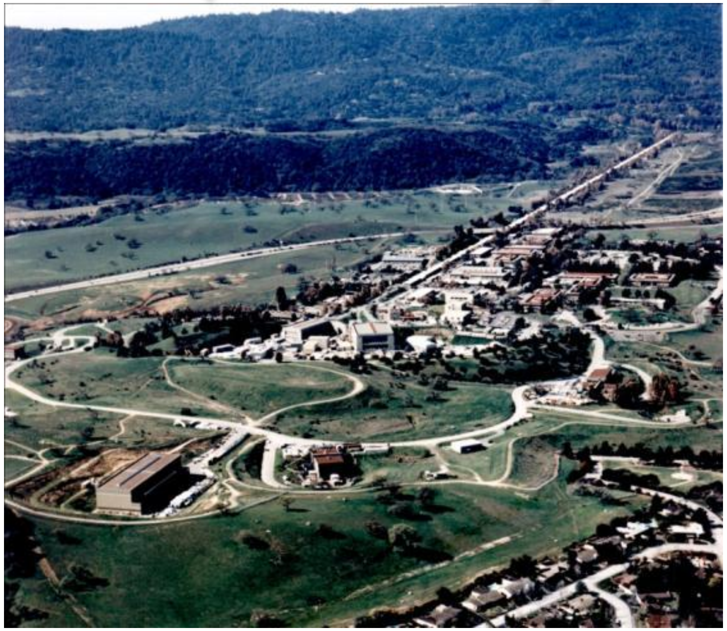
# LEP Collider, CERN

(Electron-Positron)



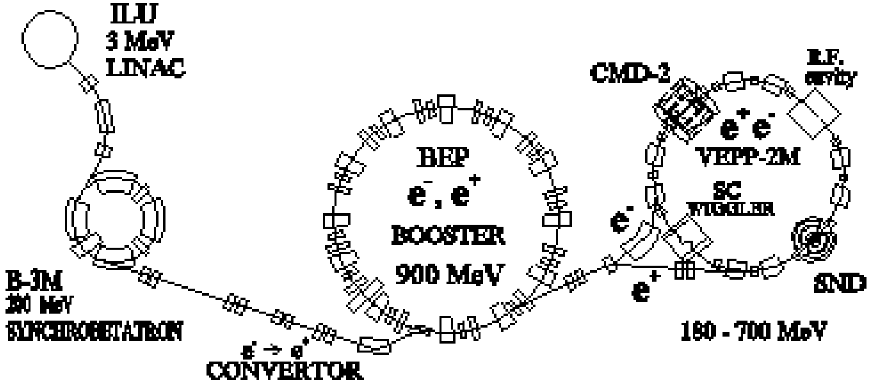
# SLAC Linear Collider

(Electron-Positron)



# VEPP Colliders BINP, Novosibirsk

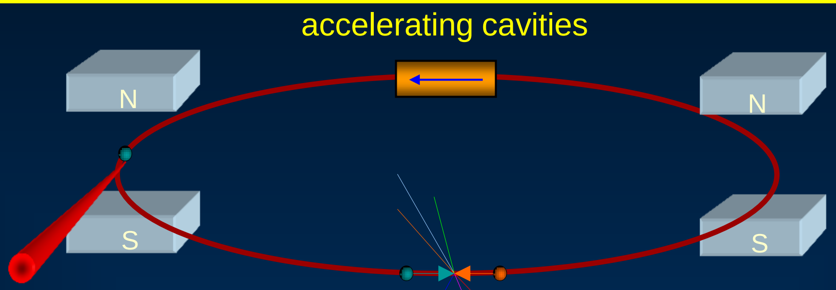
(Electron-Positron)



# Tevatron collider, Fermilab

(Proton-antiproton)

# Next e+e- Collider - Circular versus Linear

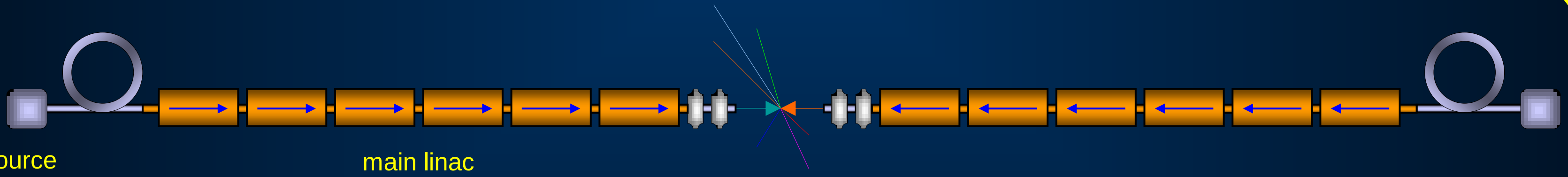


**Circular Collider**

many magnets, few cavities, stored beam

higher energy → stronger magnetic field

→ higher synchrotron radiation losses ($E^4/m^4R$)



**Linear Collider**

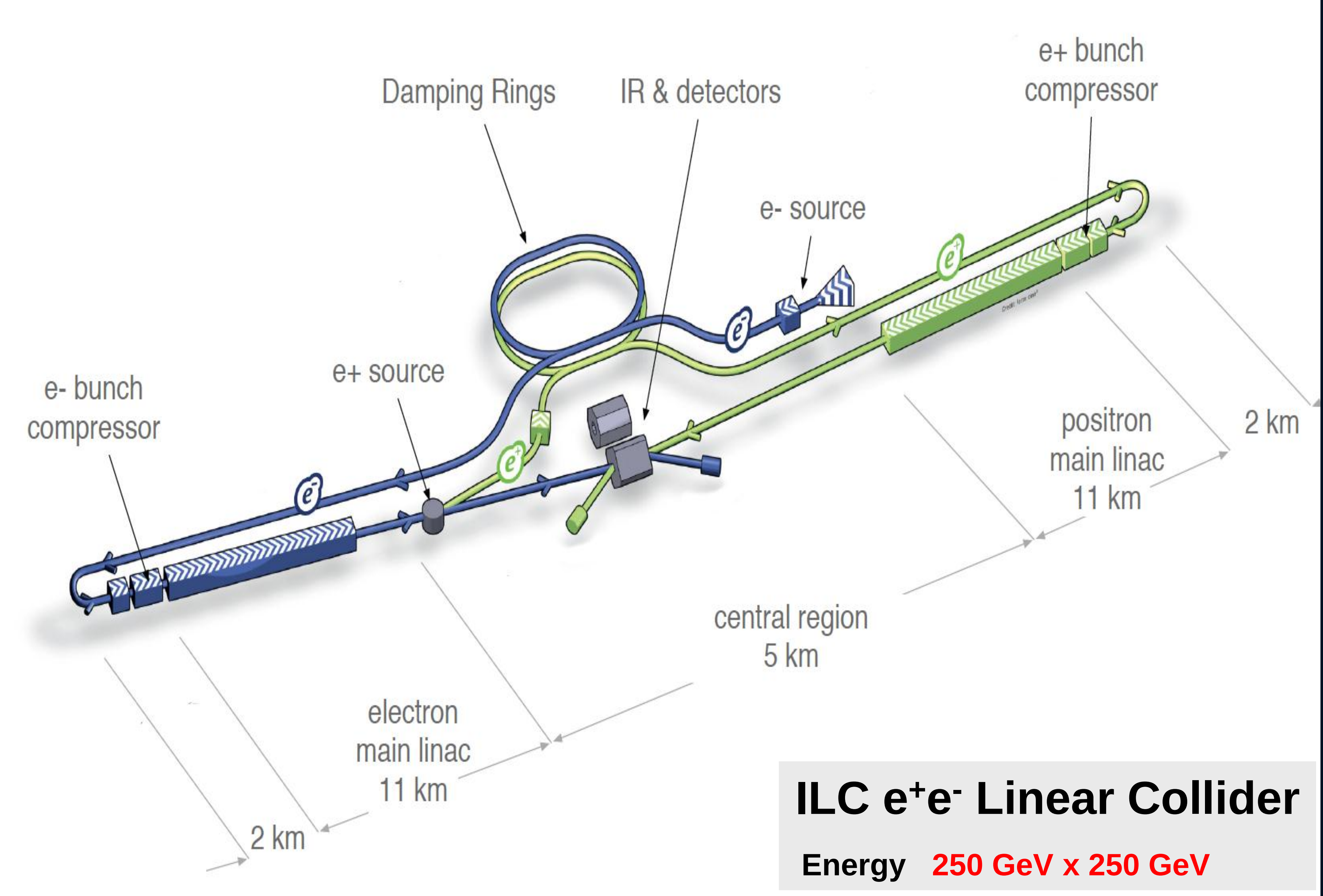
few magnets, many cavities, single pass beam

higher energy → higher accelerating gradient

higher luminosity → higher beam power (high bunch repetition)

→ no synchrotron radiation losses

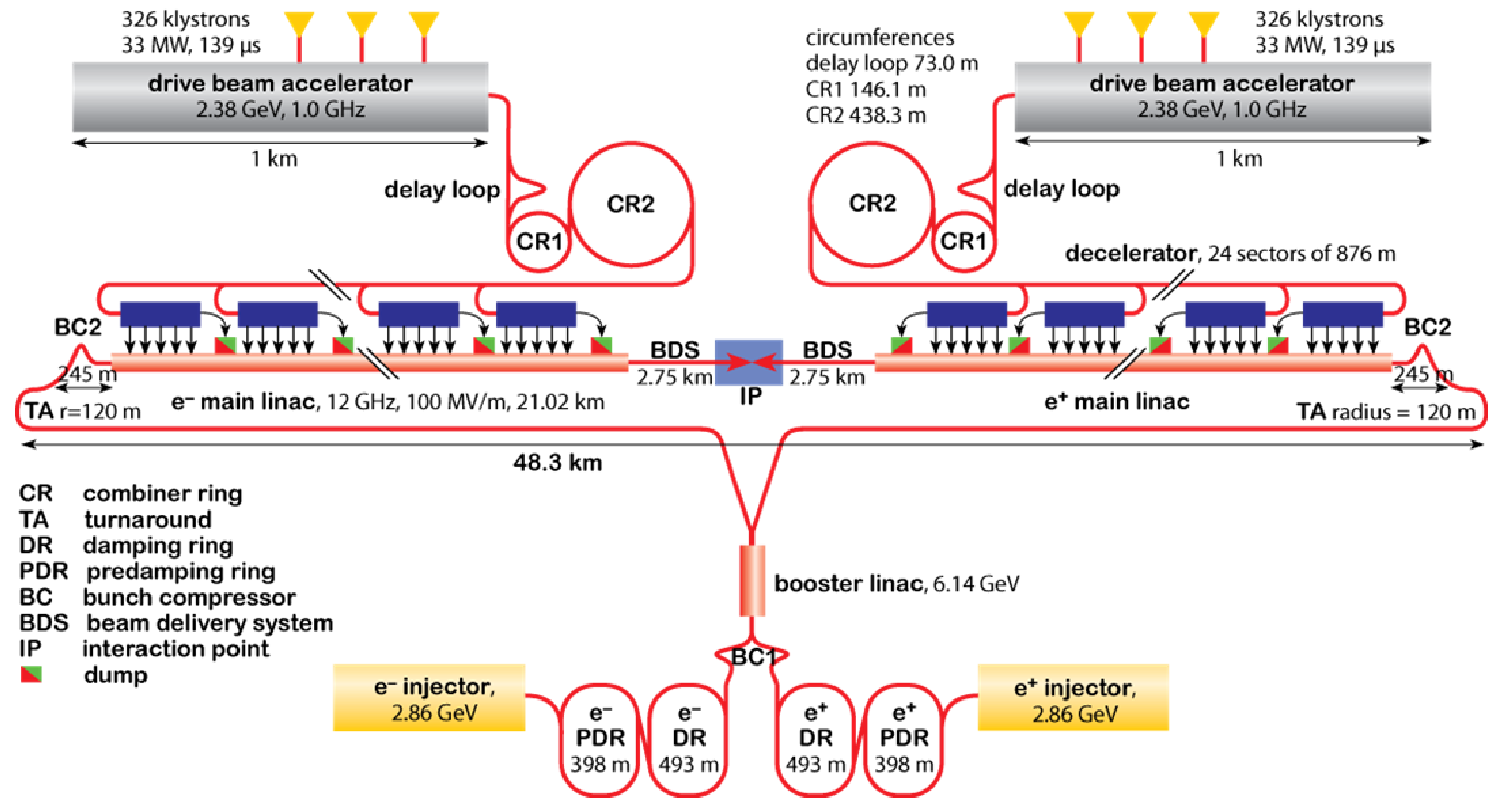
# International Linear Collider ILC



**ILC $e^+e^-$ Linear Collider**

**Energy** **250 GeV x 250 GeV**

# Compact Linear Collider  CLIC



## CLIC $e^+e^-$ Linear Collider

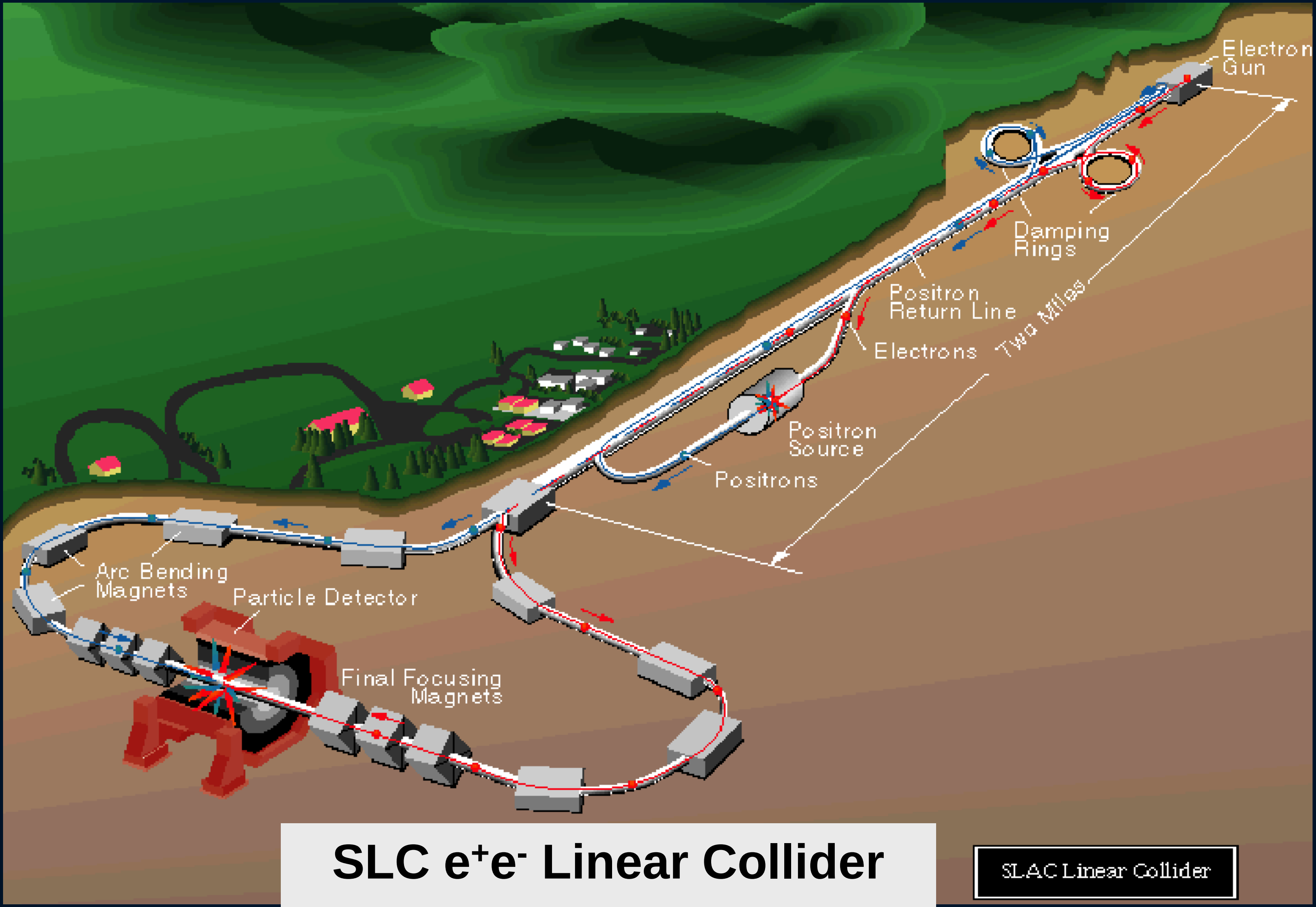
**for center of mass energy 3 TeV**

# The first ever linear collider

**SLC $e^+e^-$ Linear Collider**

for center of mass energy 50 GeV

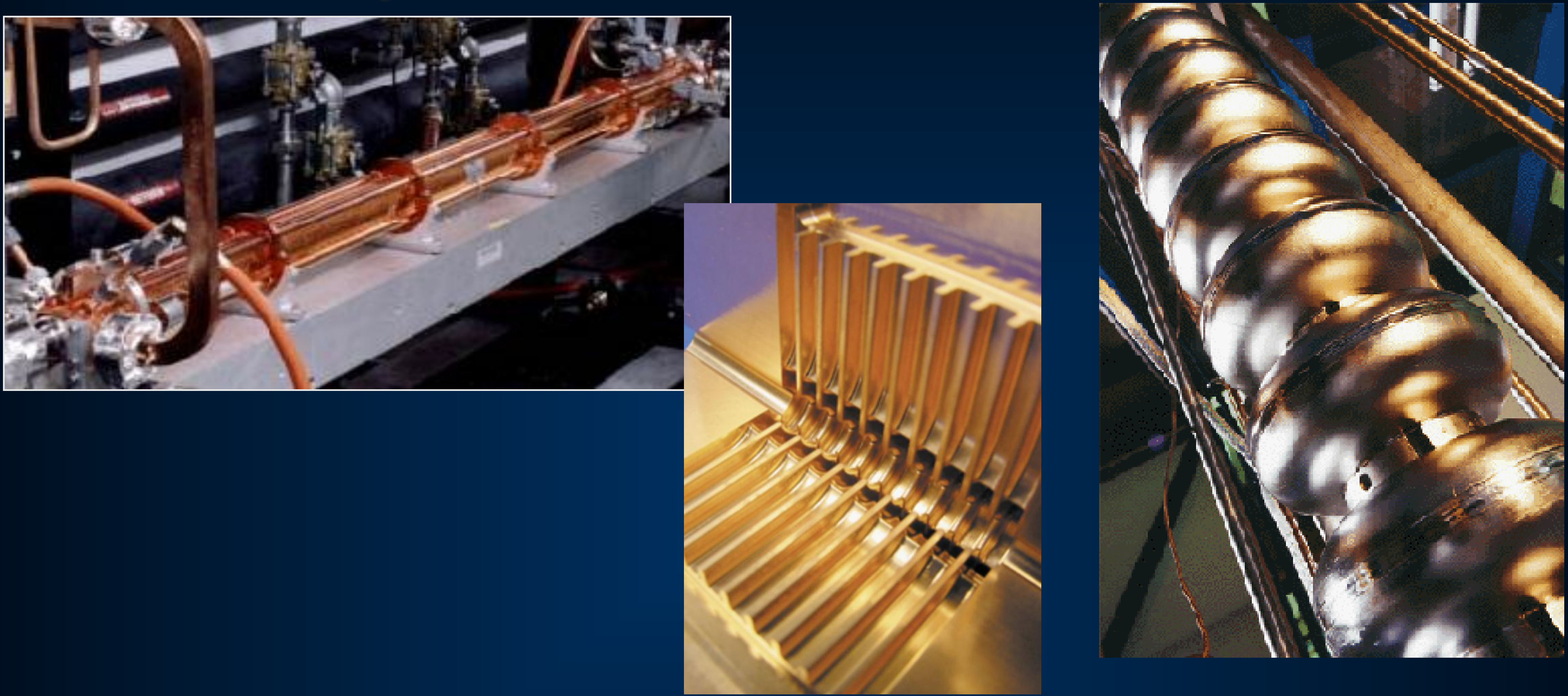
# The first ever linear collider



**SLC $e^+e^-$ Linear Collider**

**for center of mass energy 50 GeV**

# Development of linear collider designs



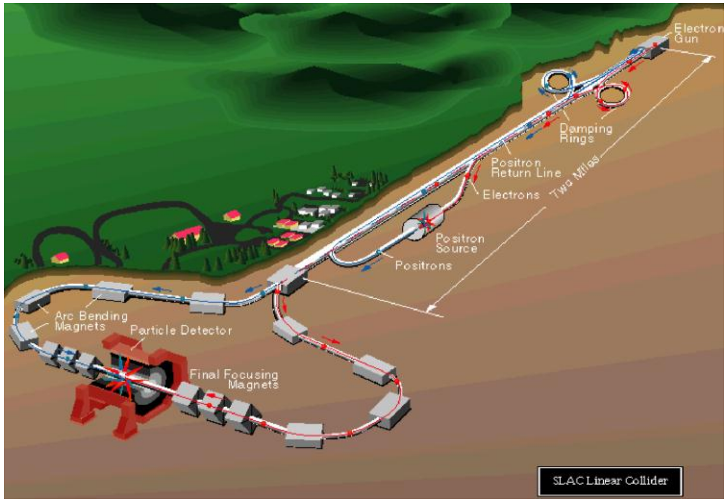
During several decades of R&D, various versions of LC were developed
Some were based on normal conductive, other on superconductive RF
Some examples given in this lecture based on studies done for NLC design

Emerged out of all these studies are ILC and CLIC projects – SC RF and two-beam RF based

# The challenge of Linear Collider – Luminosity

- Energy: initial goal 250GeV CM
  - This is "just" 5 times more than SLC

- But Luminosity: x 10000 !!!
  (vs the only so far linear collider SLC)
  - Many improvements needed, to ensure this : generation of smaller beams, their better preservation, …

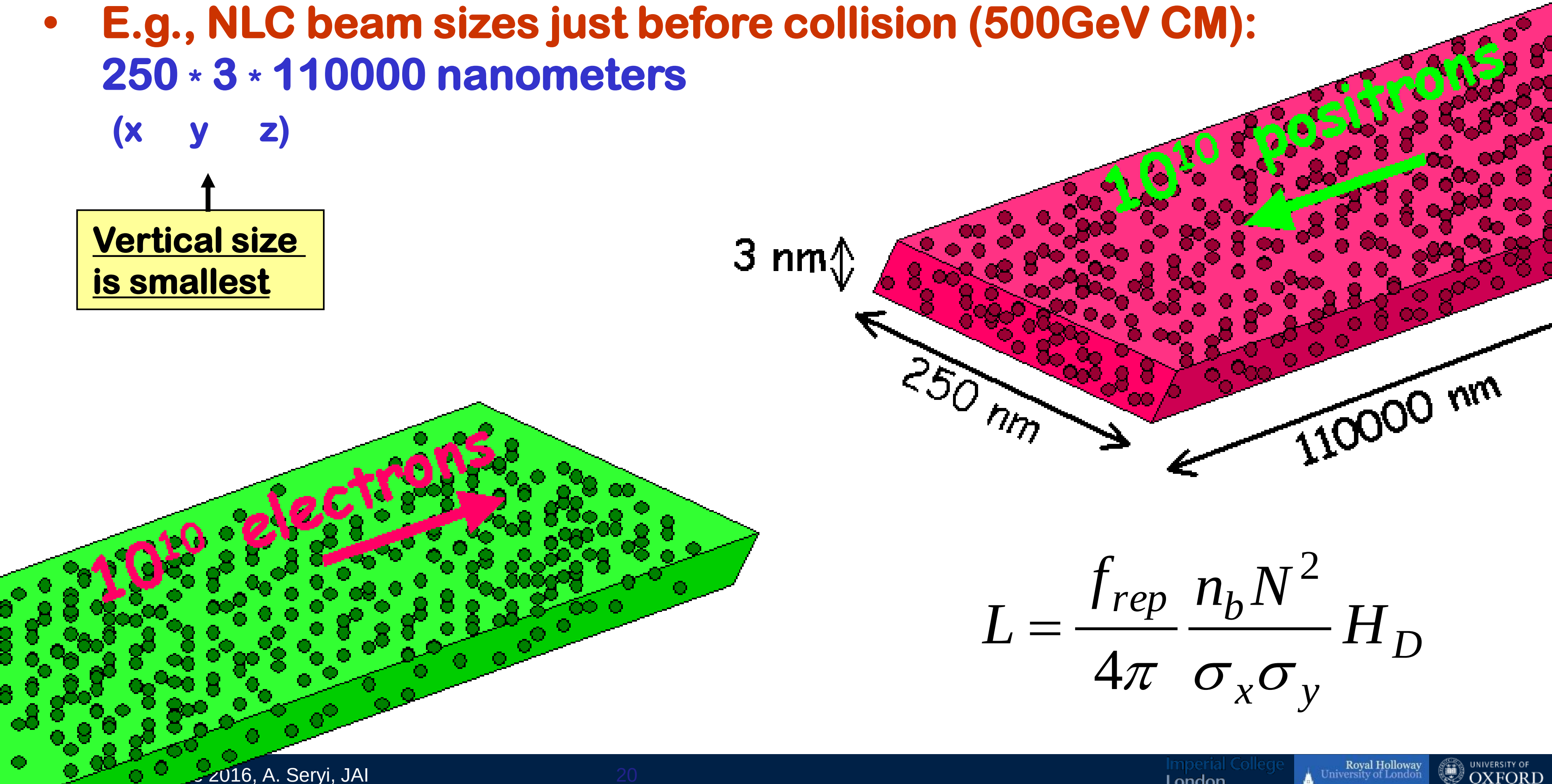


- Technical and natural vibration and natural ground motion continuously misalign components of a linear collider => may be a **limiting factor**

