“Emittance Preservation” in Beam Delivery Systems

Nick Walker
DESY

Snowmass 2001

Introduction

- Sources of Emittance Growth in BDS
- Time Scales
- Effects of Magnet Motion (Ground Motion)
  - Uncorrelated motion
  - Frequency Domain & feedback
  - “slow” drifts: ATL motion

Goal: to look at response of lattice independent of beam parameters

Sources of Emittance Growth in the BDS

- Wakefields from
  - collimator apertures
  - bellows
  - beam pipe (resistive wall)
- Synchrotron Radiation in magnets
- Optical aberrations due to magnet misalignments
  - time dependent
  - ground motion effects

concentrate on this area

Times Scales

- Two effects wrt luminosity:
  - beam-beam separation at IP
  - beam size increase due to optical aberrations
    (emittance growth)
- Two time scales:
  - fast: those effects which occur too fast to correct
  - slow: those effects which can be actively compensated.

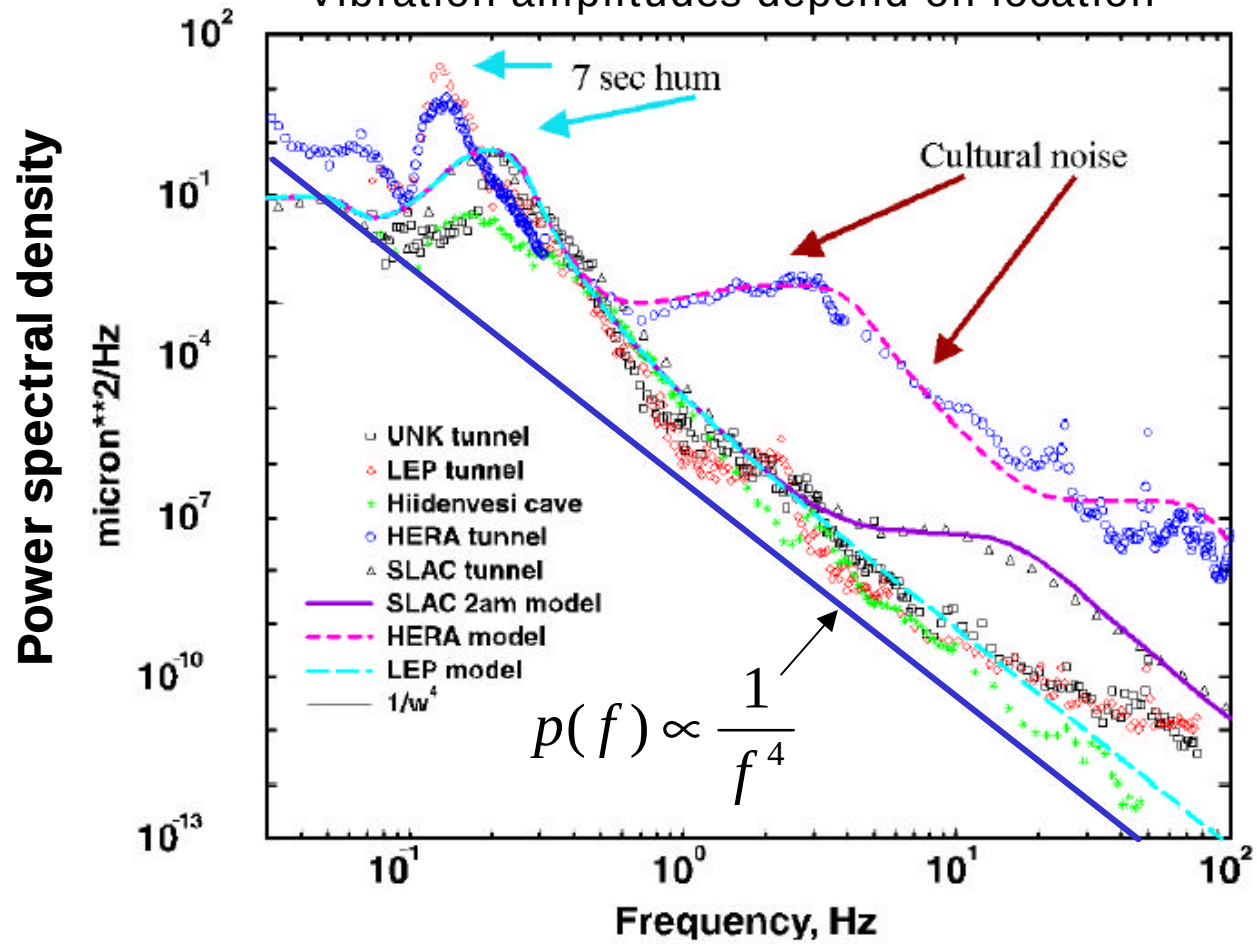
Notes on Beam-Beam Effects

- Not considered in this talk
- Especially important for TESLA since
  - high disruption regime (D_y = 25)
  - lumi. very sensitive to beam-beam offsets (2% tolerance at $\Delta y \sim \sigma_y/10 = 0.5\ \mathrm{nm}$)
  - so-called “banana” effects should be considered!
- Hence results shown for TESLA are probably optimistic!