# How to get Luminosity

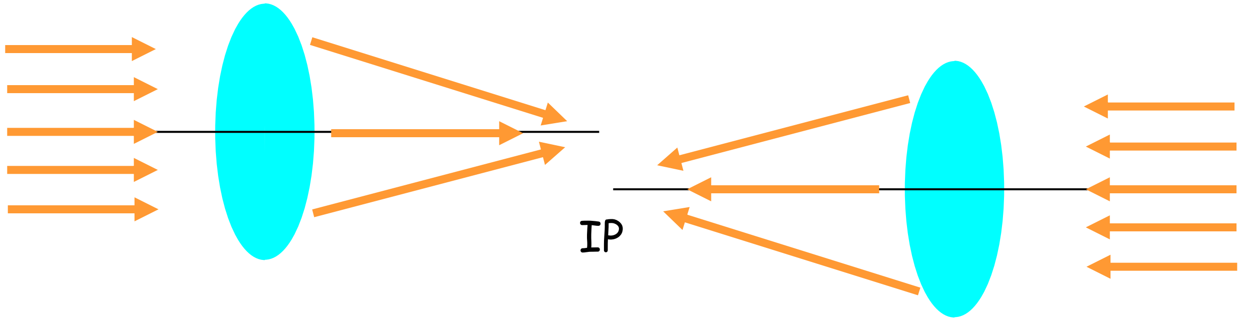
- To increase probability of direct $e^+e^-$ collisions (luminosity) and birth of new particles, beam sizes at IP must be very small
- E.g., NLC beam sizes just before collision (500GeV CM):
  250 * 3 * 110000 nanometers
  (x y z)

**Vertical size is smallest**



$$L = \frac{f_{rep}}{4\pi} \frac{n_b N^2}{\sigma_x \sigma_y} H_D$$

# Stability – tolerance to motion of final lenses



- Displacement of final lenses (final doublet - FD) cause similar same displacement of the beams at the Interaction Point (IP)

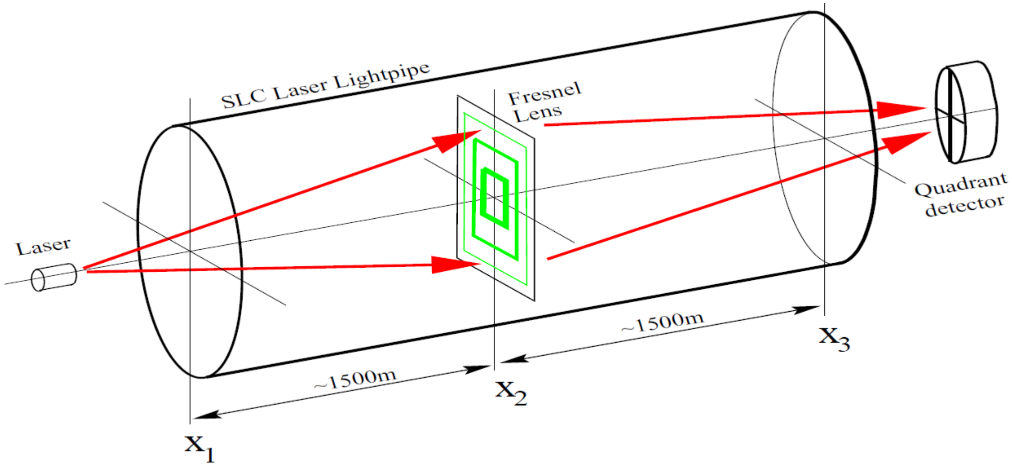
- Therefore, stability of FD need to be maintained with a fraction of nanometer accuracy
  - Slow (in comparison with repetition rate of collisions) drifts can be corrected
  - Fast motion is more dangerous

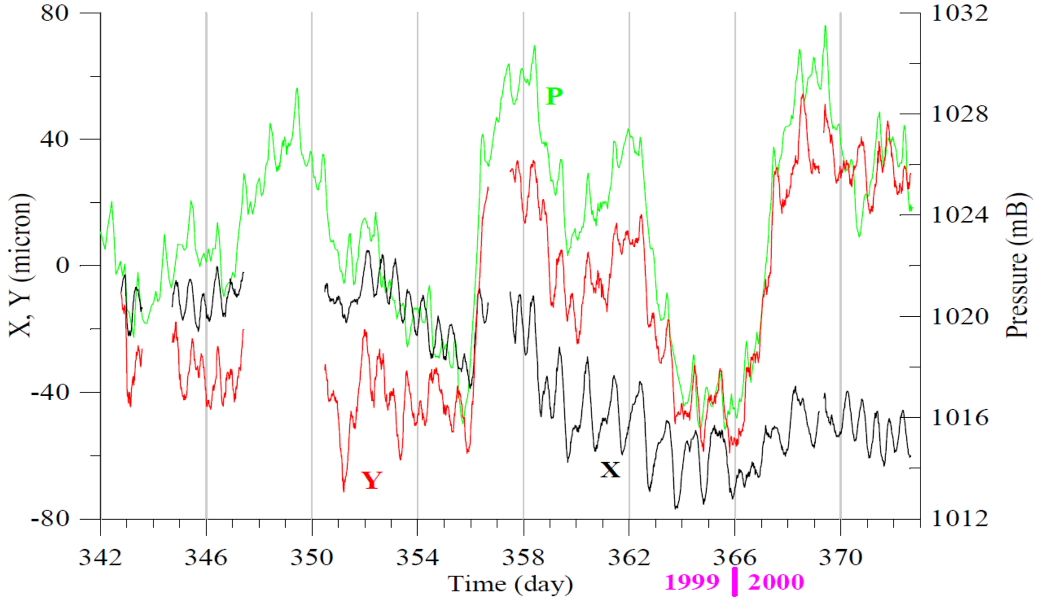
# Examples of slow motion - SLAC

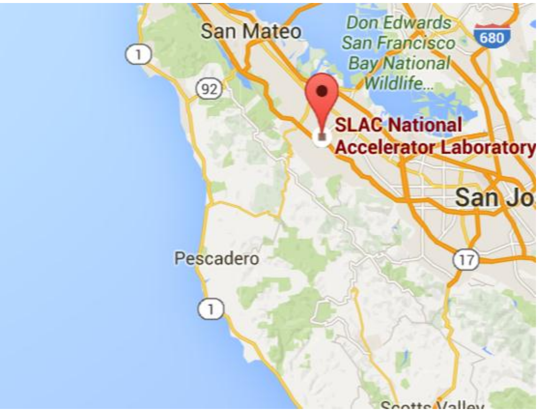
Deformation of 3km SLAC linac was measured

10 micron tidal component was observed, exceeding by 1000 times what is expected for a uniform elastic Earth

Explained by “Ocean loading” effects, which enhances the tidal deformations locally





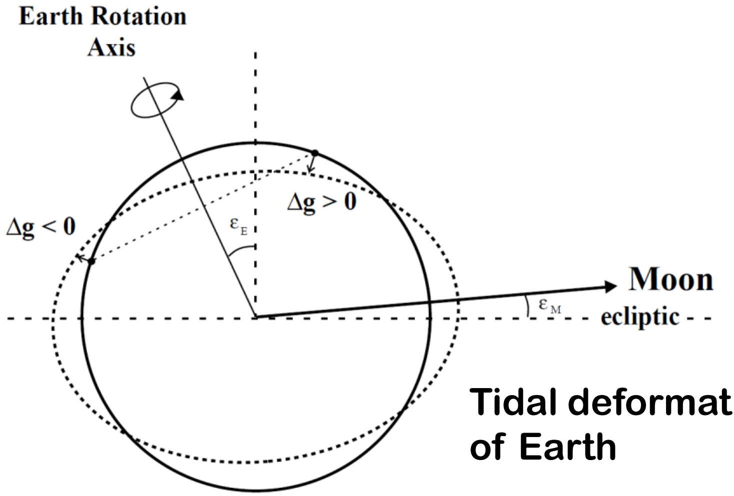


**This is peculiar, but this motion is slow, long wavelength and usually even not noticed by the accelerator**

# Examples of slow motion - LEP

Variation of LEP ring circumference was noticed, via precise measurement of the beam energy

Measured energy variation fit perfectly the predictions based on the tidal model



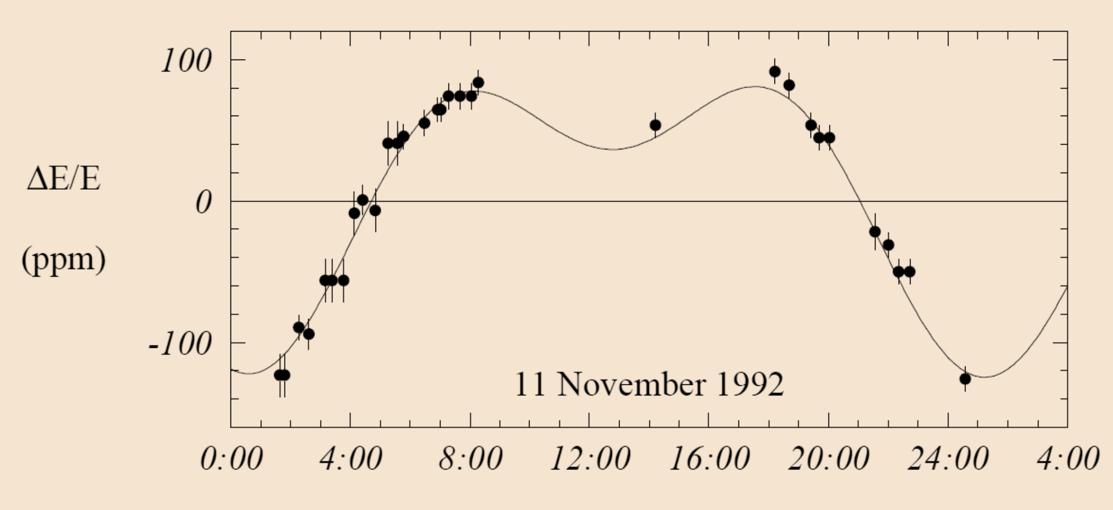
Tidal deformation of Earth

This is again peculiar example of slow motion, and this time it was noticed by the accelerator.

But this type of effects can be easily corrected for.

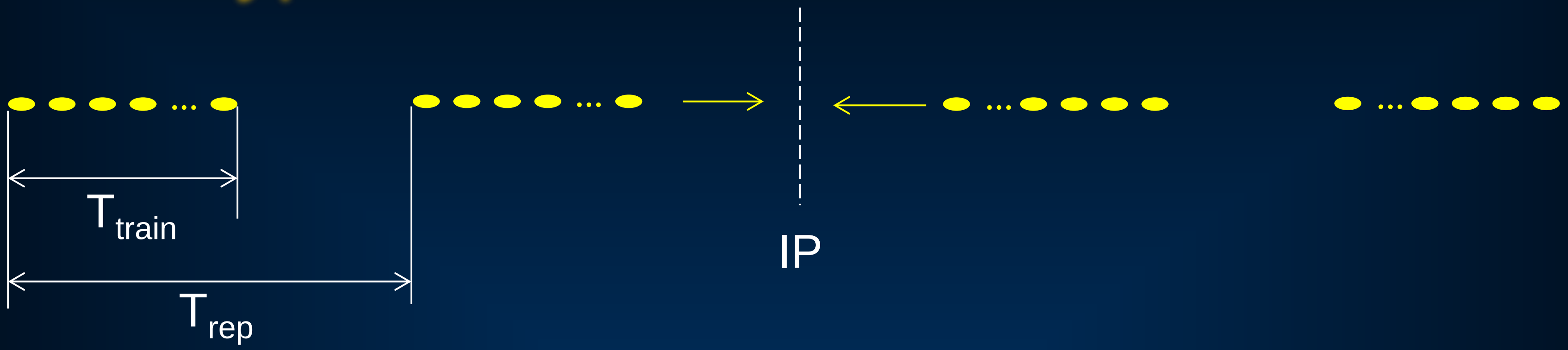
We should be more concerned about fast effects, that cannot be corrected.

What is "fast" depend on parameters…



Effects of Terrestrial Tides on the LEP Beam Energy, L. Arnaudon, et al., CERN SL/94-07 (BI)

# Typical bunch train formats in LC



Case 1: $T_{train}$ is typically 100 ns, with ~50 bunches per train
$T_{rep}$ corresponds to ~50 Hz

NC RF

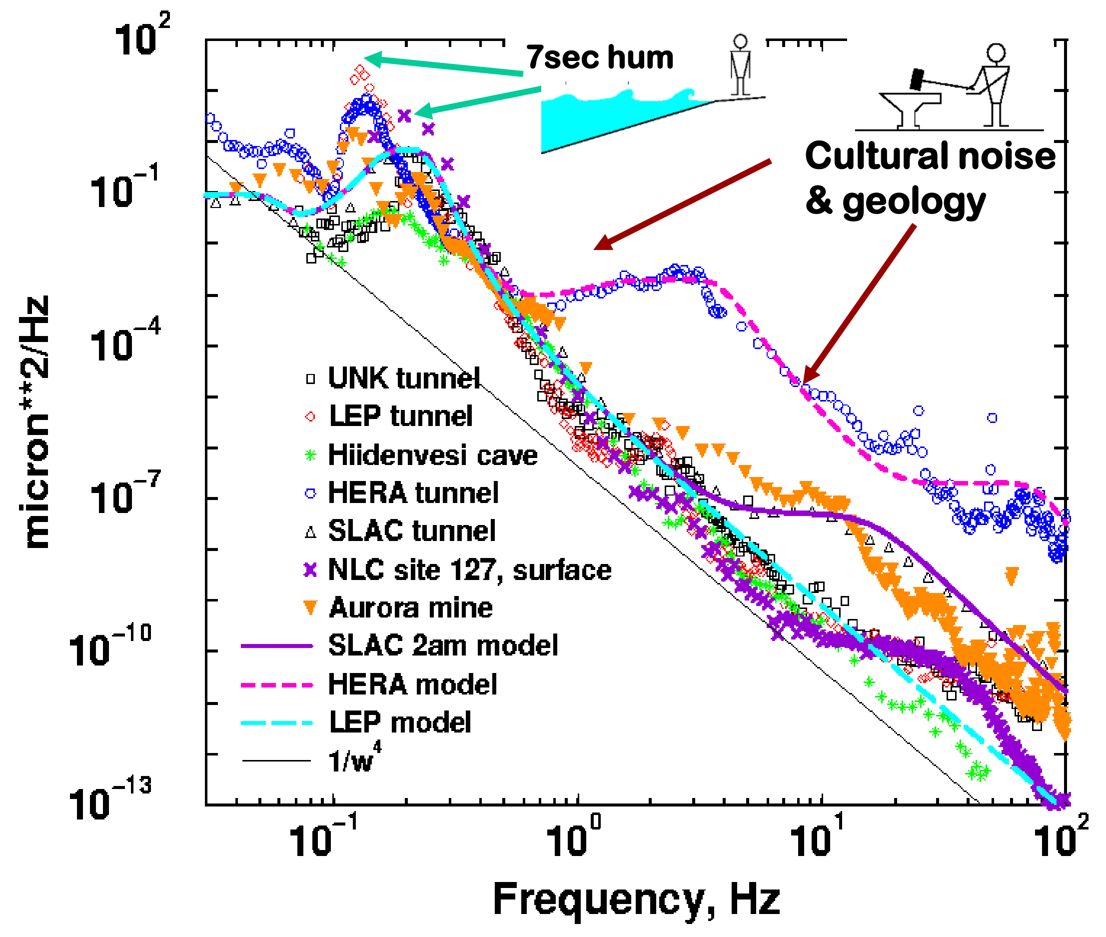
Case 2: $T_{train}$ is typically 1 ms, with ~3000 bunches per train
$T_{rep}$ corresponds to ~5 Hz

SC RF

*Capability of train-to-train and bunch-to-bunch corrections are quite different in these two cases. Also different which disturbances we consider fast and which slow. Examples shown below are for Case 1*

# Natural and man-made (cultural) ground motion is one of disturbing factors

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



**Power spectral density of absolute position**

**data from different places 1989 - 2001**

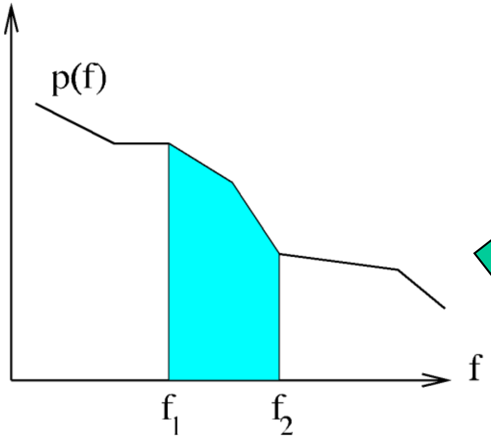
# Natural ground motion is small at high frequencies

At F>1 Hz the motion can be < 1nm (i.e. much less than beam size in LC). Is it OK?

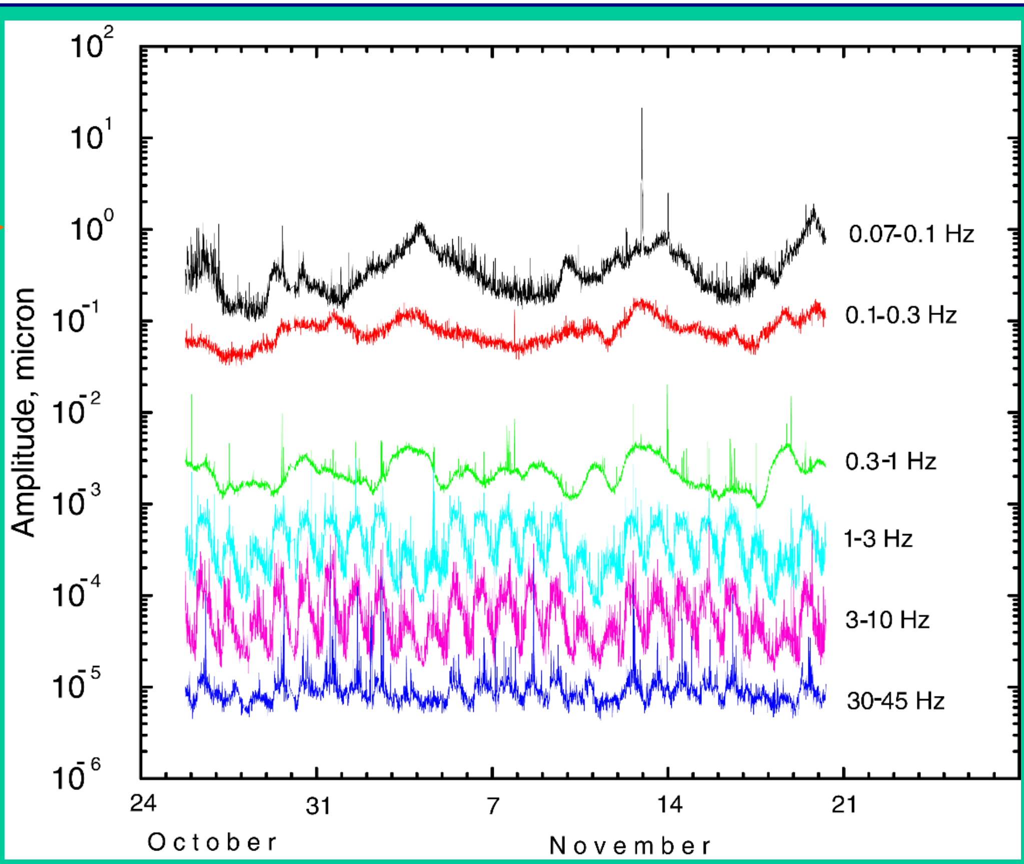
1 micron

What about low frequency motion? It is much larger…

1 nm



PSD is in m$^2$/Hz. Its integral over frequency range give square of rms amplitude of the motion in this frequency band.

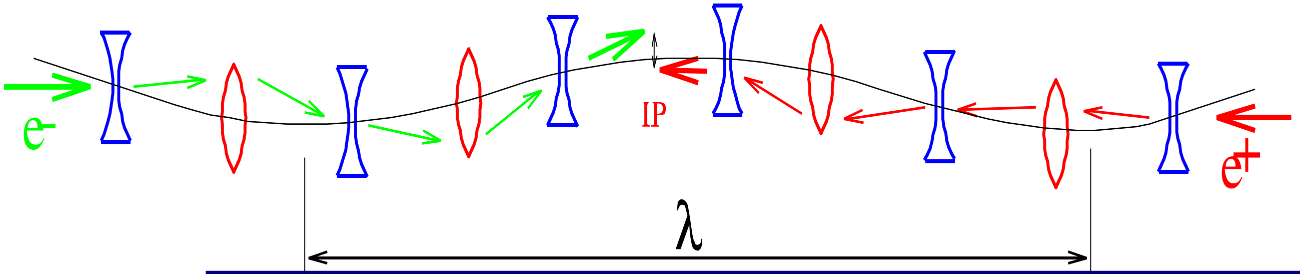


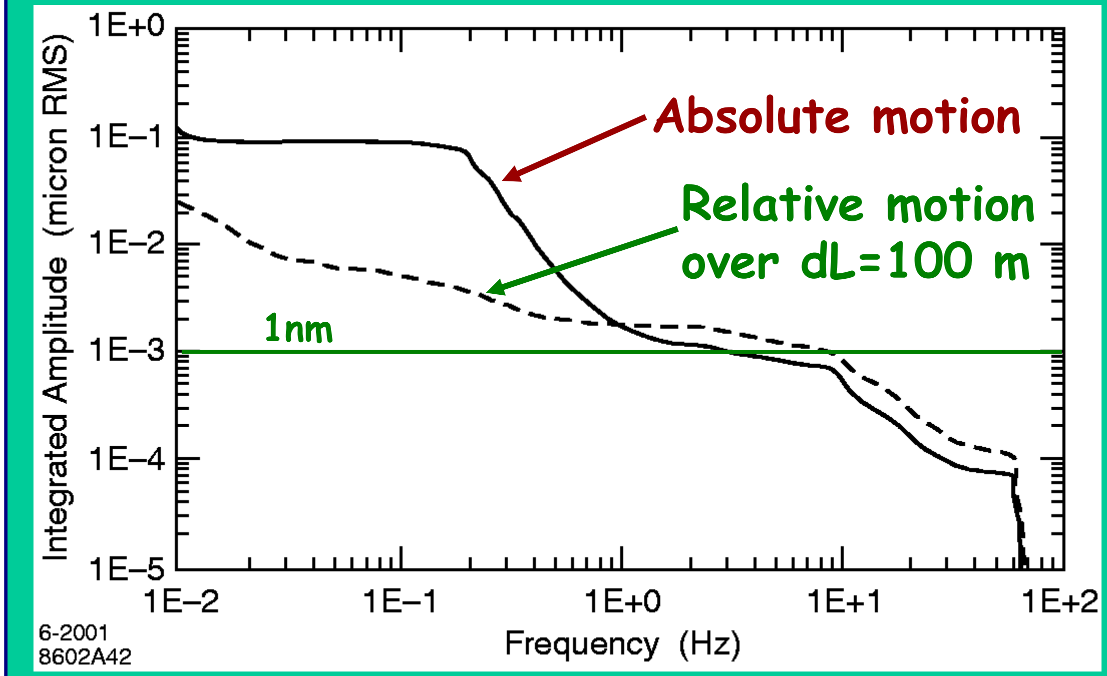
**Rms displacement in different frequency bands. Hiidenvesy cave, Finland, 1993**

# Slow absolute motion is large, but slow relative motion can be much smaller

- **Care about relative, not absolute motion**

- **Slow motion usually have long wavelength, so that the relative motion is much smaller than the absolute**





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

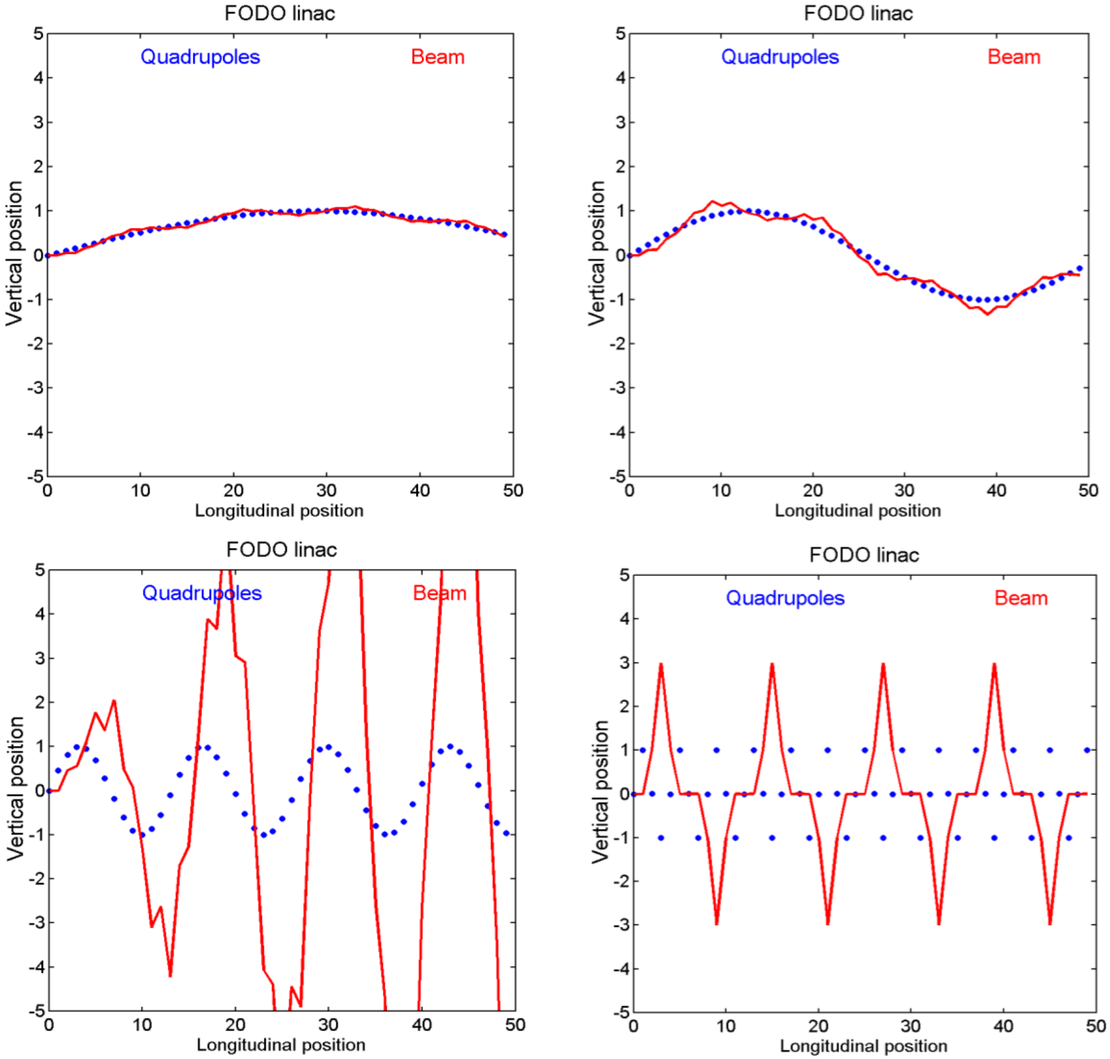
# To find out whether large slow ground motion relevant or not compare focusing wavelength of the collider with wavelength of misalignment

**Beam follows the linac if misalignment is more smooth than focusing wavelength**

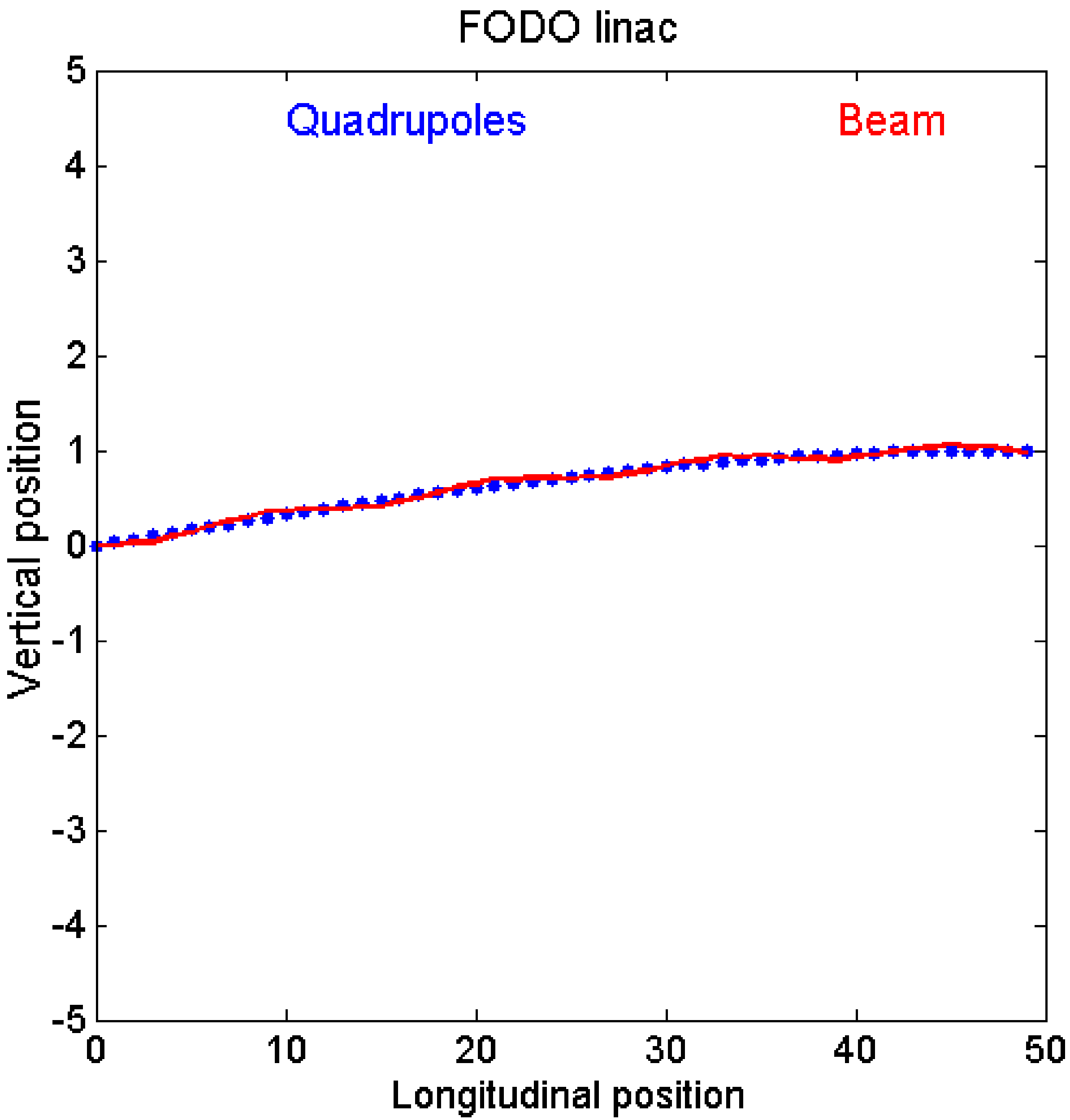
**Resonance appear if wavelength of misalignment ~ focusing wavelength**

For this beamline, focusing wavelength ~100m

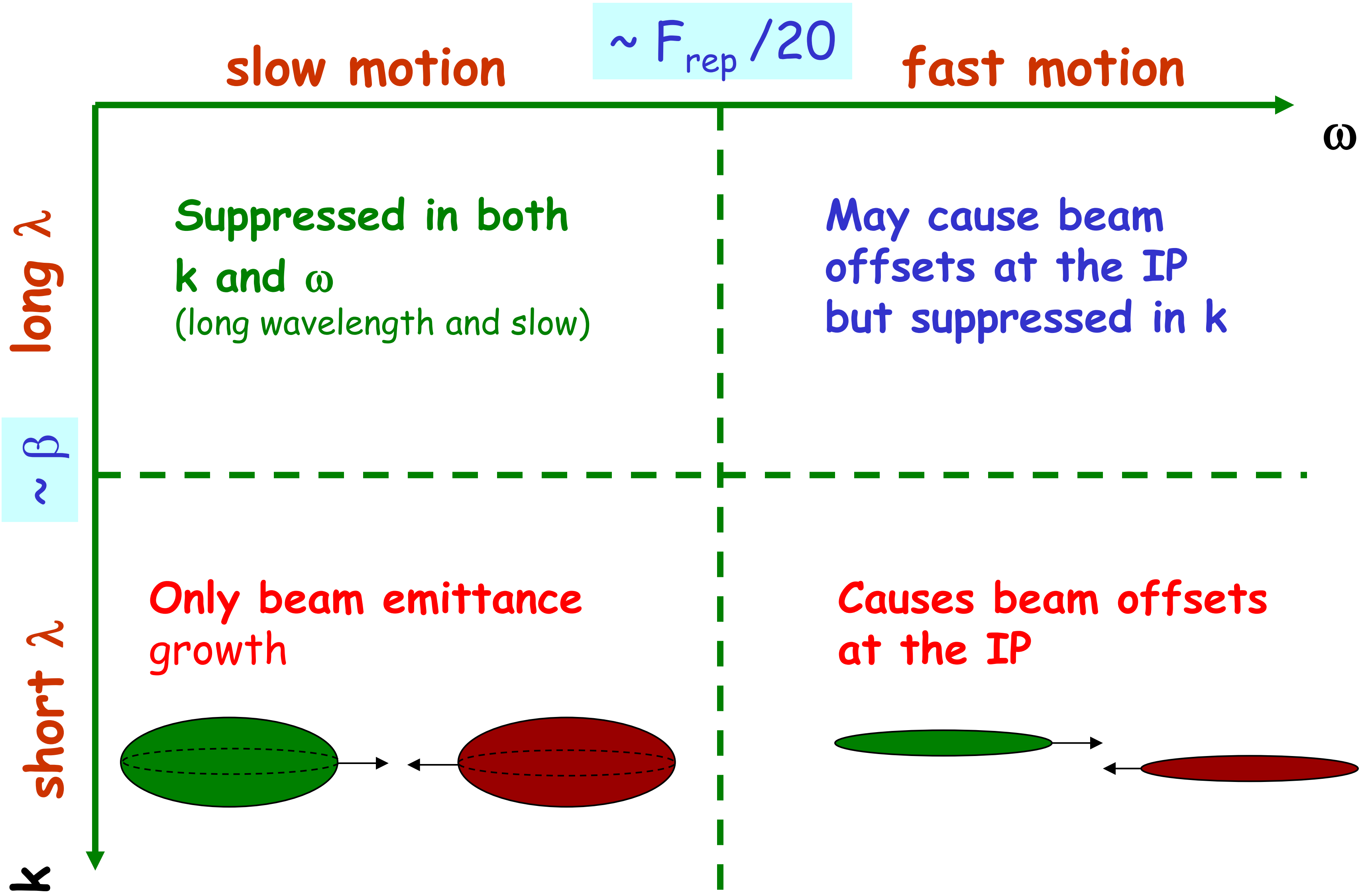
Sensitivity to more smooth misalignments is small



**Example: misaligned FODO linac**


FODO linac
Quadrupoles
Beam
5
4
3
2
1
0
-1
-2
-3
-4
-5
Vertical position
0
10
20
30
40
50
Longitudinal position

# Effects of ground motion in Linear Colliders



slow motion

$\sim F_{rep} / 20$

fast motion

$\omega$

long $\lambda$

$\sim \beta$

short $\lambda$

k

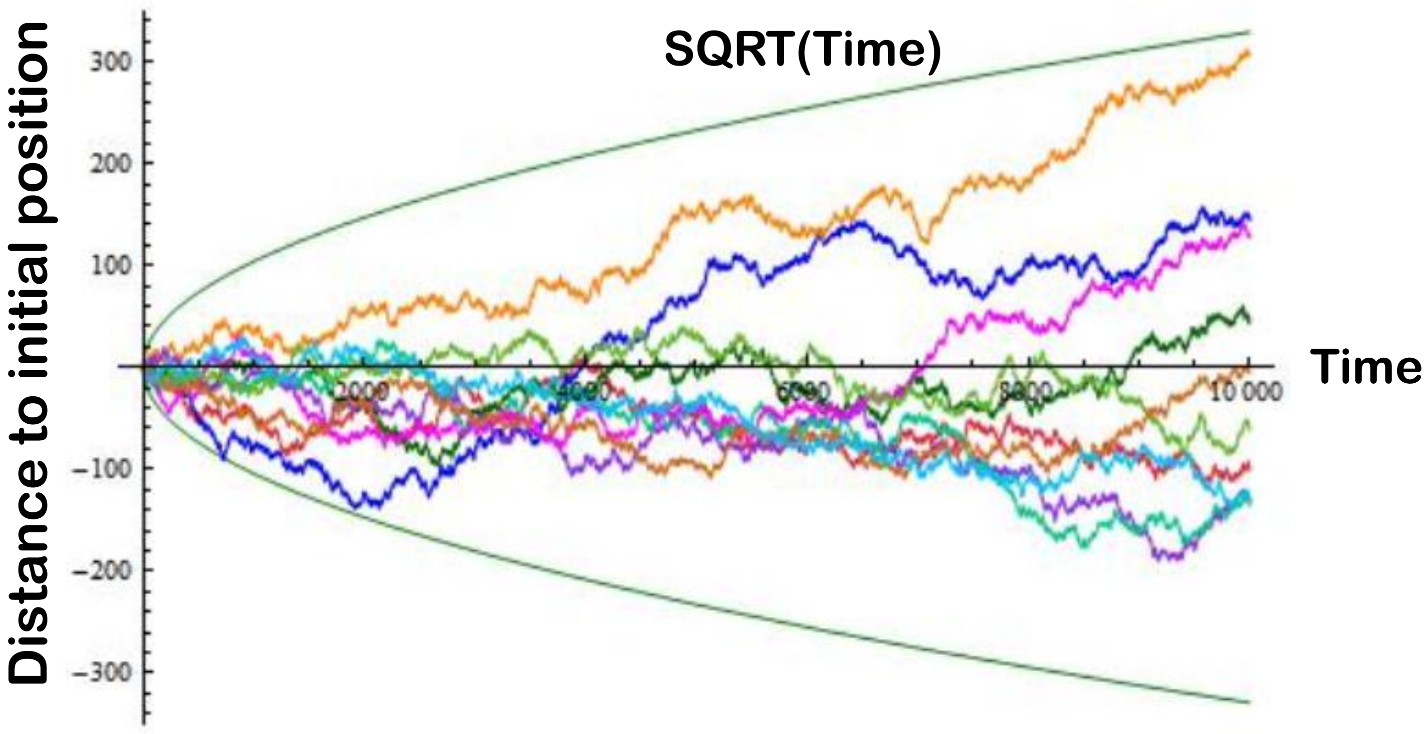
**Suppressed in both k and $\omega$**
(long wavelength and slow)

**May cause beam offsets at the IP but suppressed in k**

**Only beam emittance** growth

**Causes beam offsets at the IP**

# Random walk - diffusive motion



- **In this case distance from the initial position $\Delta X$ in average is zero**
- **However, the rms value, $\Delta X^2$ grows with time linearly**
- **I.e. $\Delta X^2 \sim AT$ (T – elapsed time, A – some constant that depend on the case)**
- **This is diffusion**

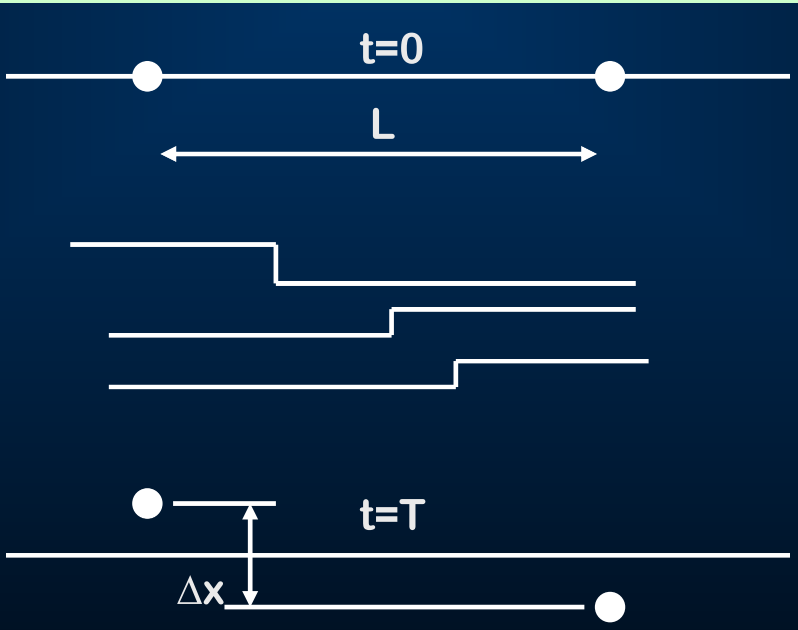
# Slow but short λ ground motion

*What if we are interested in two separated points?*

*=> ATL motion, or diffusion in space and time*

- **Diffusive** or **ATL** motion: $\Delta X^2 \sim ATL$ (T – elapsed time, L – separation between two points)
  - Caused by underground water, dissipation of high frequency motion, temperature, atmosphere, etc.
- Observed 'A' varies by ~5 orders: 10$^{-9}$ to 10$^{-4}$ $\mu m^2/(m{\cdot}s)$
  - **'A'** strongly depends on **geology**
  - **Higher 'A'** in sedimentary geology, lower A in solid rock

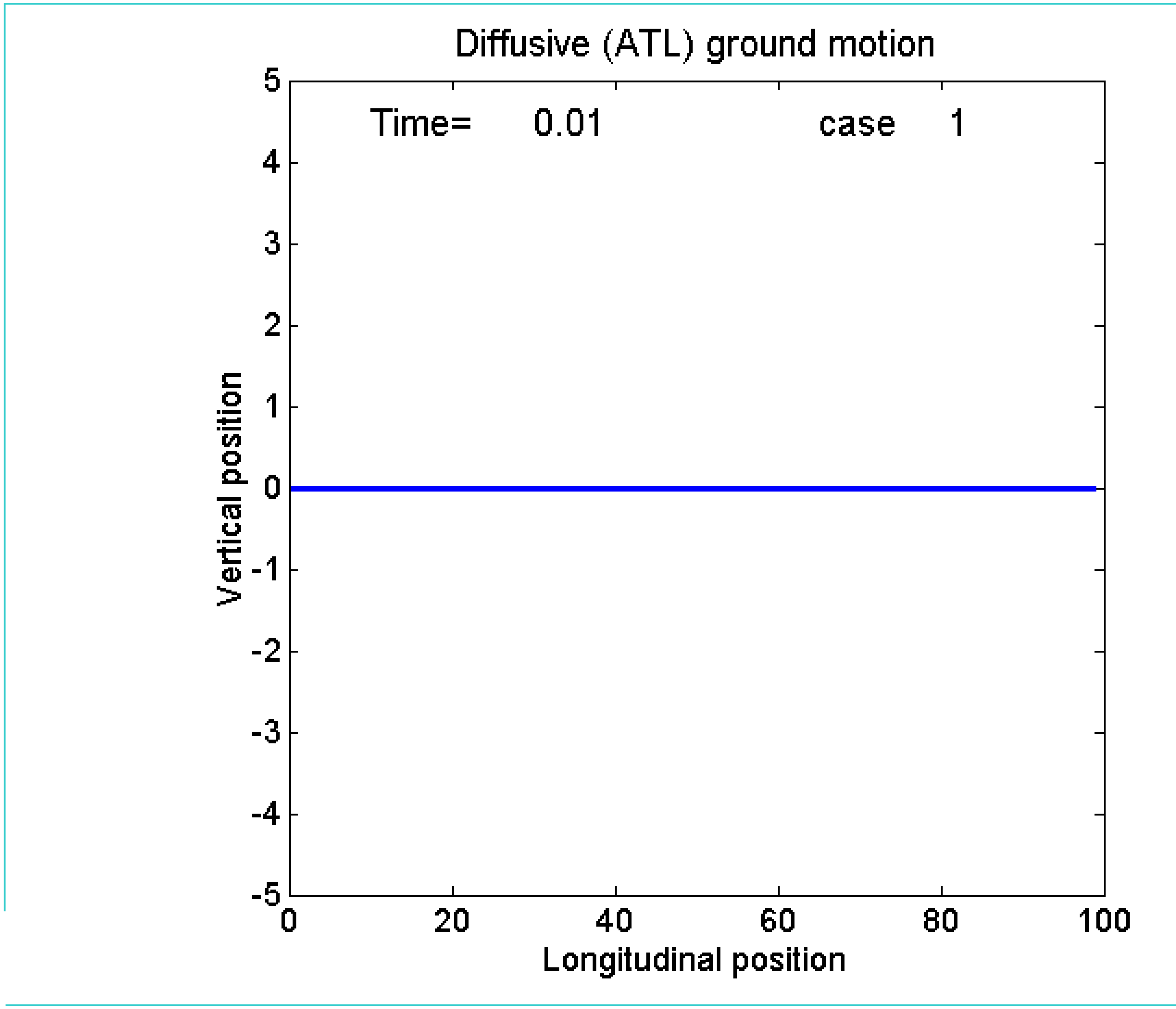
Simple illustration allowing to imagine how ATL motion happens:



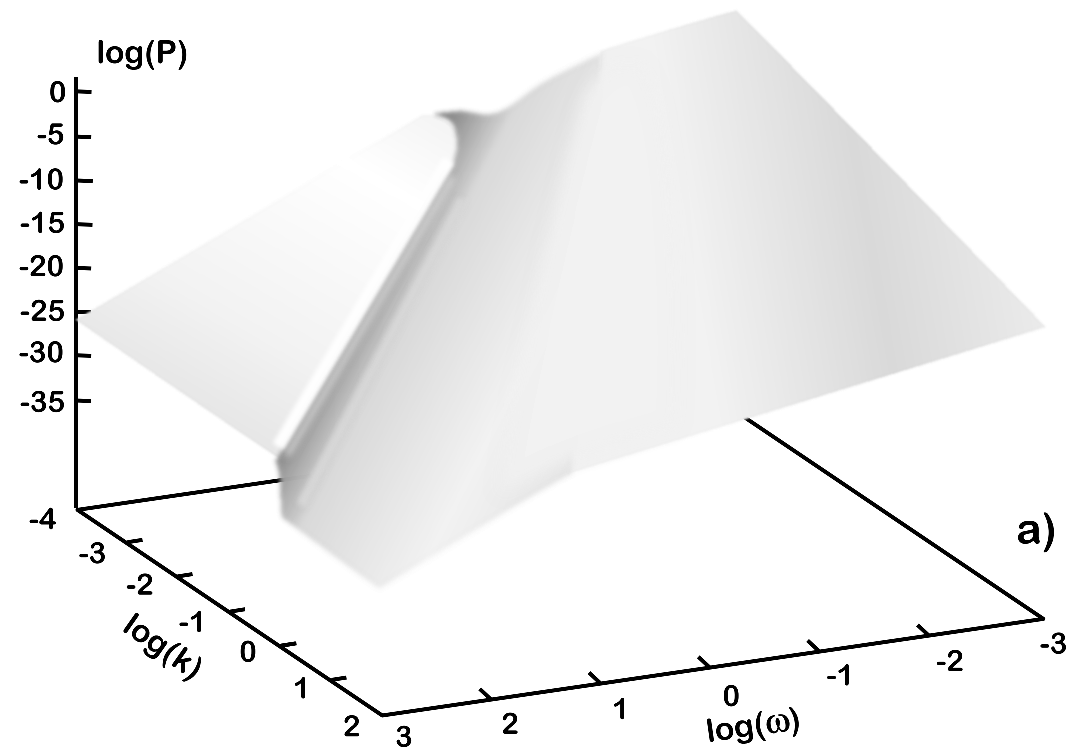
Number of random step-like displacements between two points is proportional to L &T

# How diffusive ATL motion looks like?

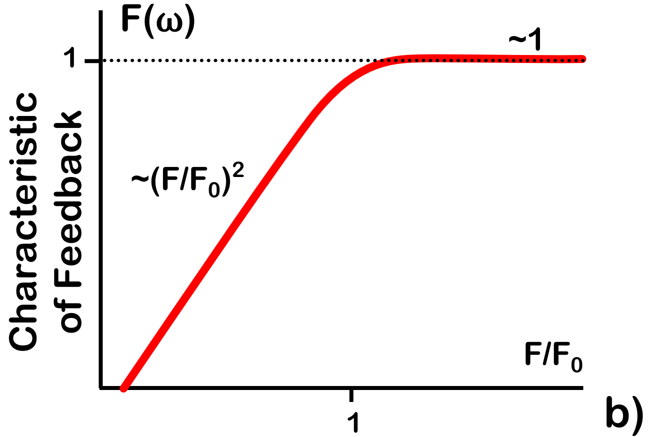
- **Movie of simulated ATL motion**
- **Note that it starts rather fast**
- **$X^2 \sim L$**
- **and it can change direction…**