Notes on Ground Motion

Long history of R&D and now relatively well understood

Vibration amplitudes depend on location



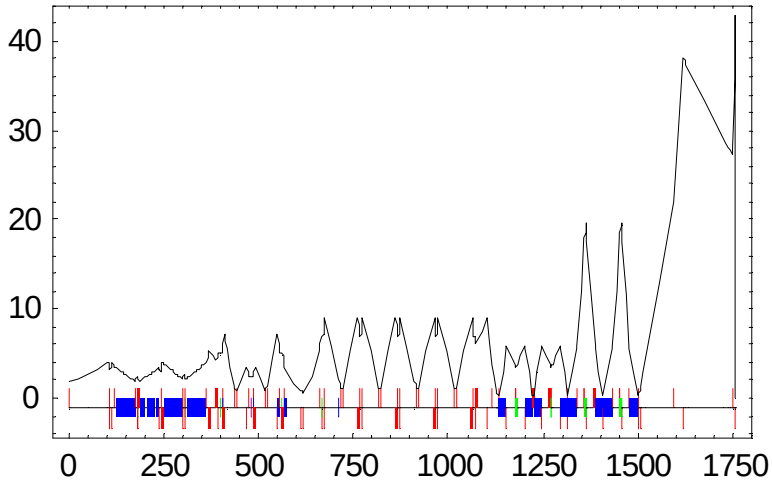
From A. Seryi, SLAC

Important Parameters

		TESLA 2000	NLC stage 1	NLC stage 2	CLIC 2000
E_{beam}	GeV	250	250	500	1500
N_{bunch}		2820	190	190	154
T_{train}	μs	950	0.27	0.27	0.1
ΔT_{bunch}	ns	337	1.4	1.4	0.67
f_{rep}	Hz	5	120	120	100
δ_{rms}	%	0.16 (0.04)	0.23 (±0.4)	0.23 (±0.4)	0.28 (±0.5)
σ_y*	nm	5	2.7	2.1	1

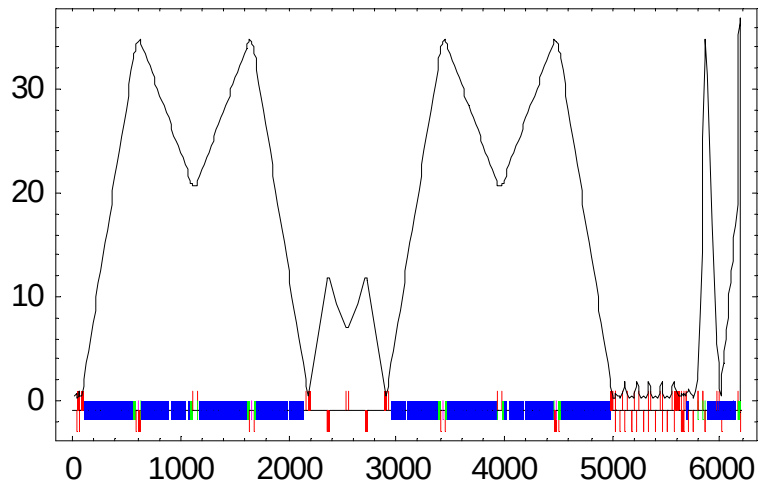
Beam Delivery Systems

TESLA 500 GeV



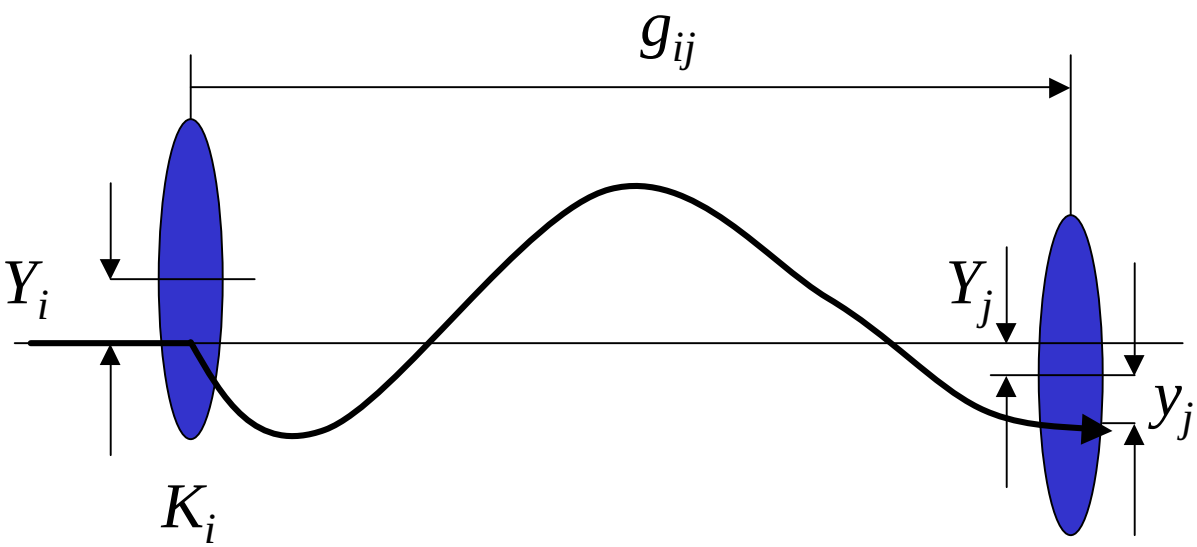
$\sigma_{x,y}$ = 550/5 nm
δ_{rms} = 0.16% (electrons)
= 0.04% (positrons)

CLIC 3TeV



$\sigma_{x,y}$ = 43/1 nm
δ_{rms} = 0.28% (±0.5%)

Analysis of Magnet Motion



$$y_j = \left(-\sum_{i=1}^{j} g_{ij} K_i Y_j \right) - Y_i$$

Analysis of Magnet Motion

Original Equation $$y_j = \left(-\sum_{i=1}^{j} g_{ij} K_i Y_j \right) - Y_i$$

Defining *Response Matrix* **Q**: $$\mathbf{Q} = \mathbf{G} \cdot \mathbf{diag(K)} + \mathbf{I}$$

Hence beam offset becomes $$\mathbf{y} = -\mathbf{Q} \cdot \mathbf{Y}$$

Covariance of beam motion $$\langle y_i y_j \rangle = \mathbf{V}_y = \mathbf{Q} \cdot \mathbf{V}_Y \cdot \mathbf{Q}^{\mathrm{T}}$$

$\mathbf{V}_Y$ contains all the information of the magnet motion

(ground motion)

Uncorrelated Motion

- $V_{ij} = 0;\ i \neq j$
- $V_{ii} = \sigma^2$ (for all i)
- $\mathbf{V}_Y = \sigma^2\ \mathbf{I}$

$$\mathbf{V}_y = s^2 \mathbf{Q} \cdot \mathbf{Q}^{\mathrm{T}}$$

- $\mathbf{Q} \times \mathbf{Q}^{\mathrm{T}}$ is a matrix of *amplification factors*
- Most interested in IP motion factor
- $\rightarrow$ last row vector of $\mathbf{Q}$

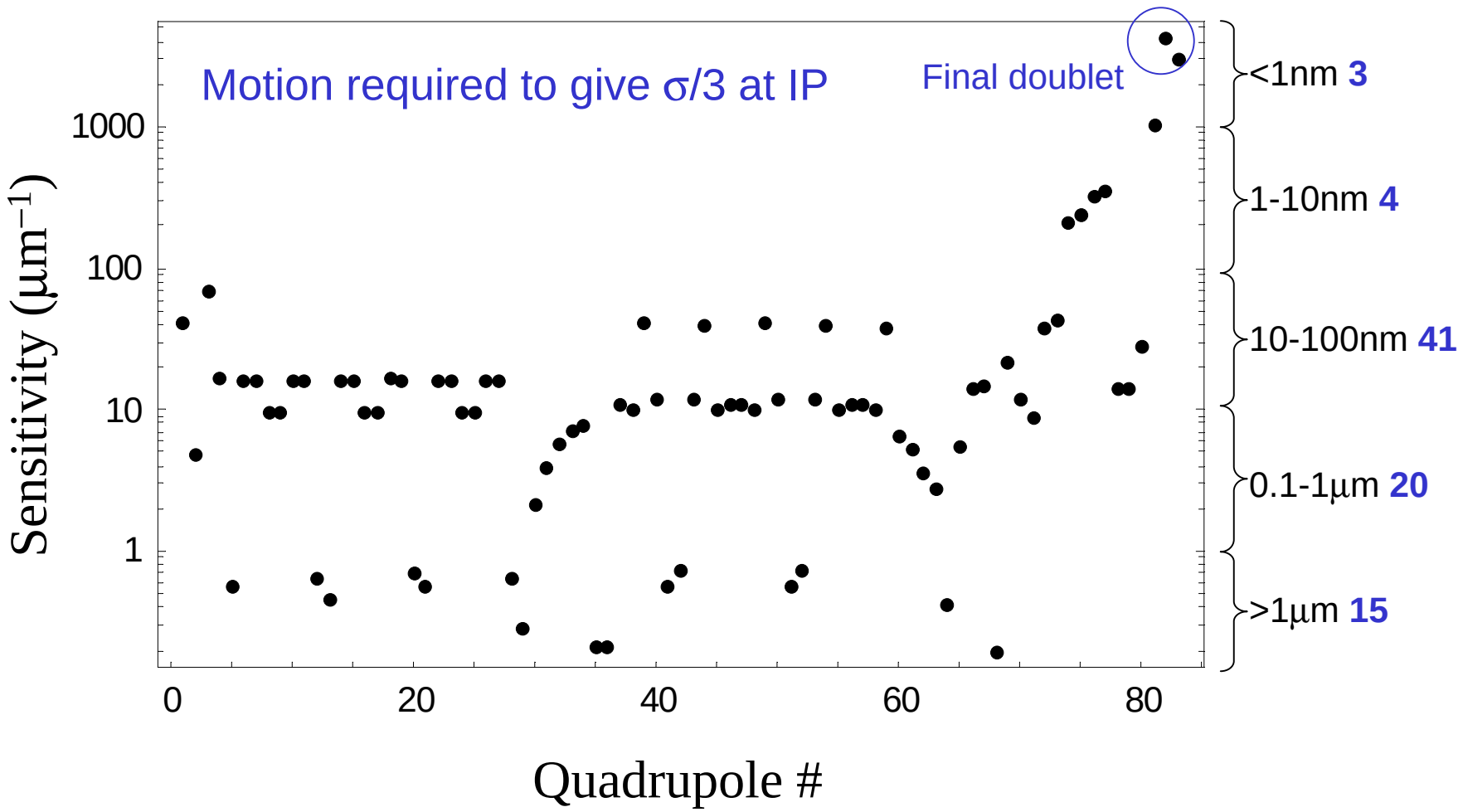
IP Vertical Motion due to Uncorrelated Magnet Motion