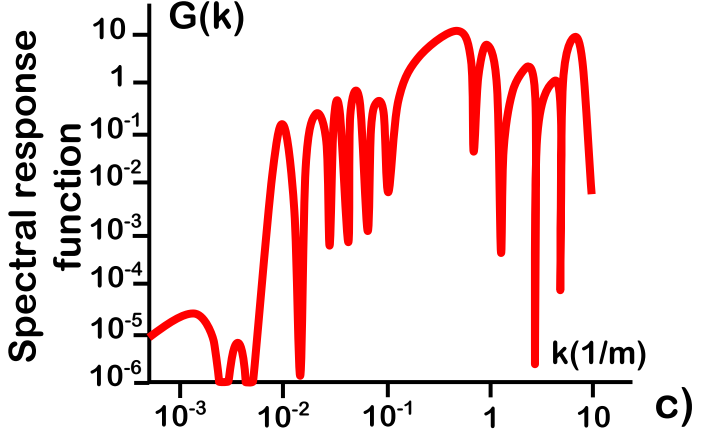


# Ground motion induced beam offset at IP

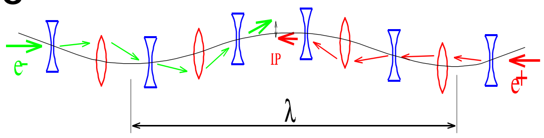


$P(\omega,k)$ - 2D spectrum of ground motion





Spectral response function $G(k)$

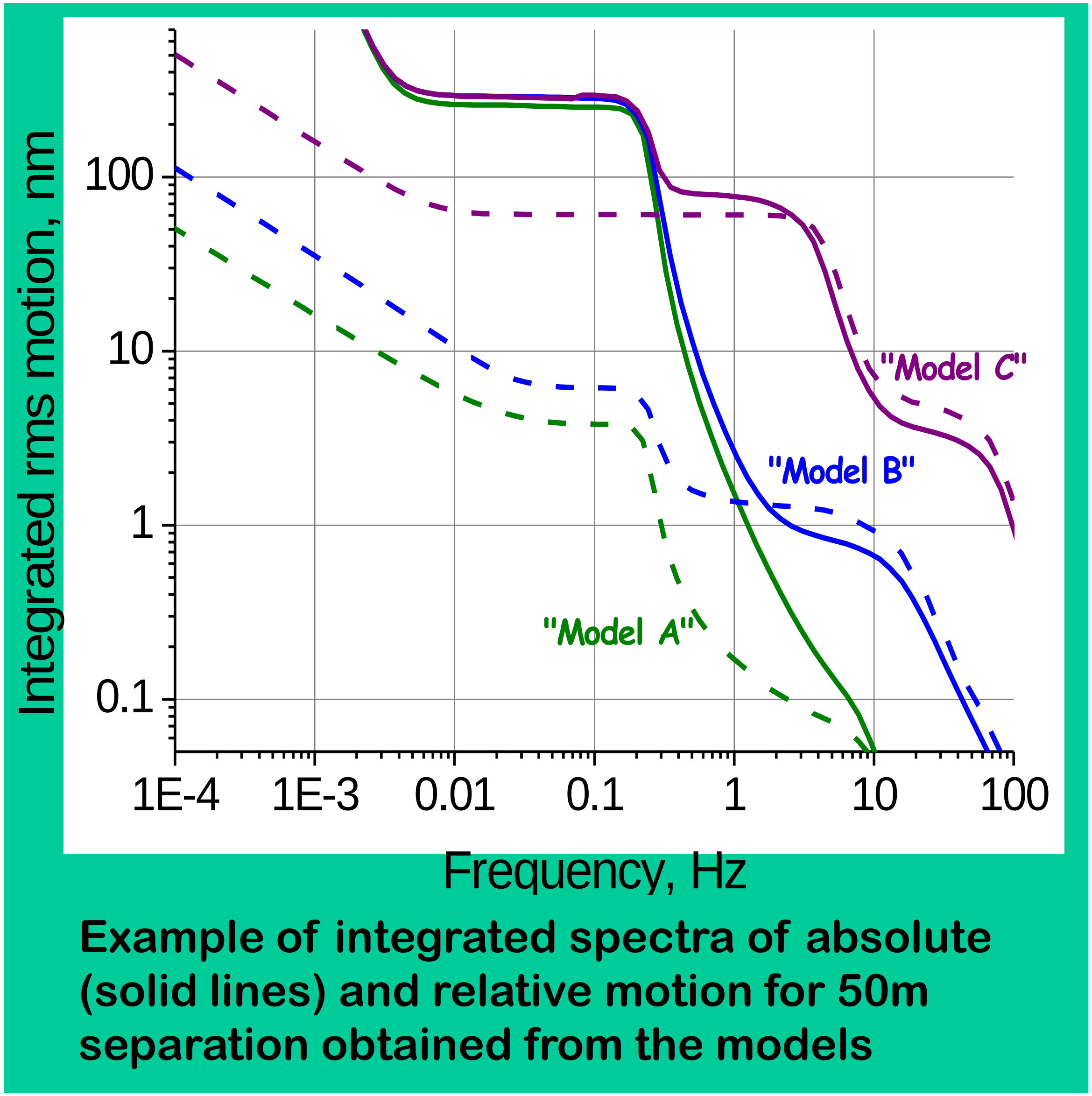


**rms beam offset at IP:** $\propto \iint P(\omega,k)\cdot G(k)\cdot F(\omega)\cdot dk\cdot d\omega$

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

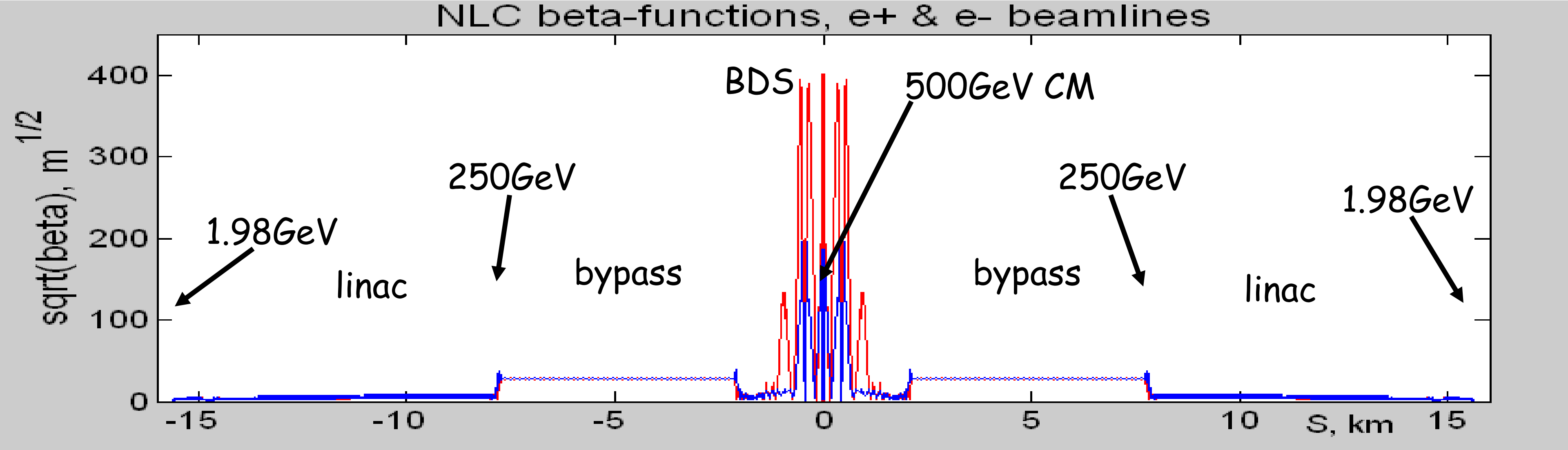
# Ground motion models

- Based on data, build modeling P(ω,k) spectrum of ground motion which includes:
  - Elastic waves
  - Slow ATL motion
  - Systematic motion
  - Cultural noises

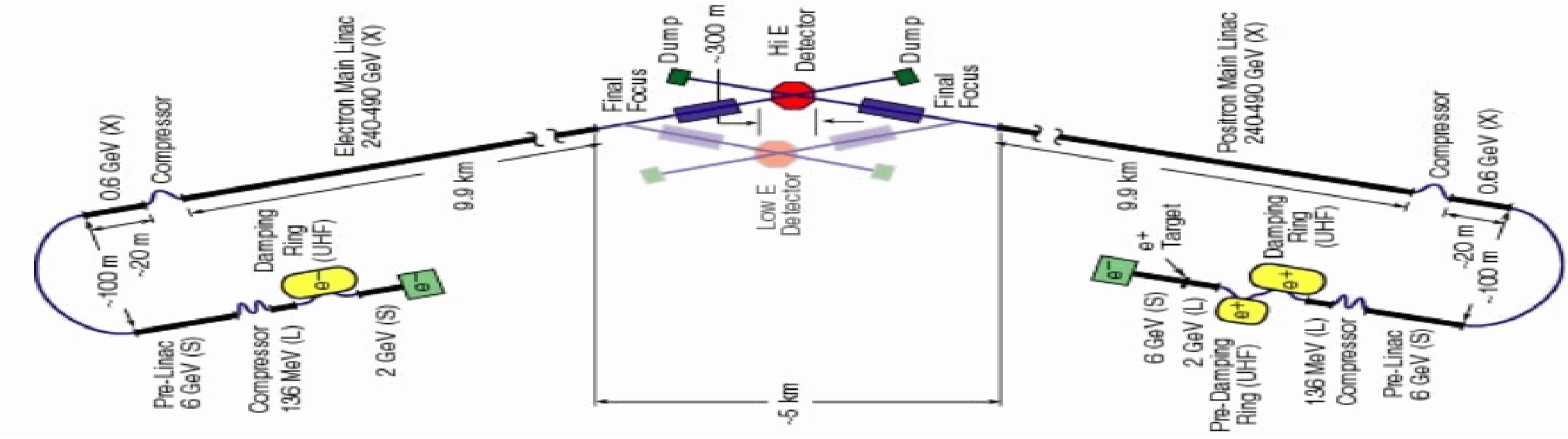


**Example of integrated spectra of absolute (solid lines) and relative motion for 50m separation obtained from the models**

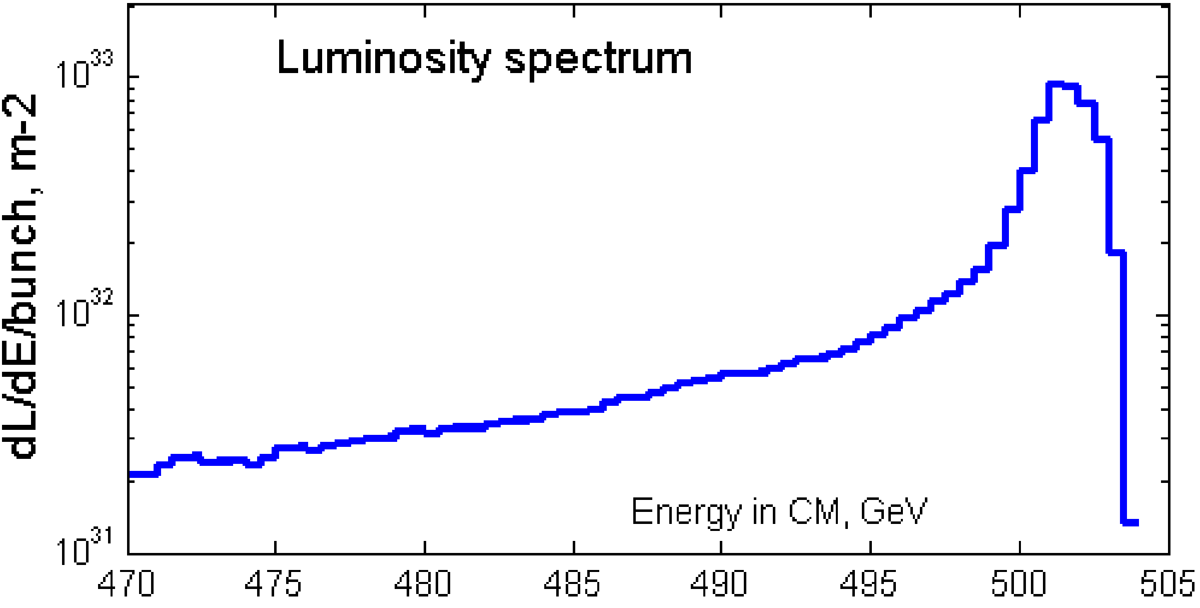
# e- source => Interaction Point <= e+ source integrated simulations

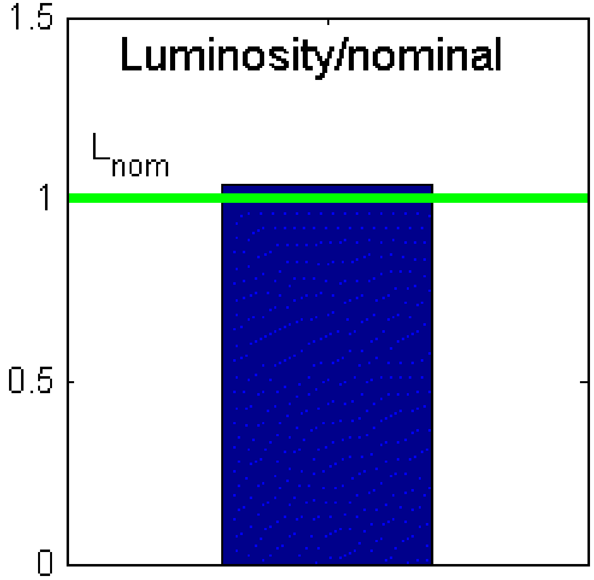


**IP**

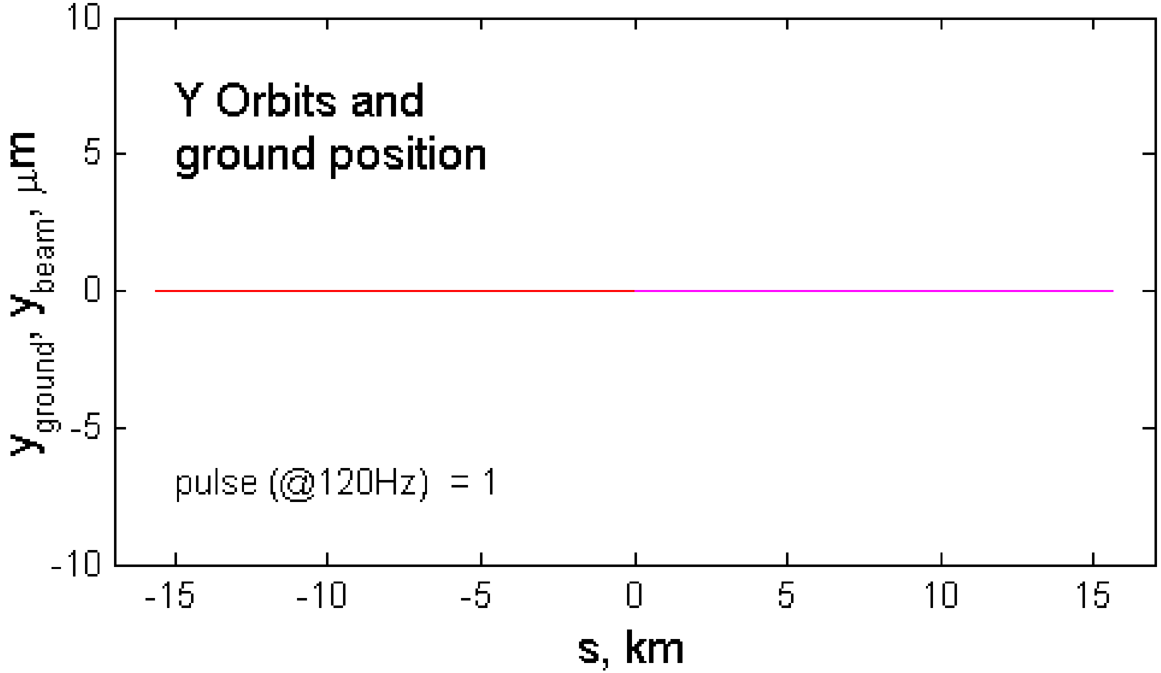


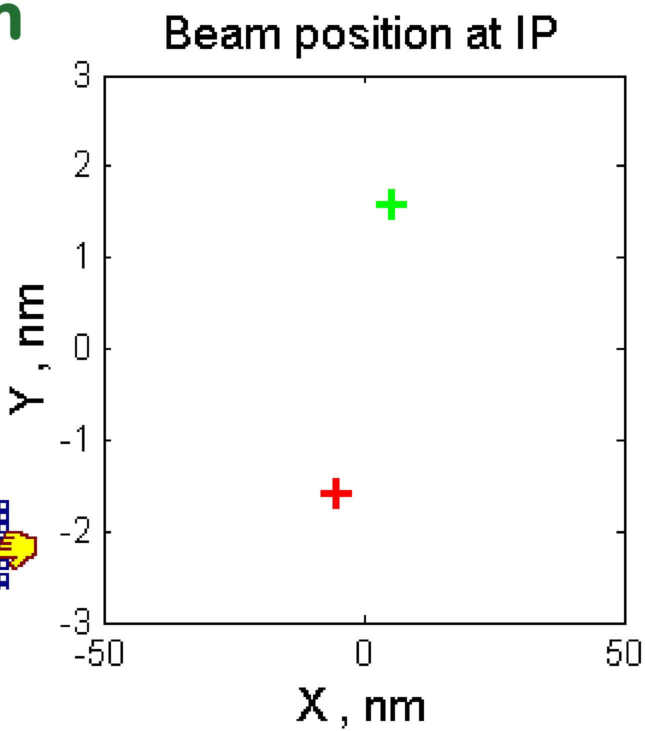
# NLC, DR>IP<DR; GM B; RF misal(x,y)=75,15 microns, IP feedback



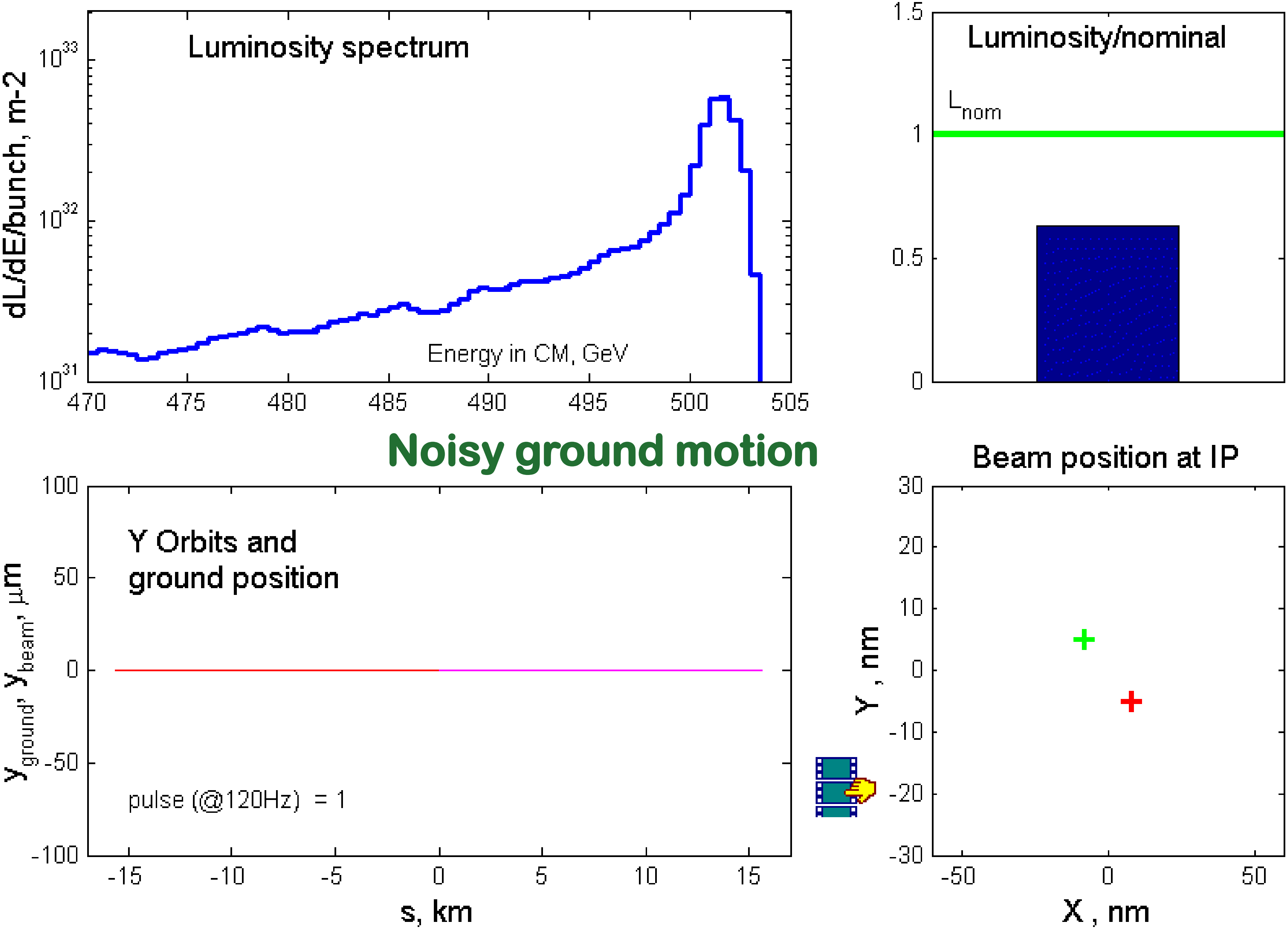


## Intermediate ground motion





# NLC, DR>IP<DR; GM C; RF misal(x,y)=75,15 microns, IP feedback

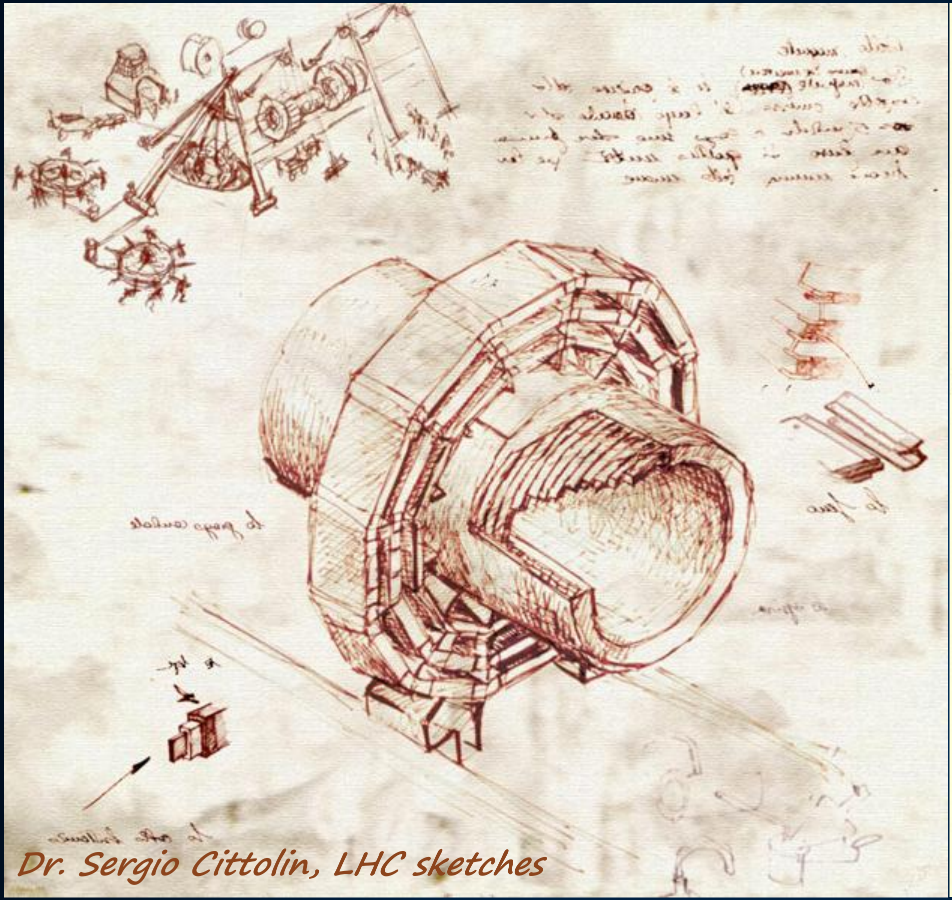


**Noisy ground motion**

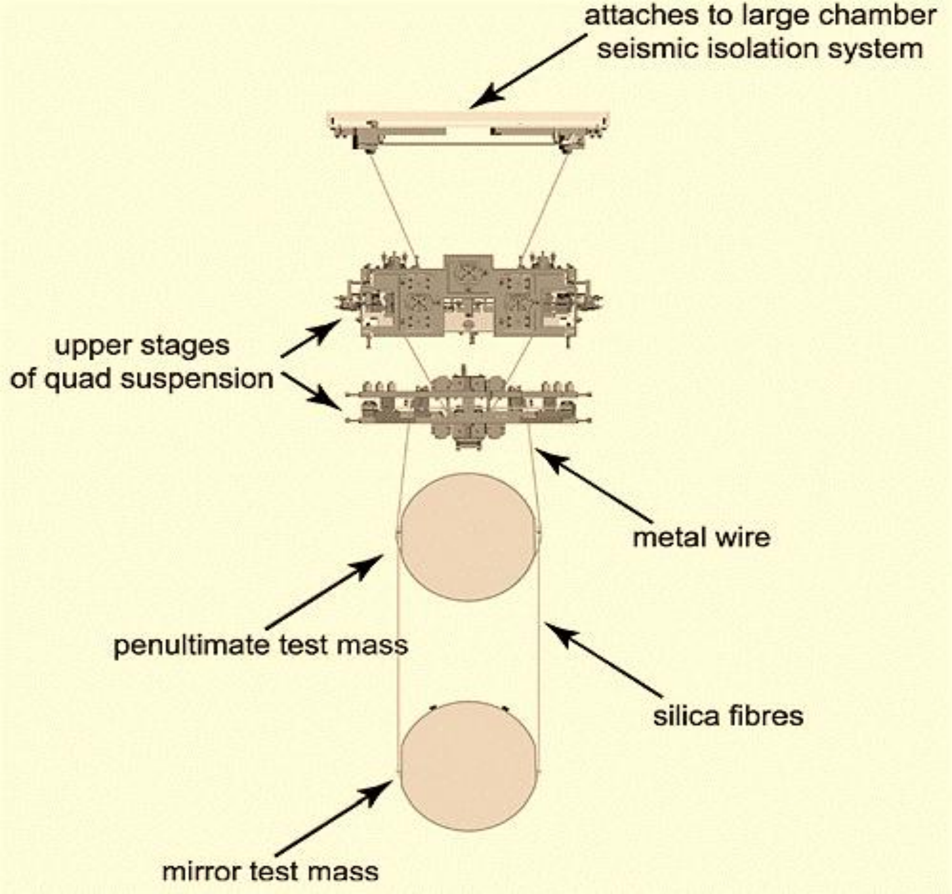
# Inventions in developments of LC

A lot of inventions happened in development of accelerators, linear colliders, and the methods to provide their stability – similarly as in providing stability of gravitational wave observatories