	Entire Lattice		No Final Doublet	
	factor	$1\times\sigma$ motion	factor	$1\times\sigma$ motion
CLIC 3TeV	1.77	0.56 nm	0.39	2.6 nm
TESLA 500GeV	2.17	2.3 nm	0.75	6.7 nm

Need:

- Beam-based Feedback
- Active (mechanical) Stabilisation of Magnets

CLIC Quadrupole Tolerances



Mechanical Stabilsation of Final Doublet (and other magnets)

- Mechanical stabilisation using piezoelectric mover
  - achieved 70→~25 nm f > few Hz
    [Montag, DESY]
  - *move the field and not the magnet*?
- Use of vibration insulation stands
  - Factor of 20 achieved at PEP (40 → 2 nm f > 2Hz)
    [Bowden, Mazaheri, SLAC]
- Optical Anchoring techniques
  - demonstrated resolution of 0.2nm [Woods, Mattison, SLAC]
  - as yet not used as part of active feedback
- Other areas interested too
  - *e.g.*. gravitation wave antennas (LIGO, 10^{-14} m)

On-going R&D (cf CLIC stability study www.cern.ch/clic-stability)

Emittance Dilution

Magnet	Generator	Type	IP generator
Quadrupole	$+K\Delta y\, yd$	Linear Dispersion	$-R_{34}K\Delta y\, y'd$
Sextupole	$-S\Delta y\, xy$	x-y coupling	$-R_{12}R_{34}S\Delta y\, x'\, y'$
	$-SD_x\Delta y\, yd$	Linear dispersion	$+R_{34}SD_x\Delta y\, y'd$
Skew-sextupole	$-\frac{1}{2}S\Delta y\, y^2$	Waist shift	$-\frac{1}{2}R_{34}^2S\Delta y\, y'^2$

x,y = phase space coordinates
Δy = beam offset wrt magnetic centre
K,S,H = integrated strength (quad, sextupole, octupole resp.)

RMS Linear Dispersion

- define the following vectors:

  $\mathbf{K}$ quad strengths

  $\mathbf{S}$ sextupole strengths

  $\mathbf{D_x}$ horizontal dispersion function

  $\mathbf{R_{34}}$ Green's functions from magnets to IP

- define $\mathbf{D} = (\mathbf{S}\otimes\mathbf{D_x}-\mathbf{K})\otimes\mathbf{R_{34}}$ such that $D_y = \mathbf{D}\times \mathrm{D}\mathbf{y}$
- Hence

$$D_y = -\mathbf{D}\times\mathbf{Q}\times\mathbf{Y}$$

$$\langle D_y^2\rangle = (\mathbf{D}\times\mathbf{Q})\times\mathbf{V_Y}\times(\mathbf{D}\times\mathbf{Q})^{\mathrm{T}}$$

- Uncorrelated: $\langle D_y^2\rangle = \sigma^2\, \mathbf{D}\times\mathbf{Q}\times\mathbf{Q}^{\mathrm{T}}\times\mathbf{D}^{\mathrm{T}}$

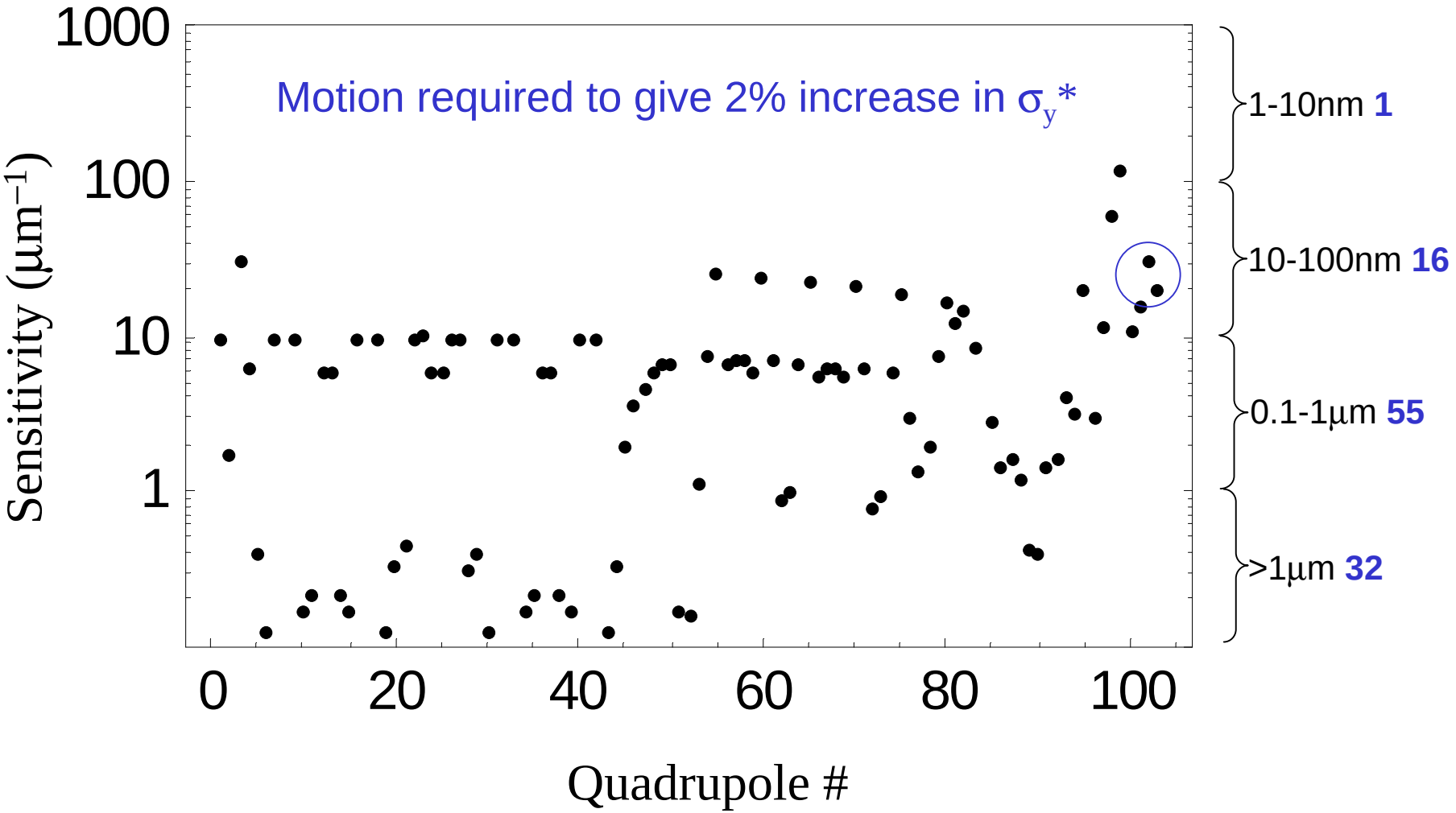
similar expressions for coupling, waist shift *etc*.

RMS Aberrations for Uncorrelated Magnet Motion

$$\left.\begin{aligned} \Delta y_{rms} &= D_y d_{rms} \\ \Delta y_{rms} &= C_{xy} q_x^* \\ \Delta y_{rms} &= h\, D_{2,y} d_{rms}^2 \end{aligned}\right\} \; D_y,\, C_{xy},\, D_{2,y} \propto s_{Y,rms}$$

		Lattice Factor	RMS motion for 2% tolerance (nm)
TESLA 500GeV	dispersion	25	25
	x-y coupling	585	47
	2nd-order dispersion	7754	35
CLIC 3TeV	dispersion	3.6	20
	x-y coupling	5161	7.3
	2nd-order dispersion	1264	23