# Particle or gravitational waves detectors

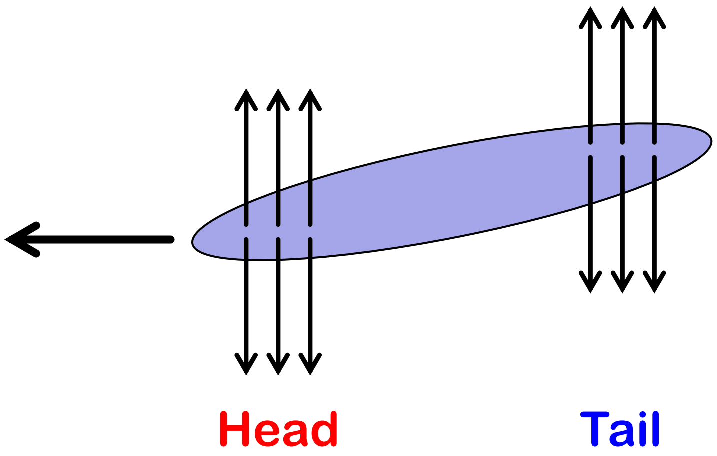


*Dr. Sergio Cittolin, LHC sketches*



…are arranged just as nested dolls…

# Stability of relativistic beams



Field of the relativistic bunch is transverse

Therefore, the tail would not know if the head have offset/oscillations or not

For instability to develop one need some agent that would carry the information from head to tail

This agent can be for example the opposite colliding beam

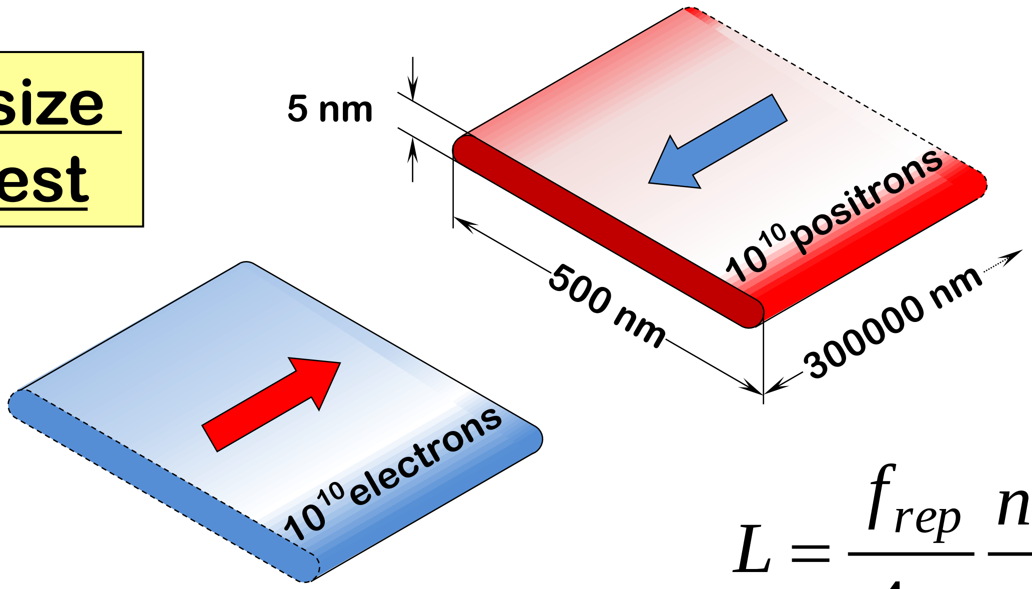
Or fields induced in surrounding structures

# How to get Luminosity

- To increase probability of direct $e^+e^-$ collisions (luminosity) and birth of new particles, beam sizes at IP must be very small
- E.g., ILC beam sizes just before collision (500GeV CM):
  500 * 5 * 300000 nanometers

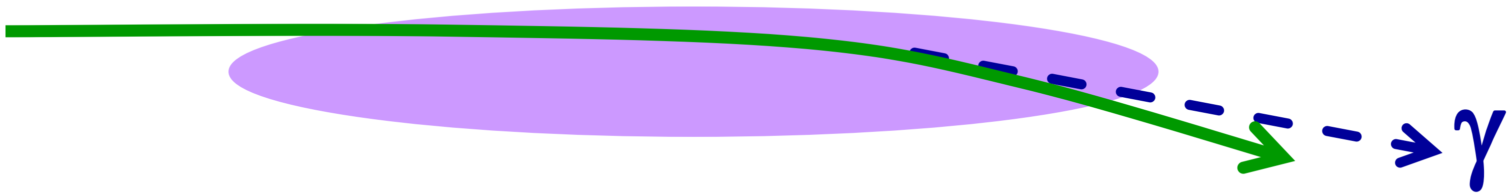
(x y z)

Vertical size is smallest



$$L = \frac{f_{rep}}{4\pi} \frac{n_b N^2}{\sigma_x \sigma_y} H_D$$

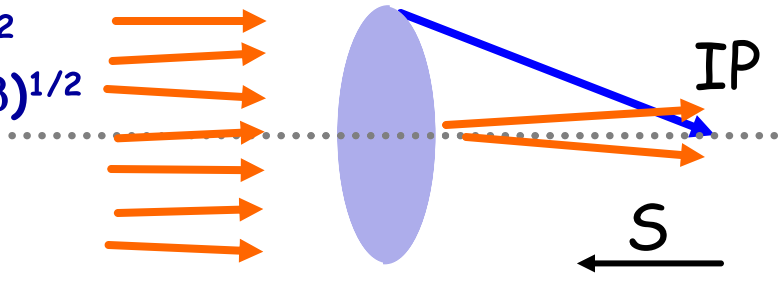
# Beam-beam interactions



- Transverse fields of ultra-relativistic bunch
  - focus the incoming beam (electric and magnetic force add)
  - reduction of beam cross-section leads to more luminosity
    - $H_D$ - the luminosity enhancement factor
  - bending of the trajectories leads to emission of beamstrahlung

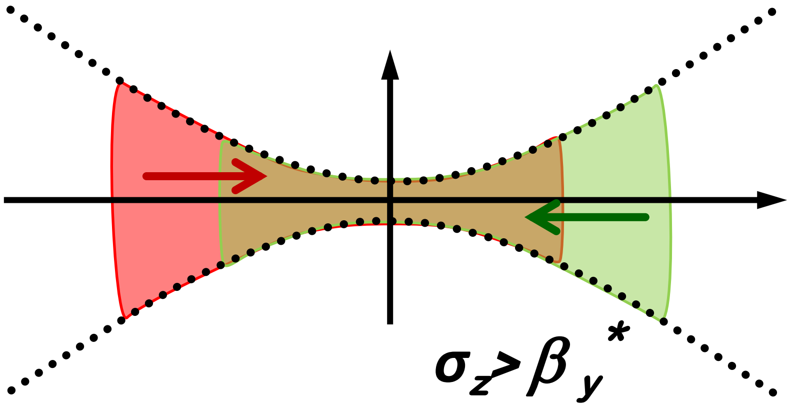
# Hourglass effect

**Size: $(\varepsilon\ \beta)^{1/2}$**
**Angles: $(\varepsilon/\beta)^{1/2}$**



$$\beta(s) = \beta^* + \frac{s^2}{\beta^*}$$

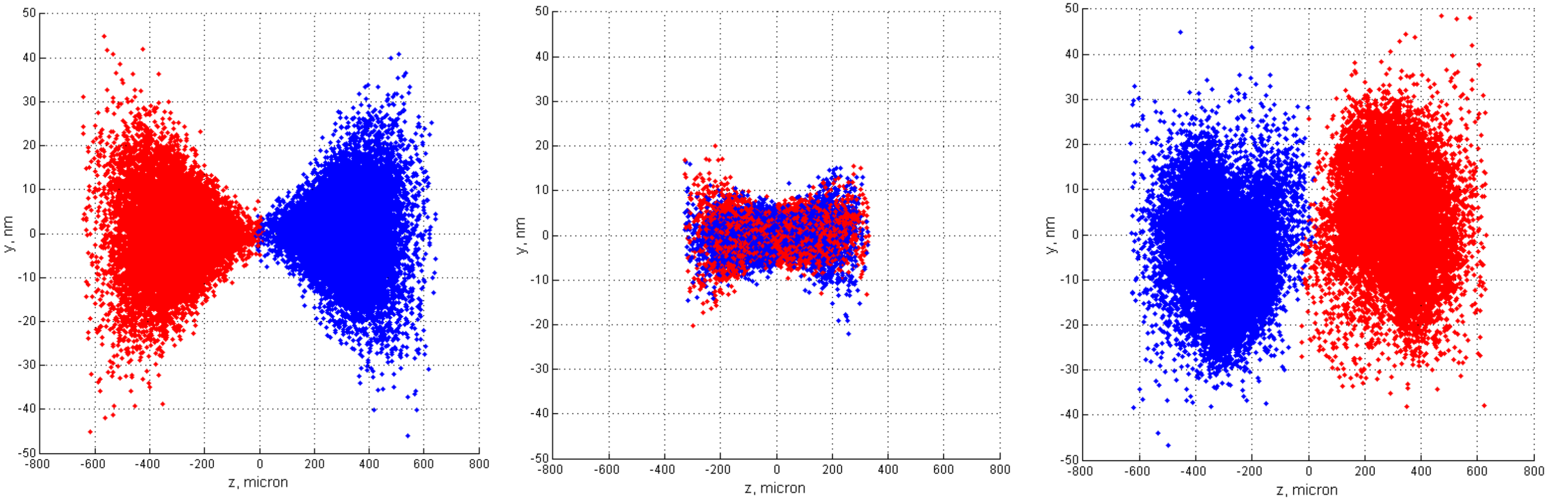
$\beta^*$ beta function at the IP



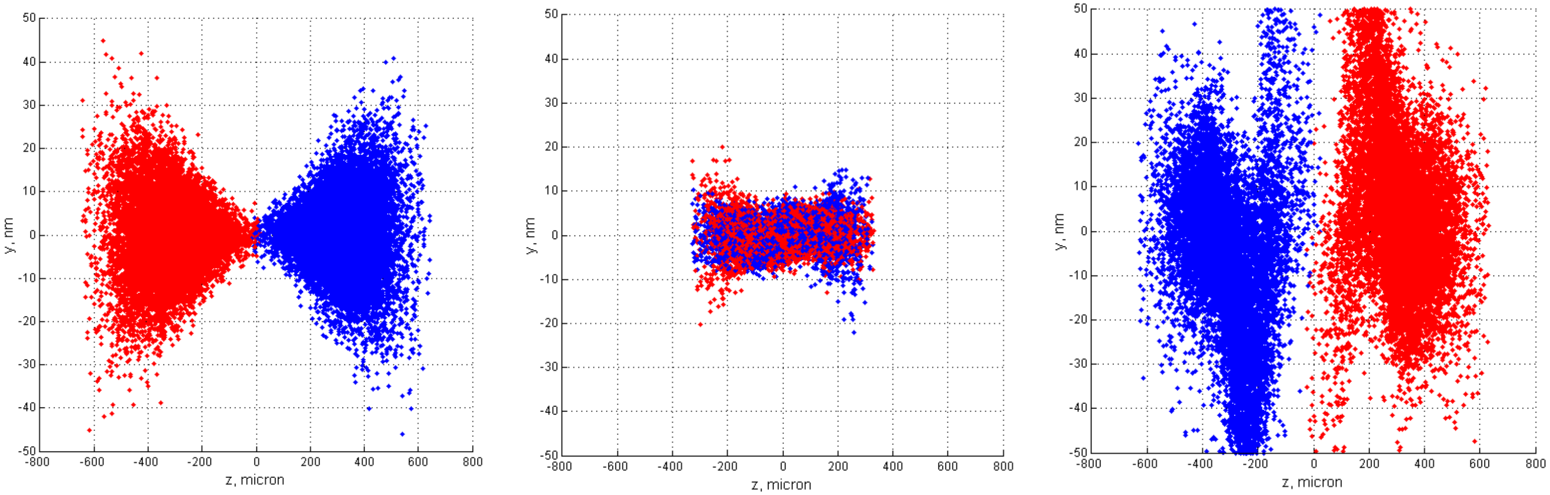
**Reduction of $\beta^*$ below $\sigma_z$ does not give further decrease of effective beam size (<u>usually</u>)**

# Stability of colliding beams
# $H_D$ and instability

$$D_y = \frac{2r_e}{\gamma}\frac{N\sigma_z}{\sigma_x\sigma_y}$$



**$D_y$~12**



**Nx2**
**$D_y$~24**

# Disruption parameter

- **For Gaussian transverse beam distribution, and for particle near the axis, the beam kick results in the final particle angle:**

$$\Delta x' = \frac{dx}{dz} = -\frac{2Nr_e}{\gamma\sigma_x\left(\sigma_x+\sigma_y\right)}\cdot x \qquad \Delta y' = \frac{dy}{dz} = -\frac{2Nr_e}{\gamma\sigma_y\left(\sigma_x+\sigma_y\right)}\cdot y$$

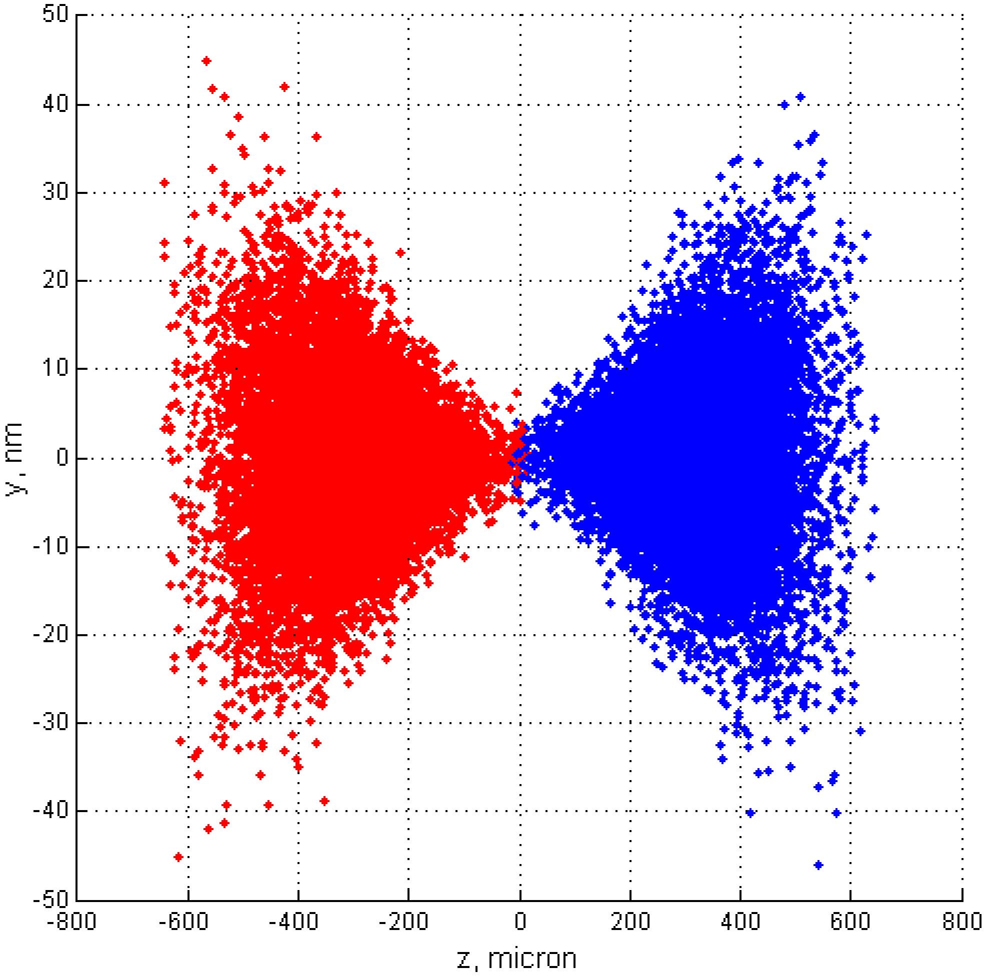
- **“Disruption parameter” – characterize focusing strength of the field of the bunch ($D_y \sim \sigma_z/f_{beam}$)**

$$D_x = \frac{2Nr_e\sigma_z}{\gamma\sigma_x\left(\sigma_x+\sigma_y\right)} \qquad D_y = \frac{2Nr_e\sigma_z}{\gamma\sigma_y\left(\sigma_x+\sigma_y\right)}$$

- **D << 1 – bunch acts as a thin lens**
- **D >> 1 – particle oscillate in the field of other bunch**
  - **If D is bigger than ~20, instability may take place**