CLIC Quadrupole Tolerances

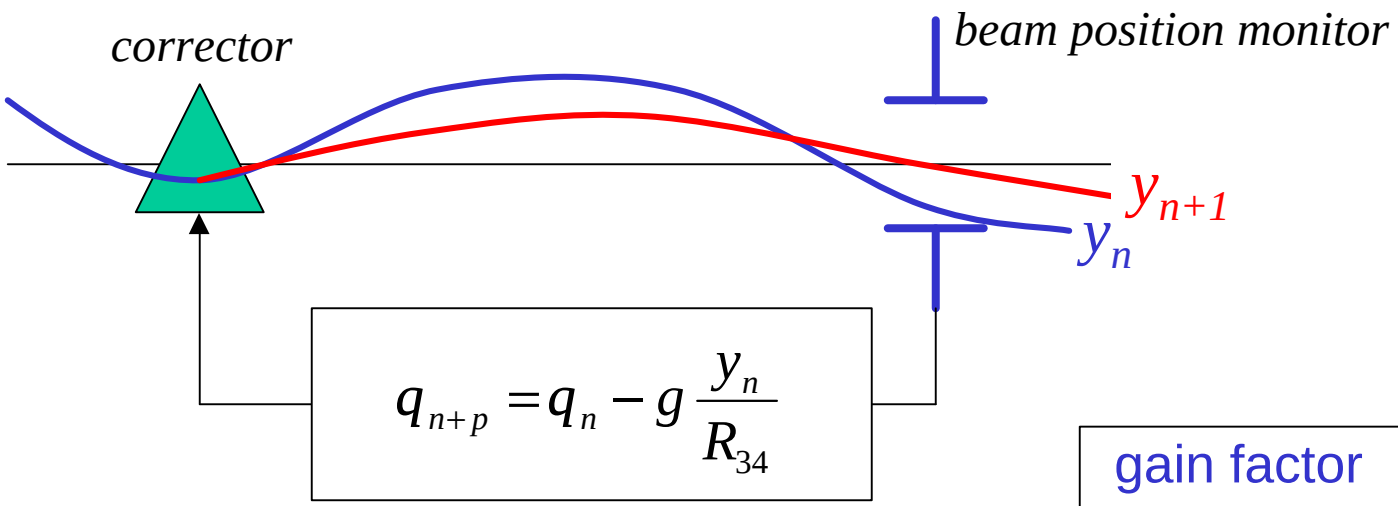


CLIC Comments

- RMS magnet motion quoted is the *required uncorrelated* motion
- Values should be achieved by application of
  - mechanical stabilisation or
  - beam based feedback correction or
  - both (most likely)
- ground motion: $p(f) \propto f^{-4}$, CLIC $f_{\mathrm{rep}} = 100\ \mathrm{Hz}$

Beam-Based Feedback

(orbit correction)



gain factor

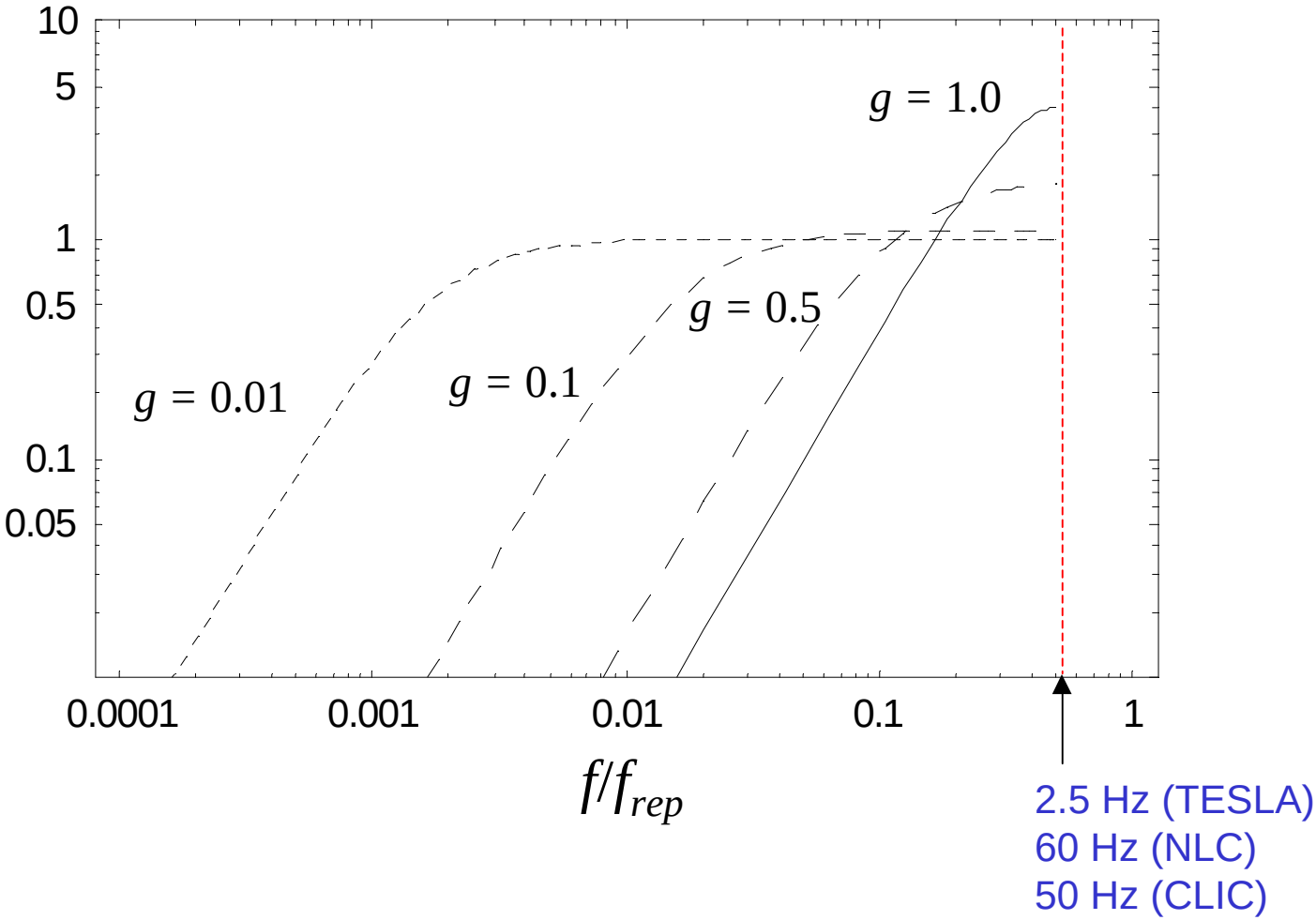
$0 < g \leq 1$

$p = 1$ 1 pulse delay

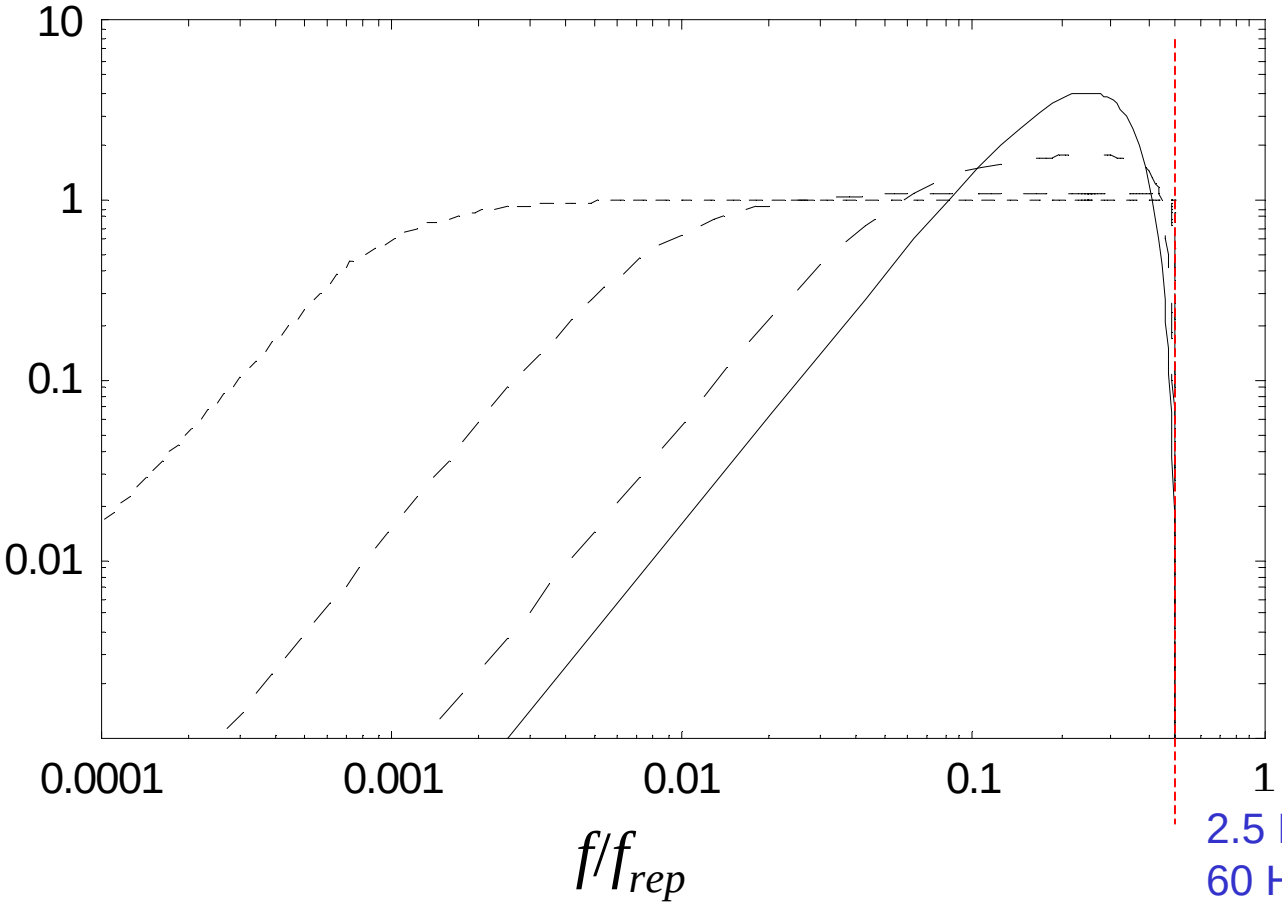
$p = 2$ 2 pulse delay *etc*.

$$y_n = y_{n-p}(1-g) + \underbrace{w_n - w_{n-p}}_{\text{beam “jitter”}} + \underbrace{b_n - b_{n-p}}_{\text{BPM noise}}$$

$p = 1$ Frequency Response



$p = 2$ Frequency Response



2.5 Hz (TESLA)
60 Hz (NLC)
50 Hz (CLIC)

Frequency Spectrum

Original Covariance $\left\langle y_i y_j \right\rangle = \left[\mathbf{Q} \cdot \mathbf{V}_Y \cdot \mathbf{Q}^{\mathrm{T}} \right]_{ij}$

$$\left\langle y_i y_j \right\rangle = \int_{-\infty}^{\infty} \underbrace{F\{y_i(t)\} F^*\{y_i(t)\}}_{\text{mutual (or cross) power spectrum}} df$$