# Beam-beam effects

## $H_D$ and instability



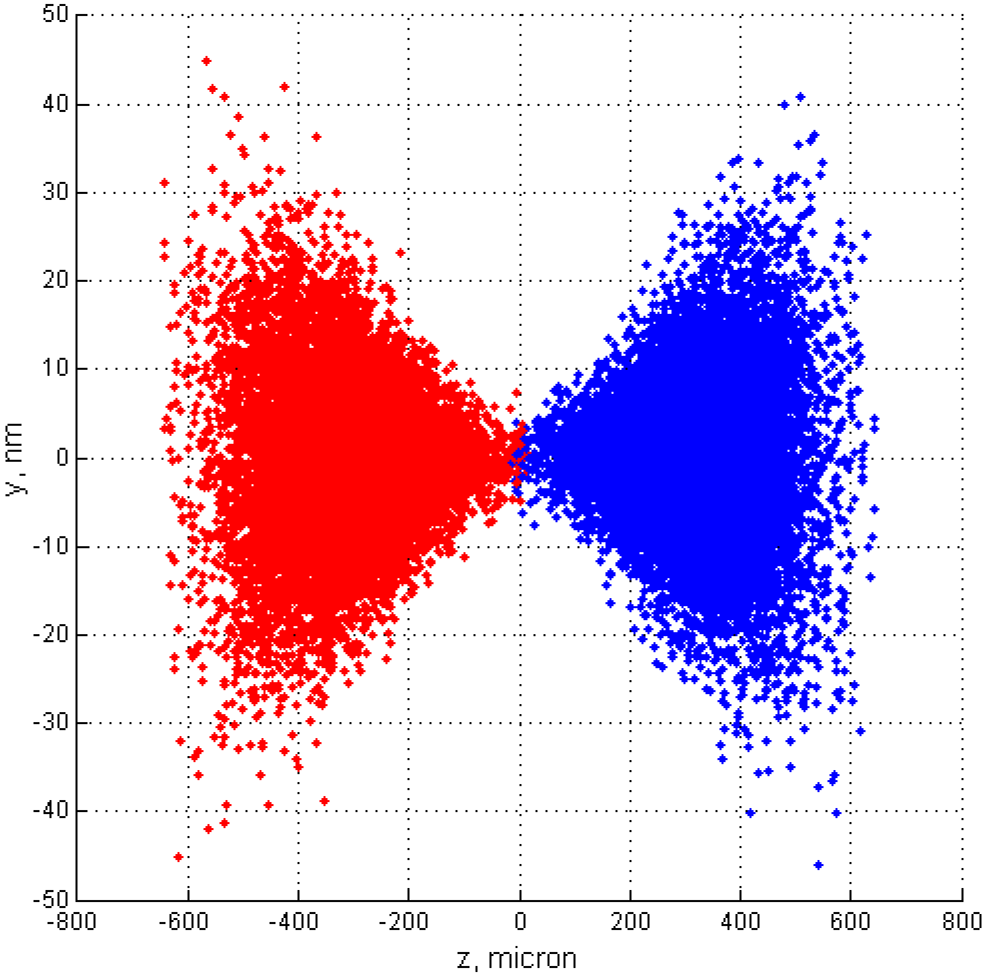
**LC parameters**
**$D_y$~12**

**Luminosity enhancement**
**$H_D$ ~ 1.4**

**Not much of an instability**

# Beam-beam effects

## $H_D$ and instability

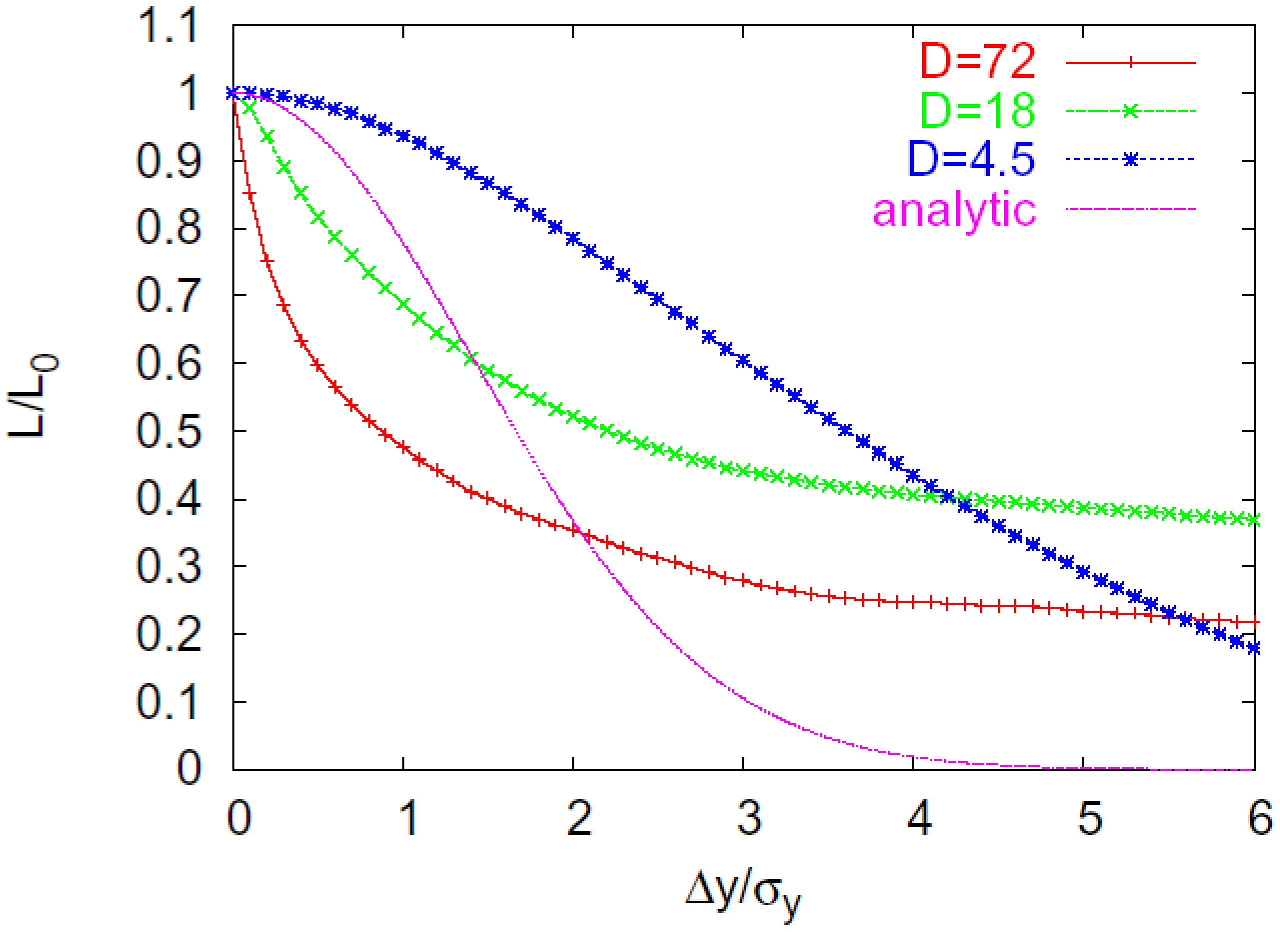


Nx2
$D_y$~24

Beam-beam instability is clearly pronounced

Luminosity enhancement is compromised by higher sensitivity to initial offsets

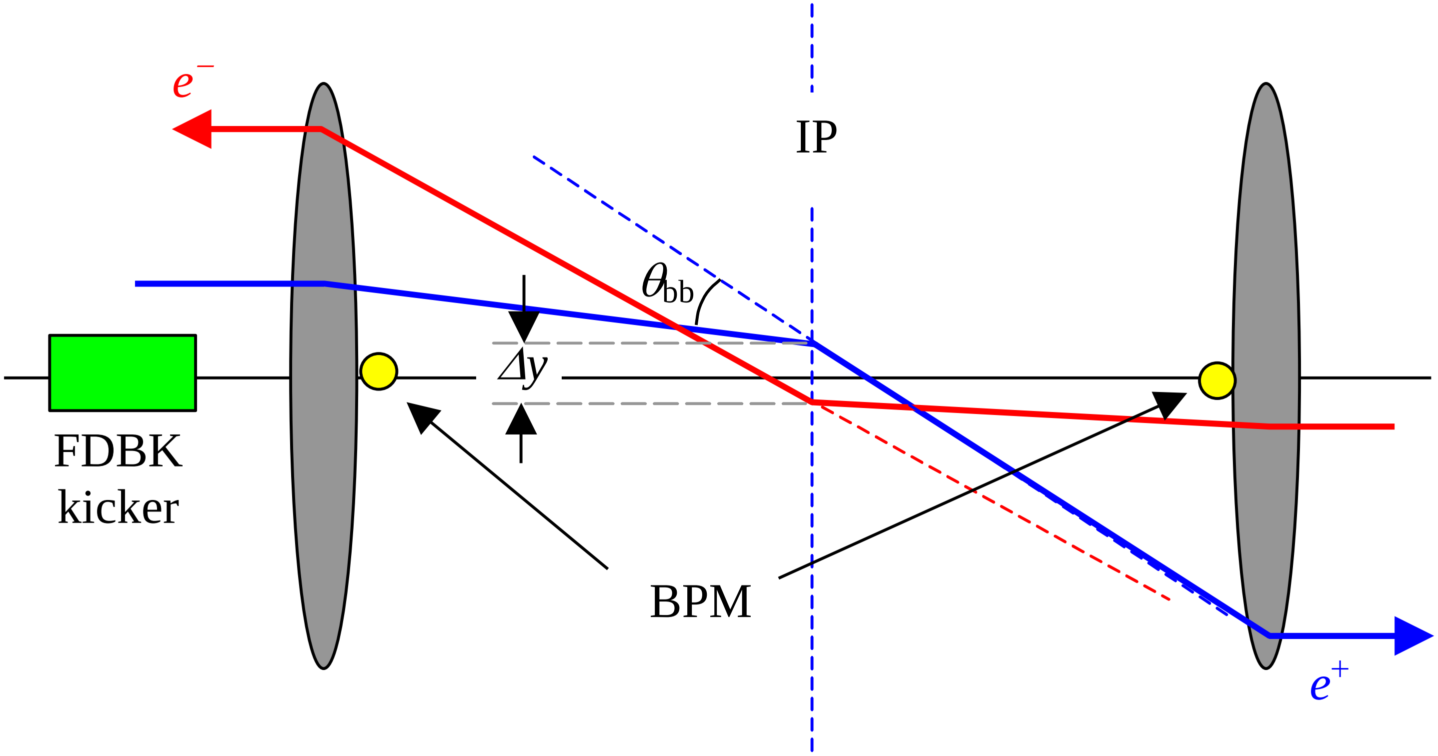
# Sensitivity to offset at IP



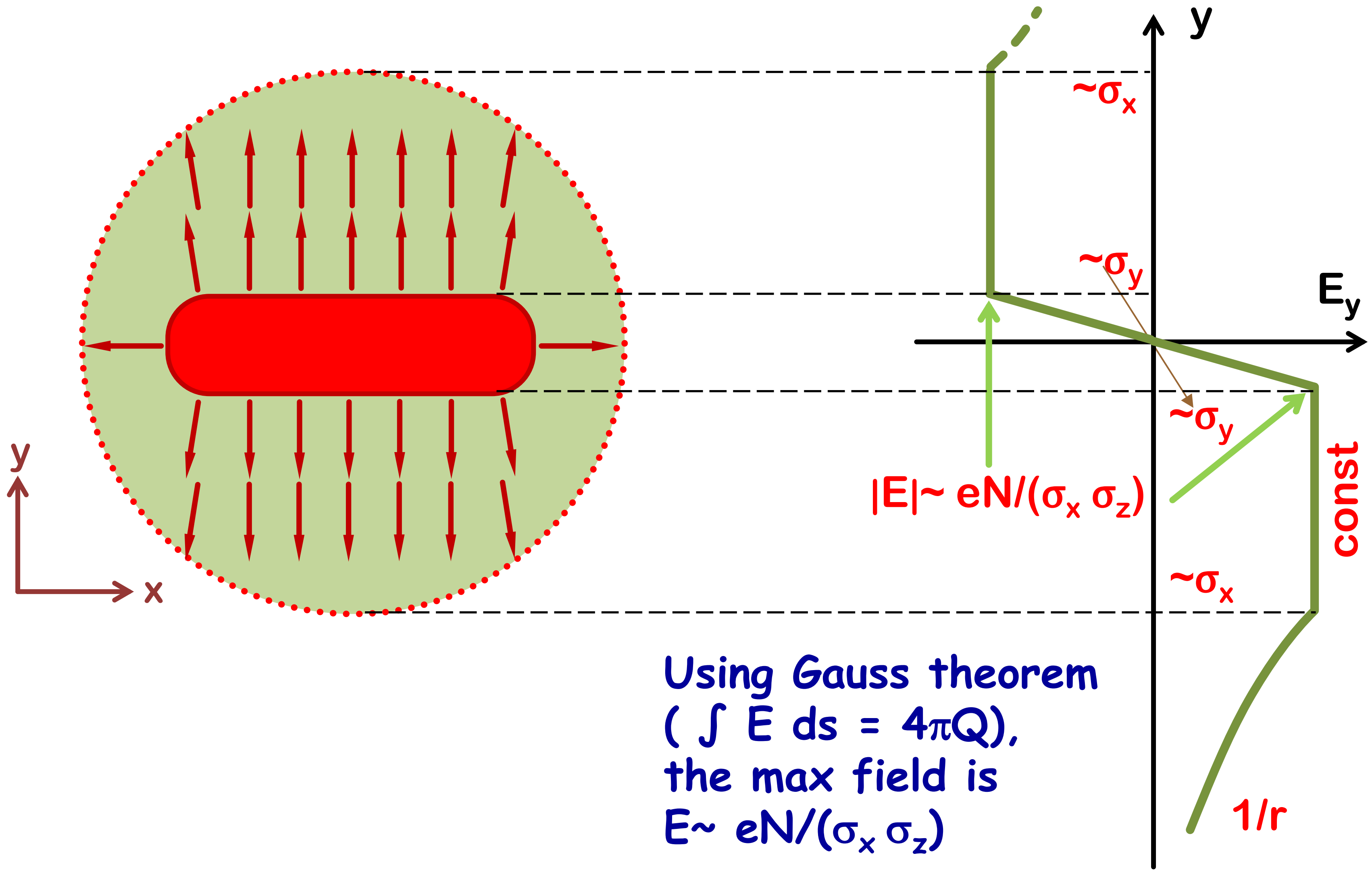
- **Luminosity (normalized) versus offset at IP for different disruption parameters**

# Beam-Beam feedback

- **Use the strong beam-beam deflection kick for keeping beams in collision**
- **Sub-nm offsets at IP cause well detectable offsets (micron scale) a few meters downstream**



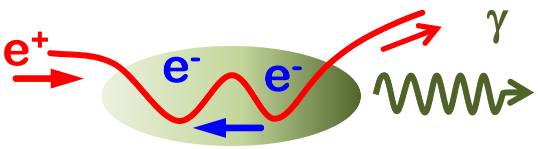
# Why beams in LC are flat



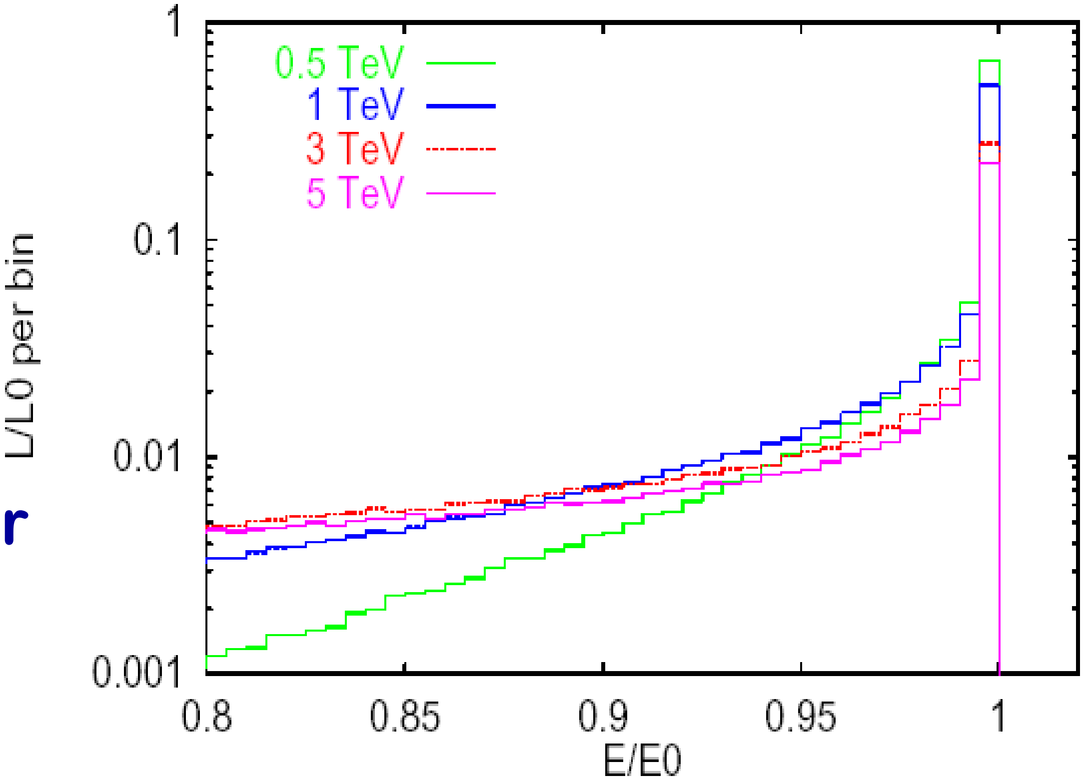
Using Gauss theorem ( $\int E\, ds = 4\pi Q$), the max field is $E\sim eN/(\sigma_x \sigma_z)$

# Beamstrahlung

- "synchrotron radiation" in the field of the opposing bunch



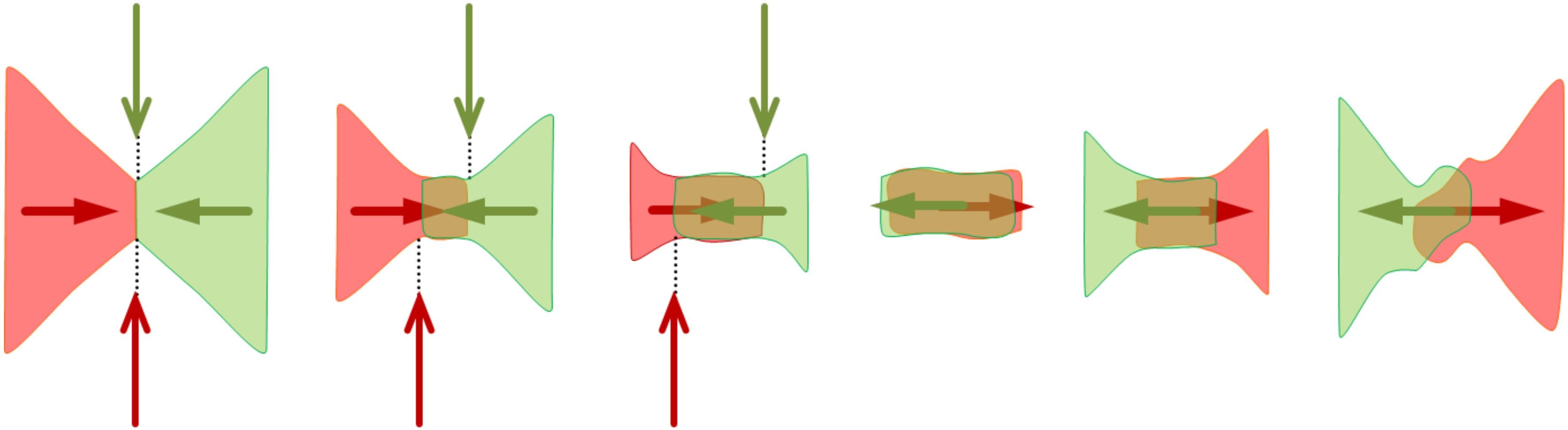
- smears out luminosity spectrum
- creates $e^+e^-$ pairs background in detector



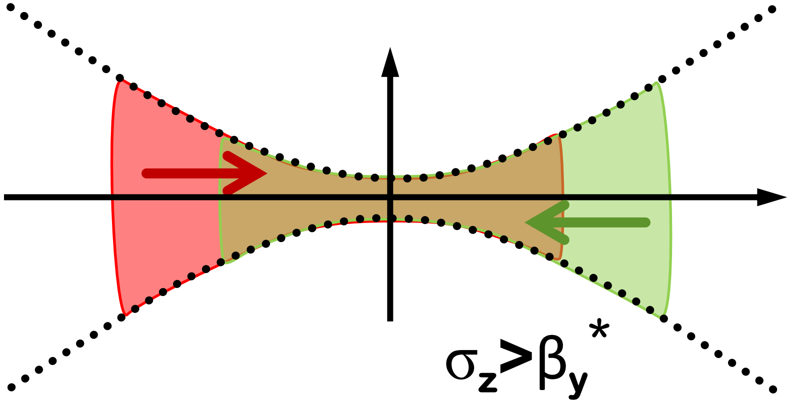
- quantified by beamstrahlung energy loss

$$\delta_{BS} \approx 0.86 \frac{r_e^3}{2m_0c^2} \left( \frac{E_{cm}}{\sigma_z} \right) \frac{N^2}{(\sigma_x + \sigma_y)^2}$$

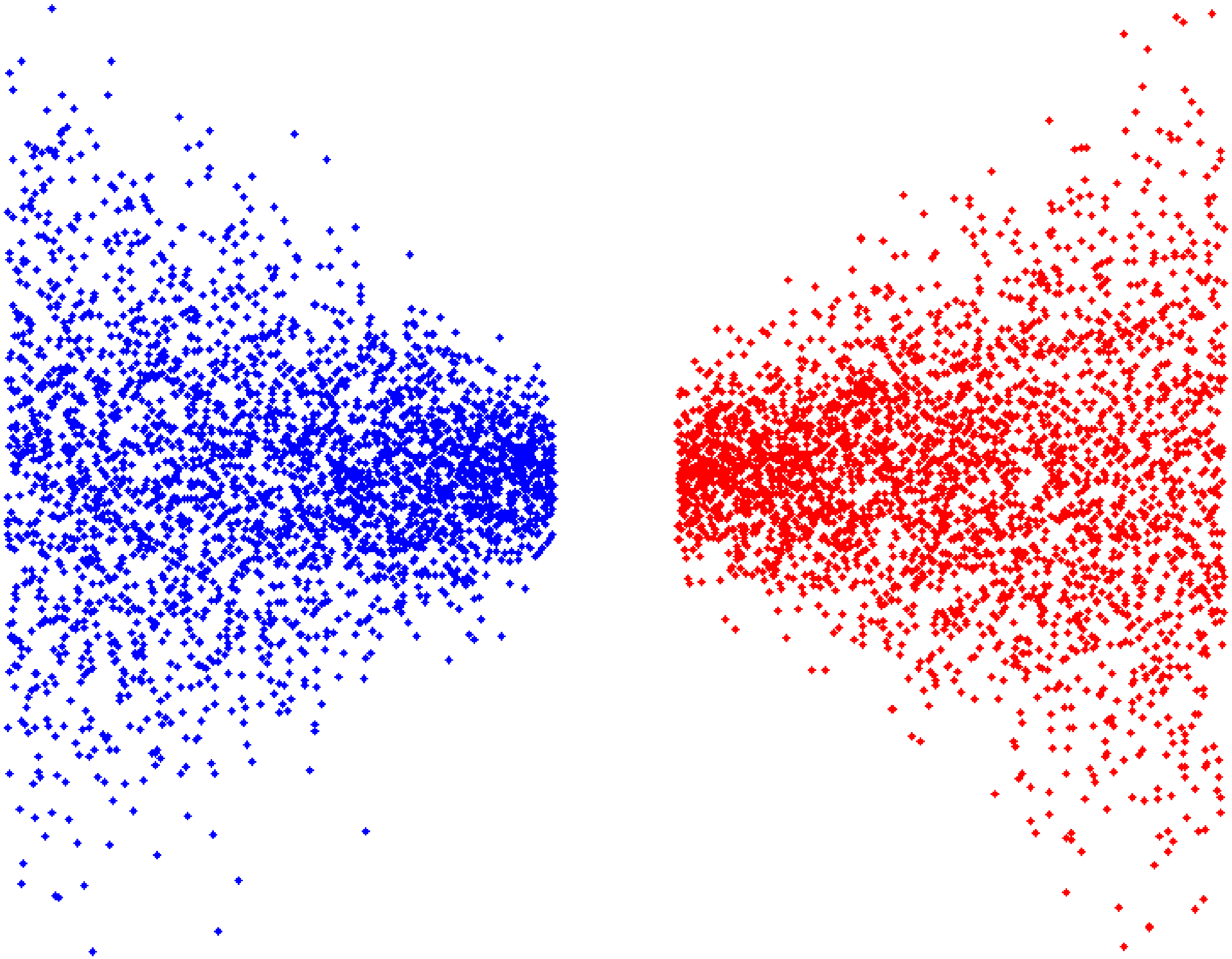
# Overcoming hour-glass effect: Travelling focus



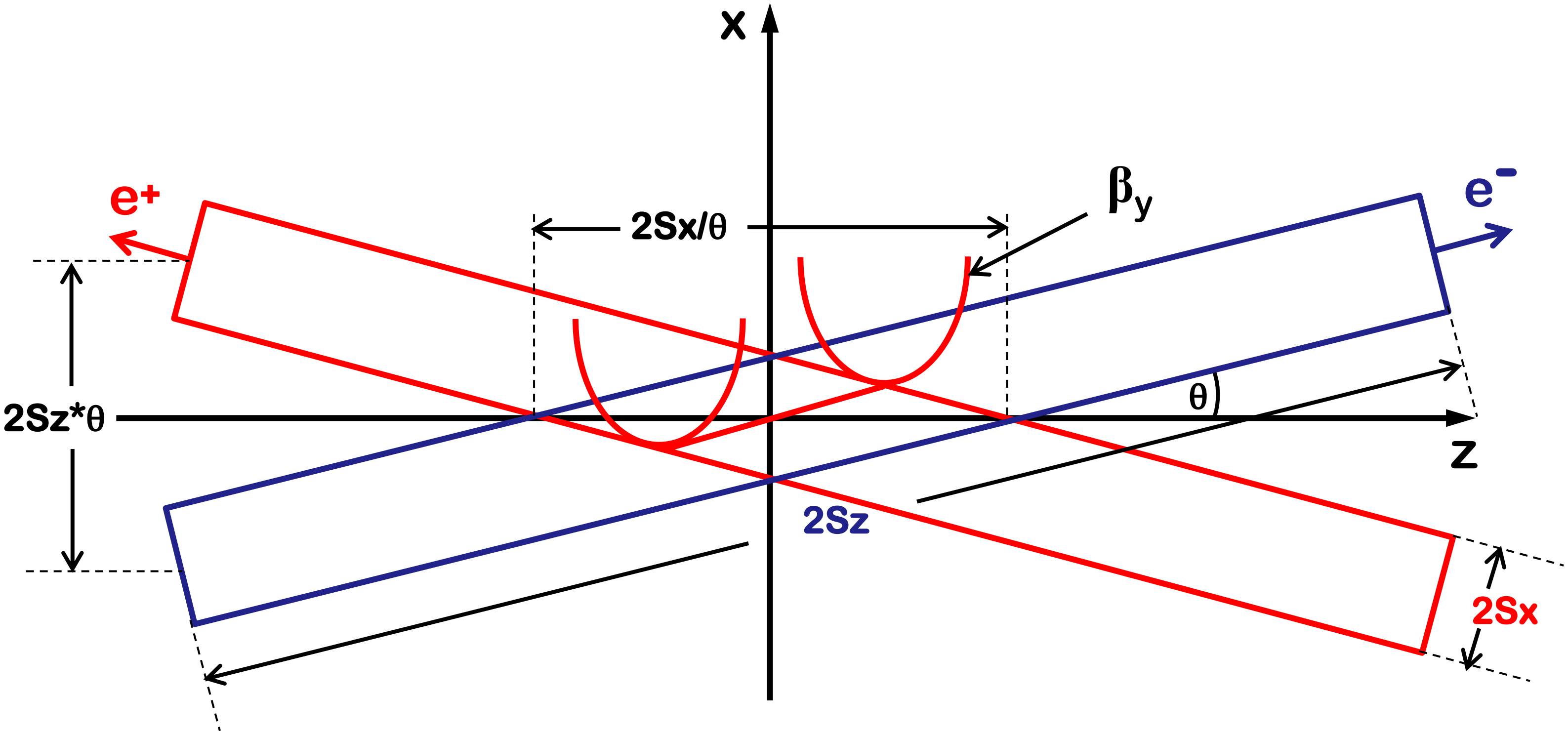
- Idea is to use beam-beam forces for additional focusing of the beam – allows some gain of luminosity or overcome somewhat the hour-glass effect
- Figure shows simulation of traveling focus. The arrows show the position of the focus point during collision
- So far not yet used experimentally



# Collision with travelling focus



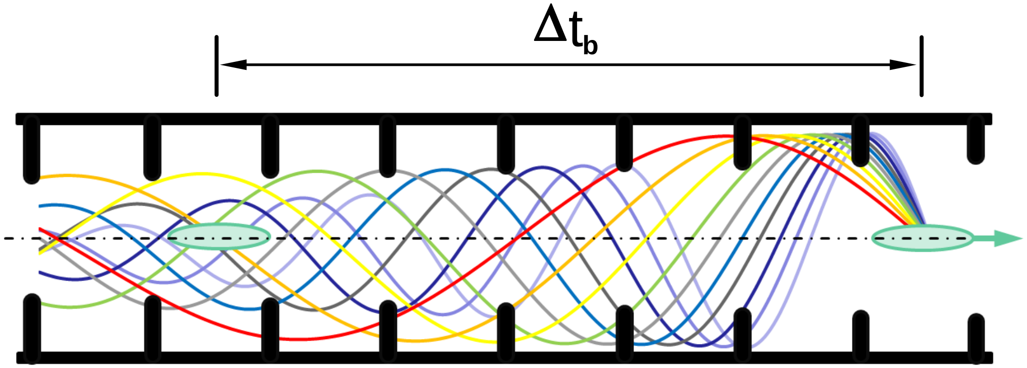
# Overcoming hour-glass effect: Crabbed-waist



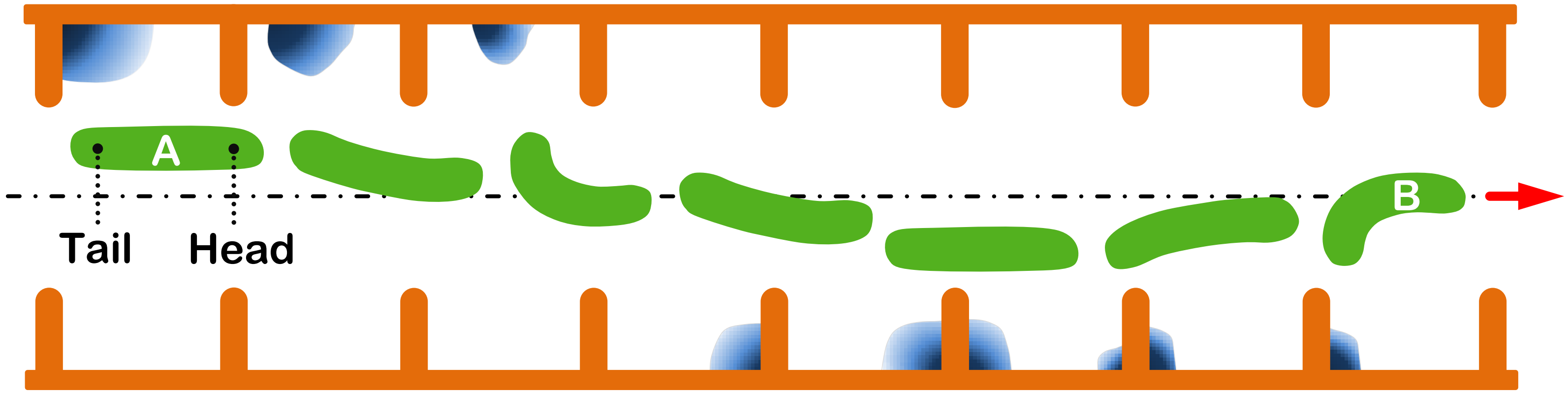
- Suggested by P.Raimondi for Super-B factory
- Vertical waist has to be a function of X. In this case coupling produced by beam-beam is eliminated
- Experimentally verified at DAFNE

# Beam stability issues: wakefields

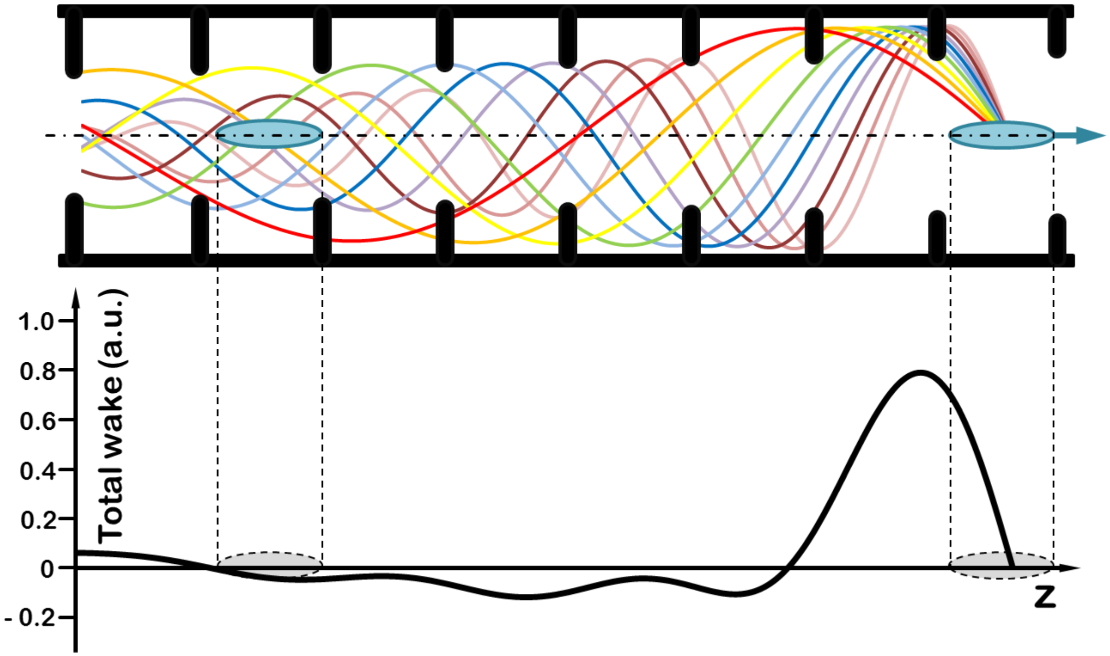
**The interaction of the charged beam with the RF cavity and the vacuum chamber in general generate e.m. fields which act back on the bunch itself**



**In the RF cavity these fields can build up resonantly and disrupt the bunch itself in the so called single beam break up or multi bunch break up**



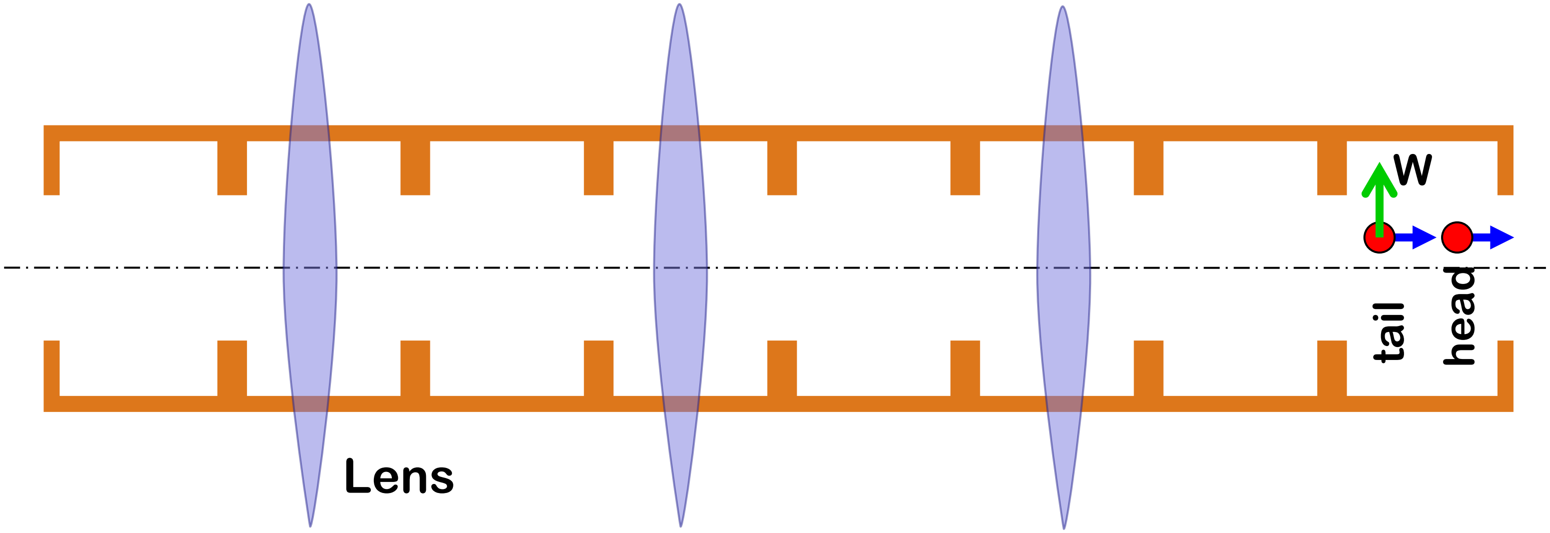
# Linac: transverse wakefields



- Bunches induce field in the cavities
- Later bunches are perturbed by these fields
- Bunches passing off-centre excite transverse higher order modes (HOM)
- Fields can build up resonantly
- Later bunches are kicked transversely
- => multi- and single-bunch beam break-up (MBBU, SBBU)
- Emittance growth!!!

# Beam Break Up and its cure - BNS

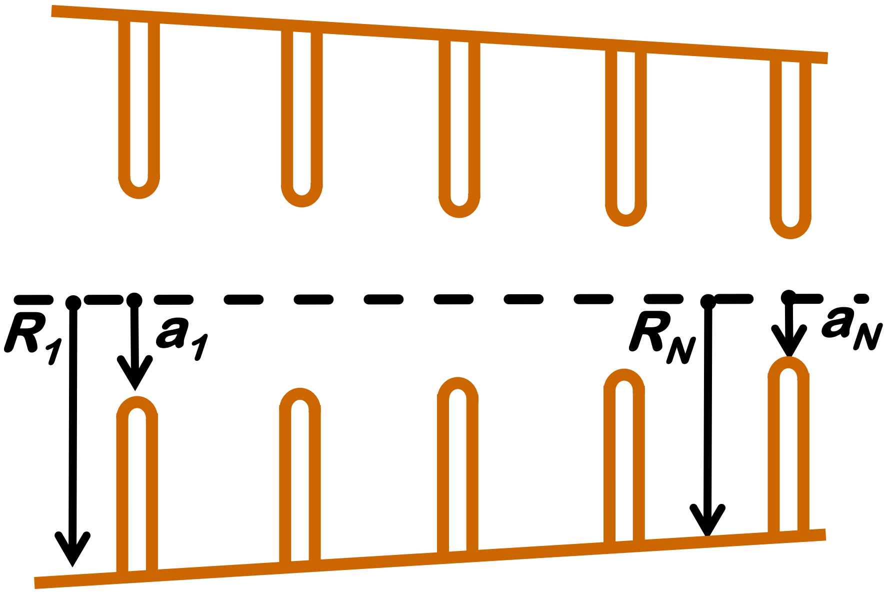
**Assume the bunch is off-center in accelerating cavity and the bunch head excites transverse dipole wakefield W that causes transverse deflection of the tail which can result in BBU – this BBU can be mitigated by BNS damping**



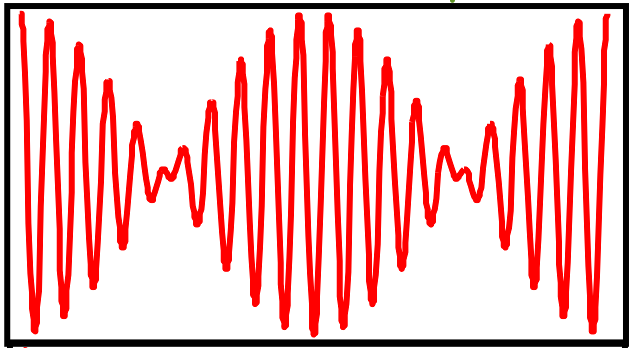
**BNS damping – the wake W acting on the tail is additional defocusing – to compensate it one need to decrease energy of the tail in such a way that effectively increasing focusing by lenses in the accelerator channel will exactly cancel the defocusing effect of the wakes**
**So, the BNS damping achieved by placing bunch off-crest of RF pulse, which creates corresponding and optimal BNS energy spread over the bunch (E-z correlation)**

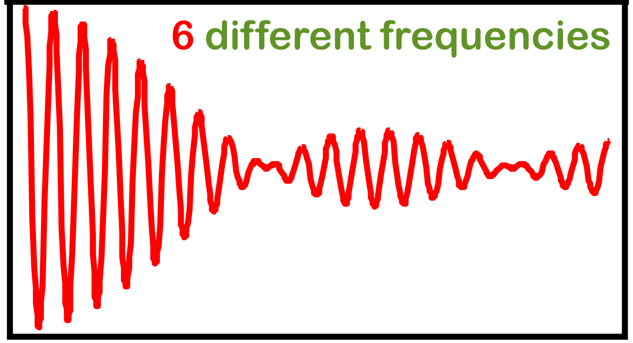
# Transverse wakefields

- Effect depends on $a/\lambda$ ($a$ iris aperture) and structure design details
- transverse wakefields roughly scale as $W_\perp \propto f^3$
- less important for lower frequency:
  Super-Conducting (SW) cavities suffer less from wakefields
- Long-range minimised by structure design
- Dipole mode detuning



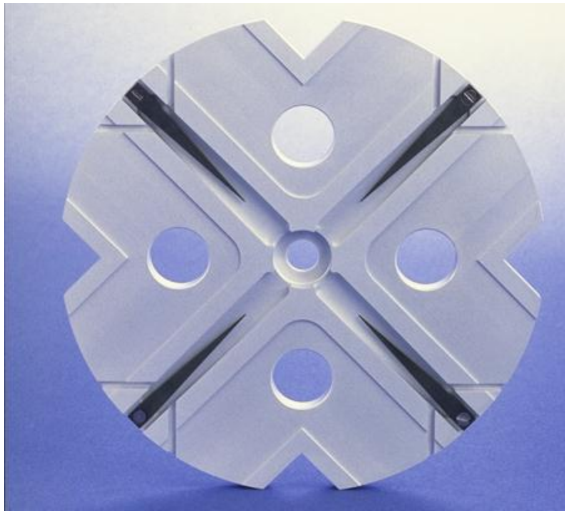
Long range wake of a dipole mode
spread over 2 different frequencies

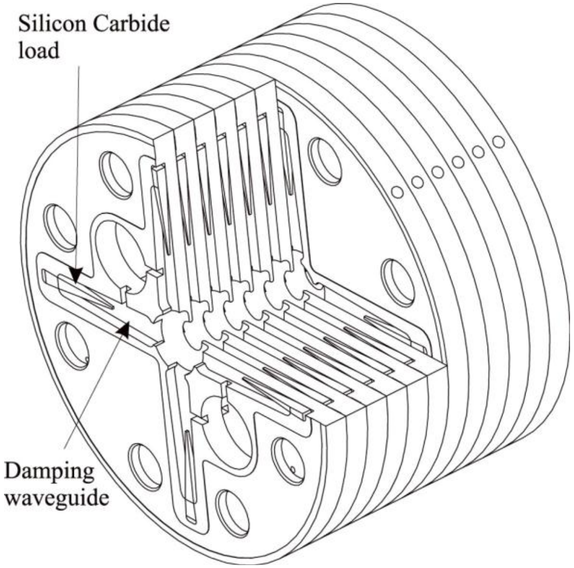




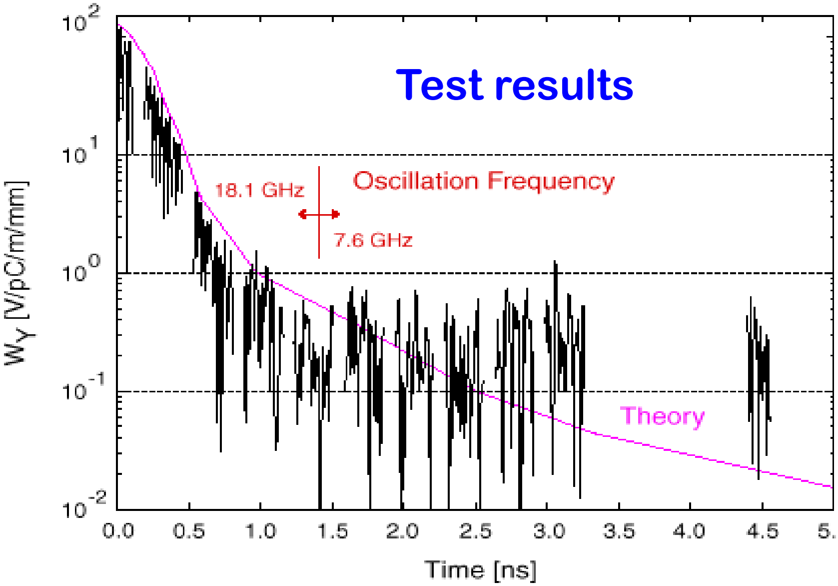
6 different frequencies

# HOM damping



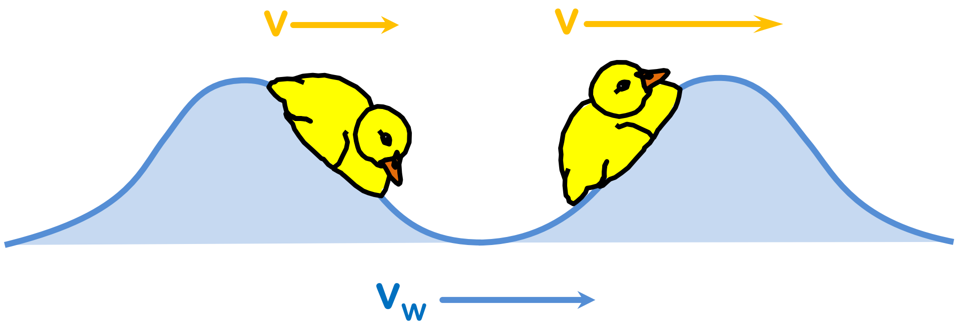


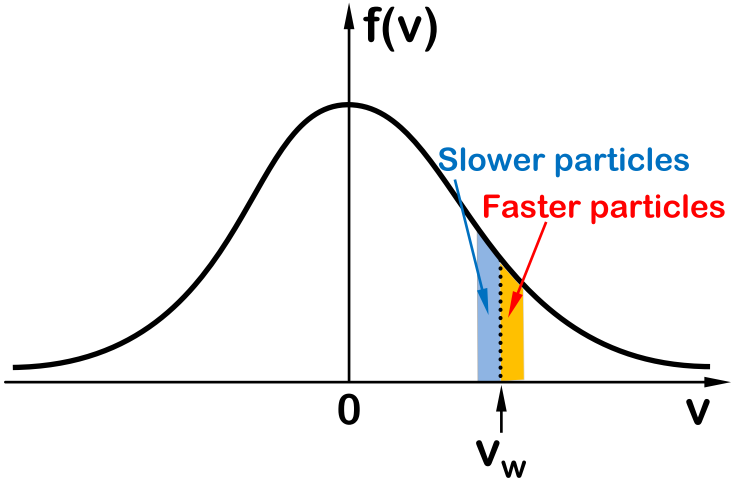
- Each cell damped by 4 radial WGs
- terminated by SiC RF loads
- HOM enter WG
- Long-range wake efficiently damped



# Landau damping

- Mechanism first discovered in plasma



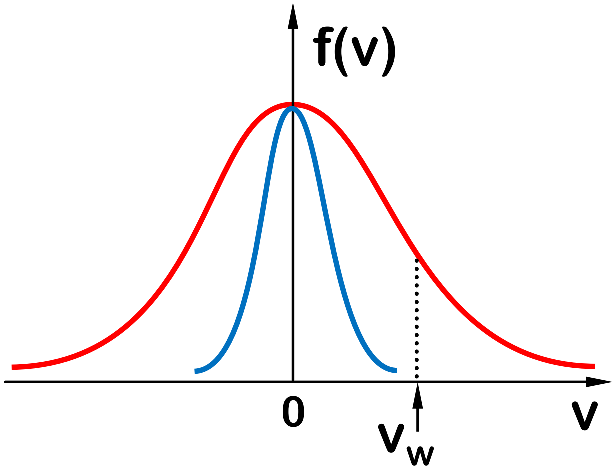


Analogy with duck trapped in ocean wave

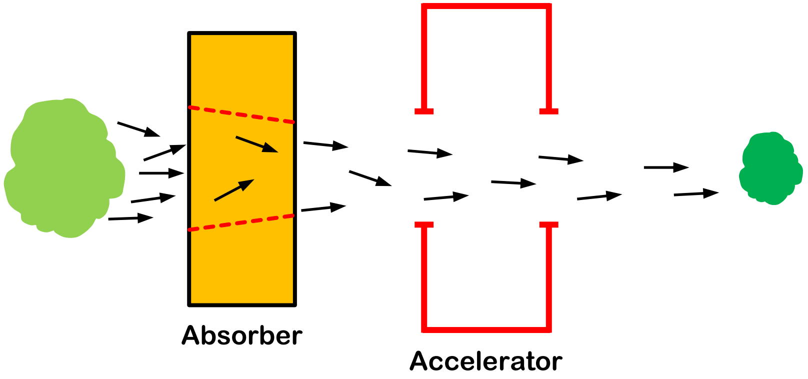
If duck was initially moving slower, it will accelerate, when trapped, thus take the energy from the wave

Since normally there are more slower ducks, the wave will damp

Important to have enough of reasonably fast ducks

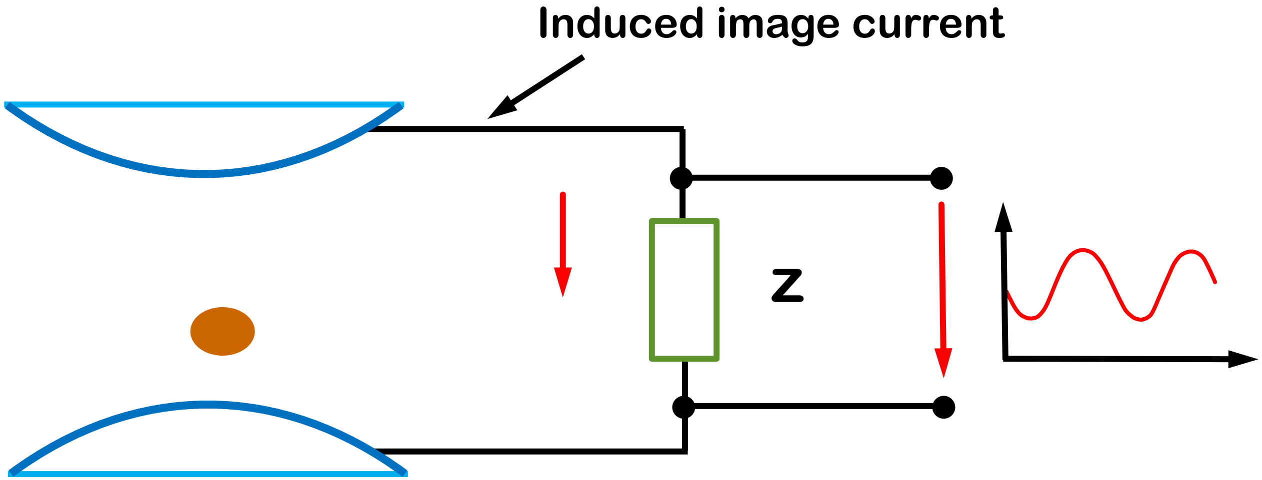


# Beam and ion cooling



Ionization cooling concept

Ionization cooling: although conceptually simple, it is extremely challenging technologically. Under study. Can be the only way to cool short-lived particles like muons.

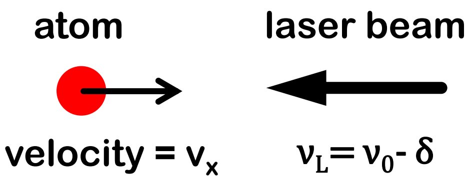


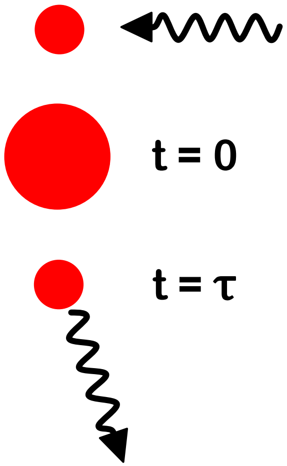
Resistive cooling of ions in traps

Resistive cooling: the trap electrodes are connected to external circuit to dissipate energy from the ions through induced currents

# Laser ion cooling

**Doppler frequency shift – key for laser cooling**



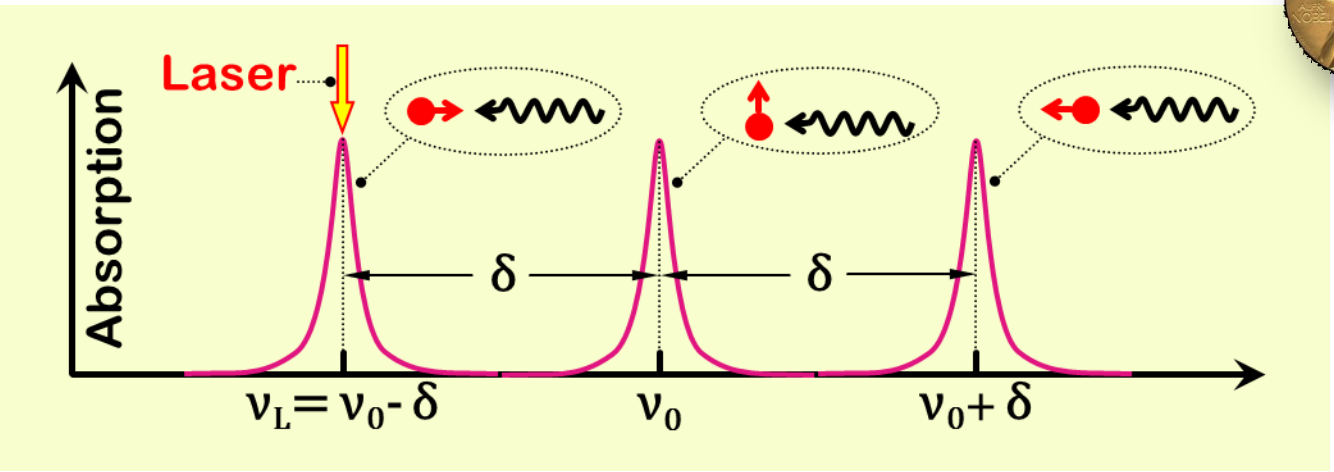


Laser photon impinges the atom

Atom absorbs the photon and gets to an excited state

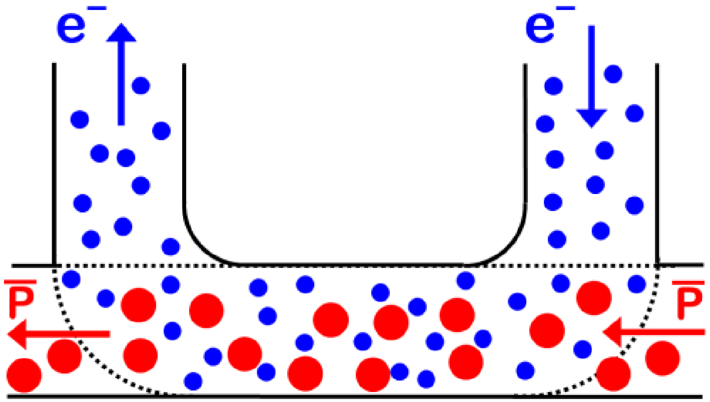
Atom re-emits a photon into a random direction

Nobel prize of 1997 for laser cooling of ions

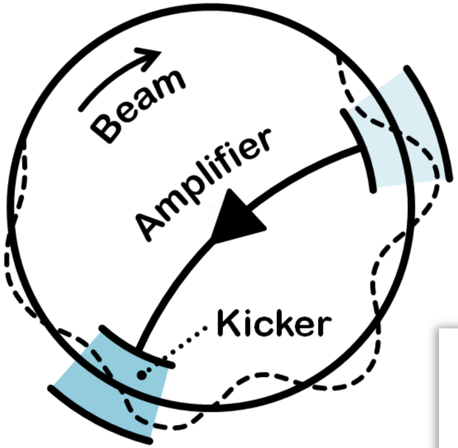


Laser in resonance with atoms when they are moving towards the laser, but not if they are moving sideways or away

# Beam cooling



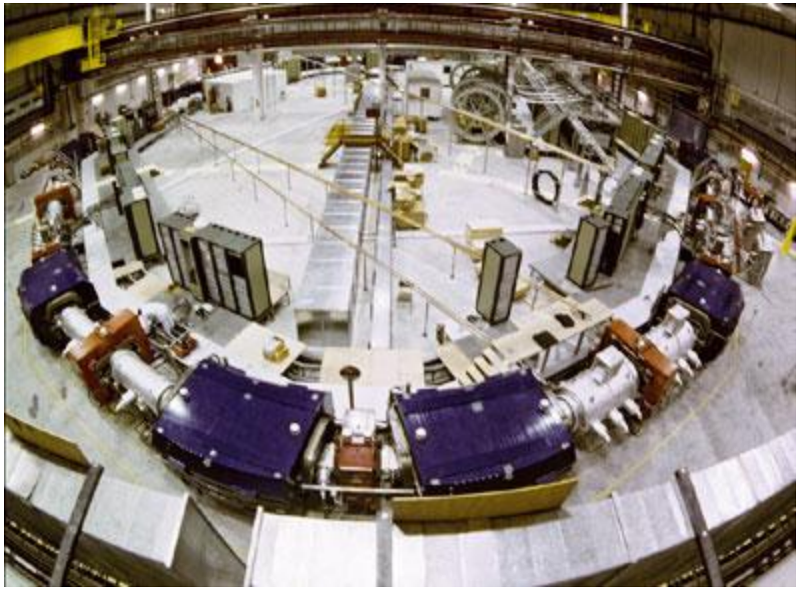
Electron cooling



Stochastic cooling

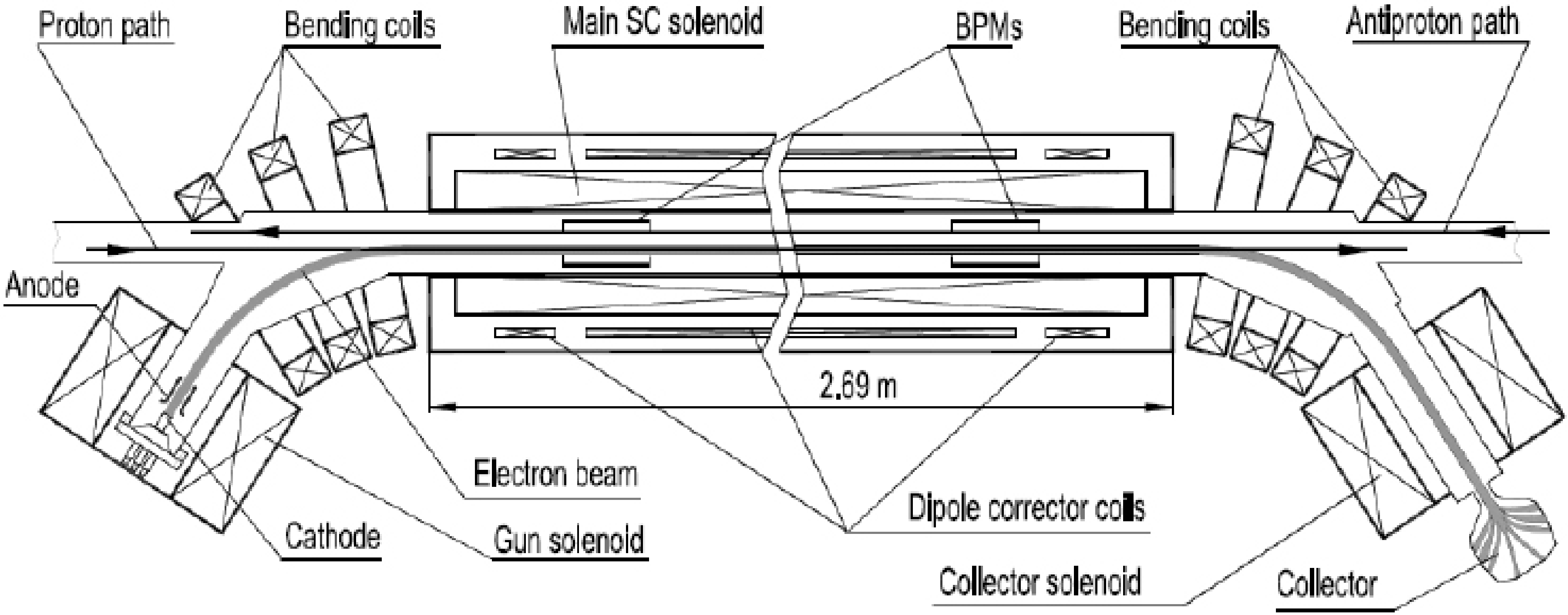
Nobel of 1984
for discovery of
W and Z Bosons

First e-cooler at BINP



Antiproton accumulator at CERN

# Electron lens

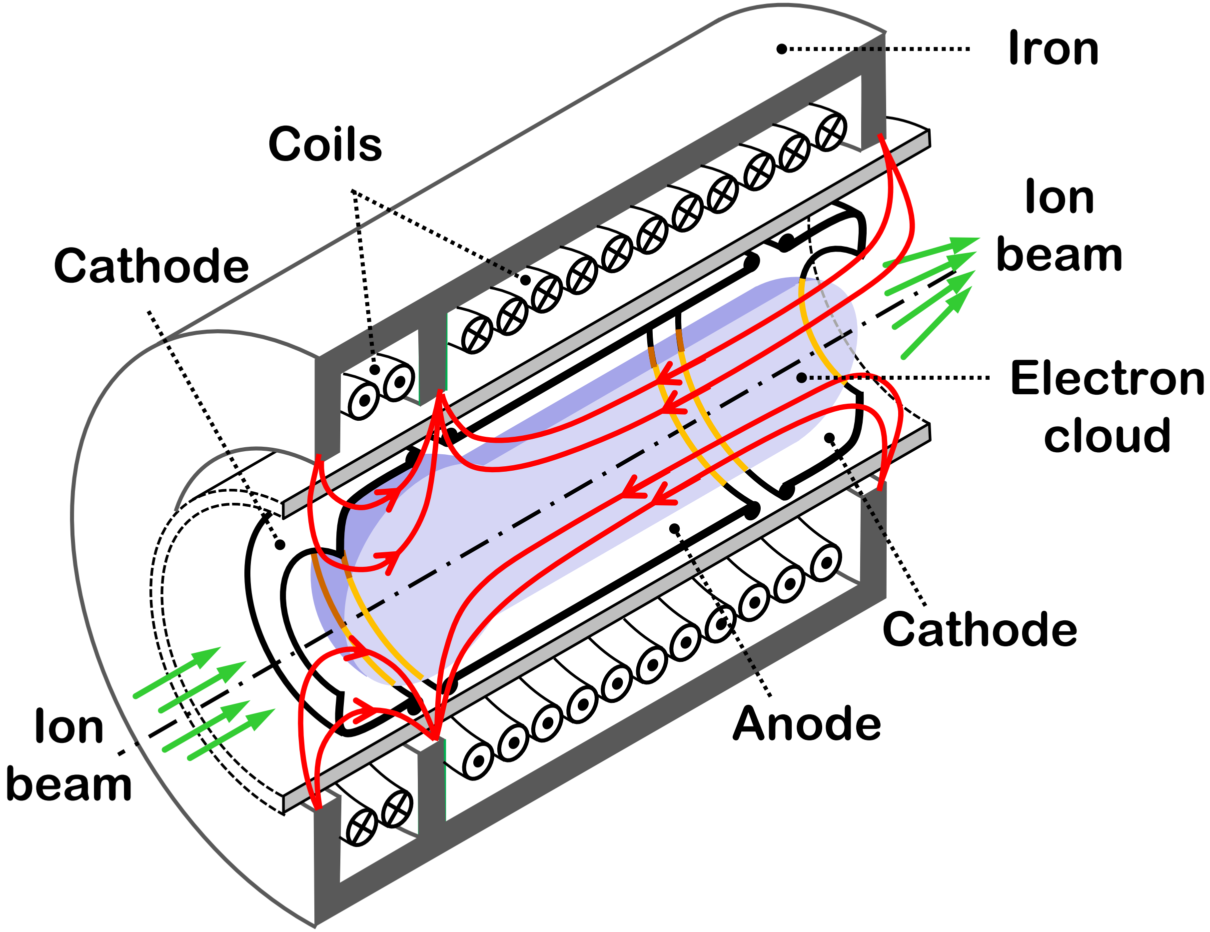


**Field of e- beam gives additional tune shift for p-bar bunches, reducing beam-beam induced betatron tune spread**

**Hollow e- lens is considered for the collimation system for LHC upgrade**

Schematic of Tevatron electron lens (V.Shiltsev et al)

# Gabor Lens

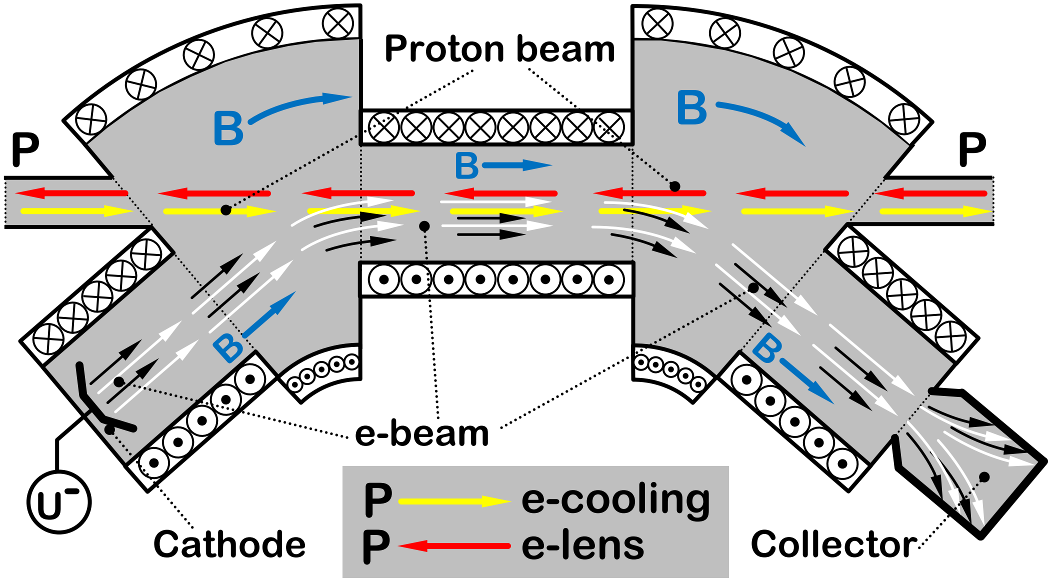


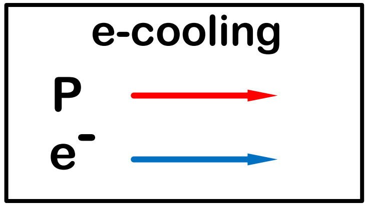
In the steady state electrons rotate around the axis so that electrostatic repulsion together with centrifugal force balance the radial Lorentz force produced by magnetic field.

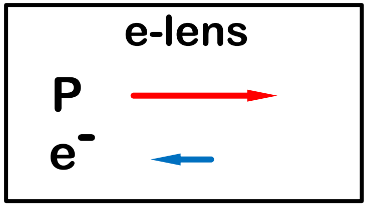
=> max density of electrons: $n = -\frac{B^2}{8\pi m_e c^2}$

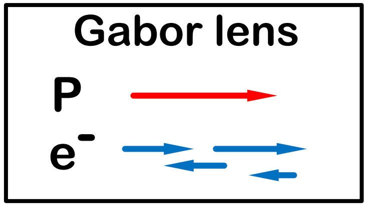
D. GABOR, "A Space-Charge Lens for the Focusing of Ion Beams", Nature 160, 89-90 (19 July 1947)

# Similarities between 3 methods



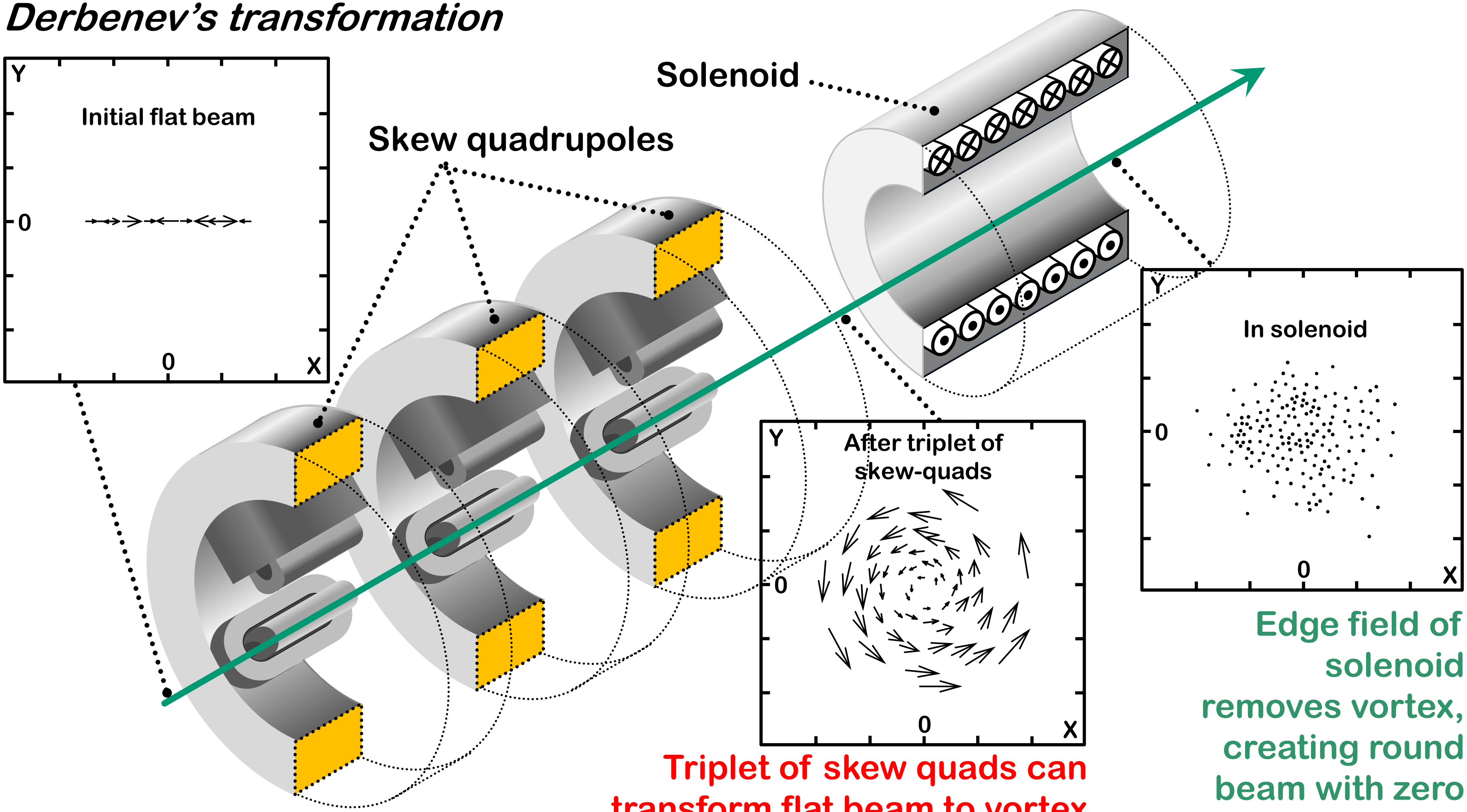






# Flat to round beam transfer

*Derbenev's transformation*

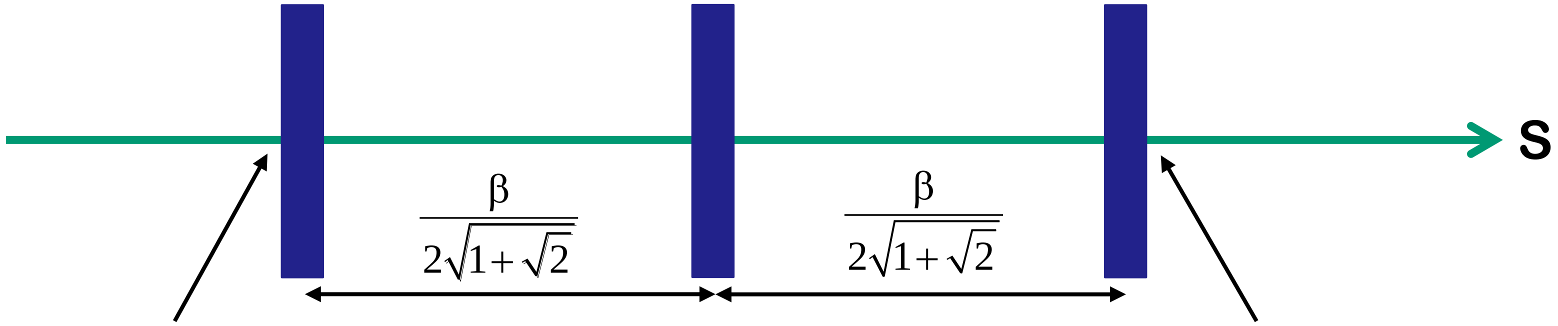


Triplet of skew quads can transform flat beam to vortex

Edge field of solenoid removes vortex, creating round beam with zero angles

We often have flat beams, e.g. SR rings naturally have y emittance much smaller than x emittance

# Skew triplet for flat to round beam transform



**skew quadrupole**

$$k_{1s}L = -\frac{1+\sqrt{2}}{\beta}$$

**skew quadrupole**

$$k_{1s}L = \frac{2\sqrt{2}}{\beta}$$

**skew quadrupole**

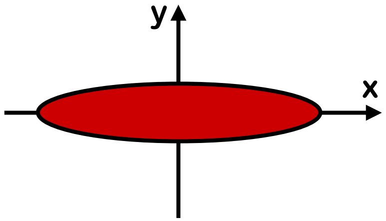
$$k_{1s}L = -\frac{1+\sqrt{2}}{\beta}$$

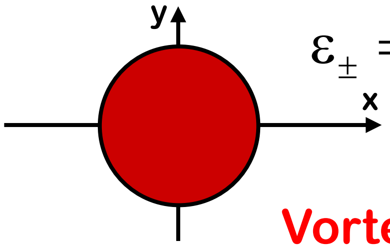
$$\frac{\beta}{2\sqrt{1+\sqrt{2}}}$$

$$\frac{\beta}{2\sqrt{1+\sqrt{2}}}$$

$$\Sigma = \begin{pmatrix} \beta\varepsilon_x & 0 & 0 & 0 \\ 0 & \frac{\varepsilon_x}{\beta} & 0 & 0 \\ 0 & 0 & \beta\varepsilon_y & 0 \\ 0 & 0 & 0 & \frac{\varepsilon_y}{\beta} \end{pmatrix}$$

$$\Sigma = \begin{pmatrix} \frac{1}{2}\beta\varepsilon_+ & 0 & 0 & \frac{1}{2}\varepsilon_- \\ 0 & \frac{1}{2\beta}\varepsilon_+ & -\frac{1}{2}\varepsilon_- & 0 \\ 0 & -\frac{1}{2}\varepsilon_- & \frac{1}{2}\beta\varepsilon_+ & 0 \\ \frac{1}{2}\varepsilon_- & 0 & 0 & \frac{1}{2\beta}\varepsilon_+ \end{pmatrix}$$



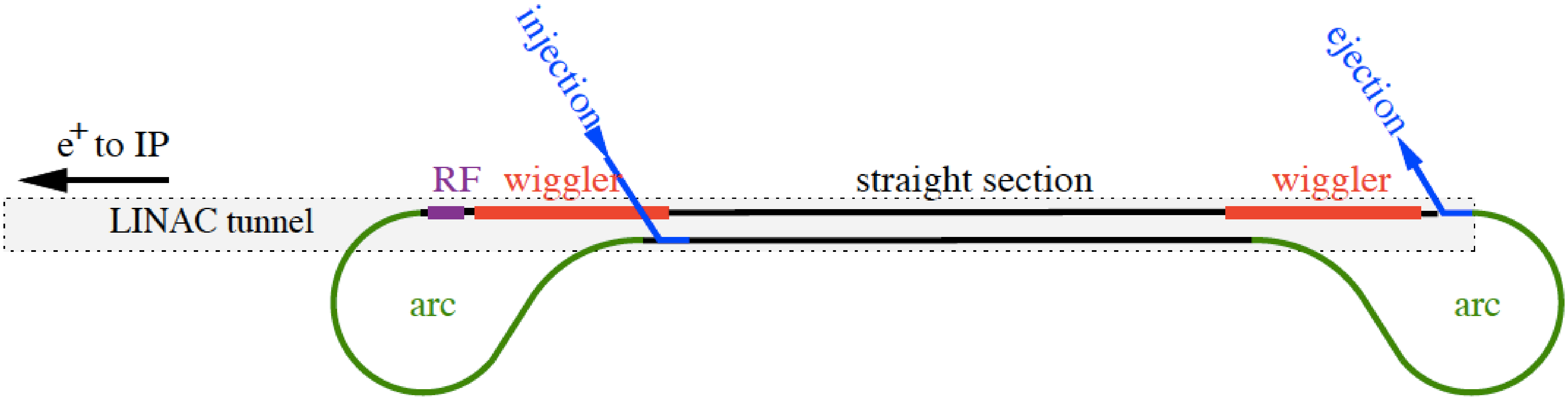


$$\varepsilon_\pm = \varepsilon_x \pm \varepsilon_y$$

**Vortex inside!**

# Example of use of flat to round beam transfer

**TESLA collider needed to cool ~3000 bunches. Assuming 20ns kicker rise time, the minimal circumference is 17km => DR partially located in tunnels**



**Large circumference => unacceptably large incoherent tune shift**

**Decision to use Derbenev's transformation to have flat beams only in arcs, and round beam in long straight sections => reduction of tune shift**

# Summary of the lecture

- Stability of beams
  - Colliders and LIGO
  - Beam-beam effects
  - BNS damping
- Damping and cooling
  - Landau damping
  - Laser cooling
  - Ionization cooling
  - Round to flat beam transfer, etc.