For Ground Motion:

$$\left\langle Y_i Y_j \right\rangle = \int_{-\infty}^{\infty} F\{Y_i(t)\} F^*\{Y_i(t)\} df$$

$$= \int_{-\infty}^{\infty} p(f) C_{ij}(f) df$$

absolute power spectrum

correlation function

Frequency Spectrum

Original Covariance $\left\langle y_i y_j \right\rangle = \left[\mathbf{Q} \cdot \mathbf{V}_Y \cdot \mathbf{Q}^{\mathrm{T}}\right]_{ij}$

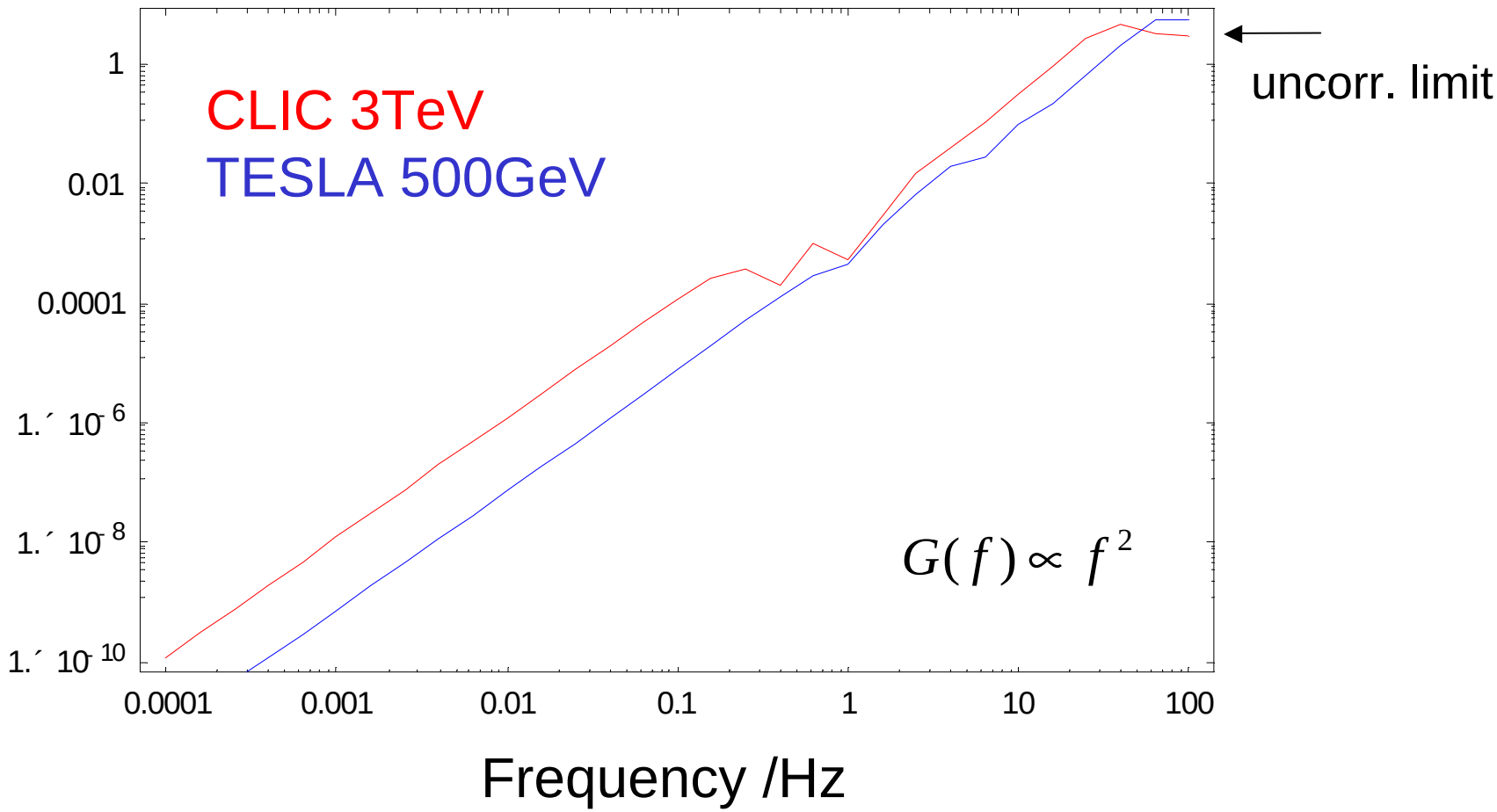
$$F\{y_i(t)\}F^*\{y_j(t)\} = p(f)\underbrace{\left[\mathbf{Q} \cdot \mathbf{C}(f) \cdot \mathbf{Q}^{\mathrm{T}}\right]_{ij}}_{\text{Lattice Response (“filter”)}}$$

SLAC Ground Motion Model:

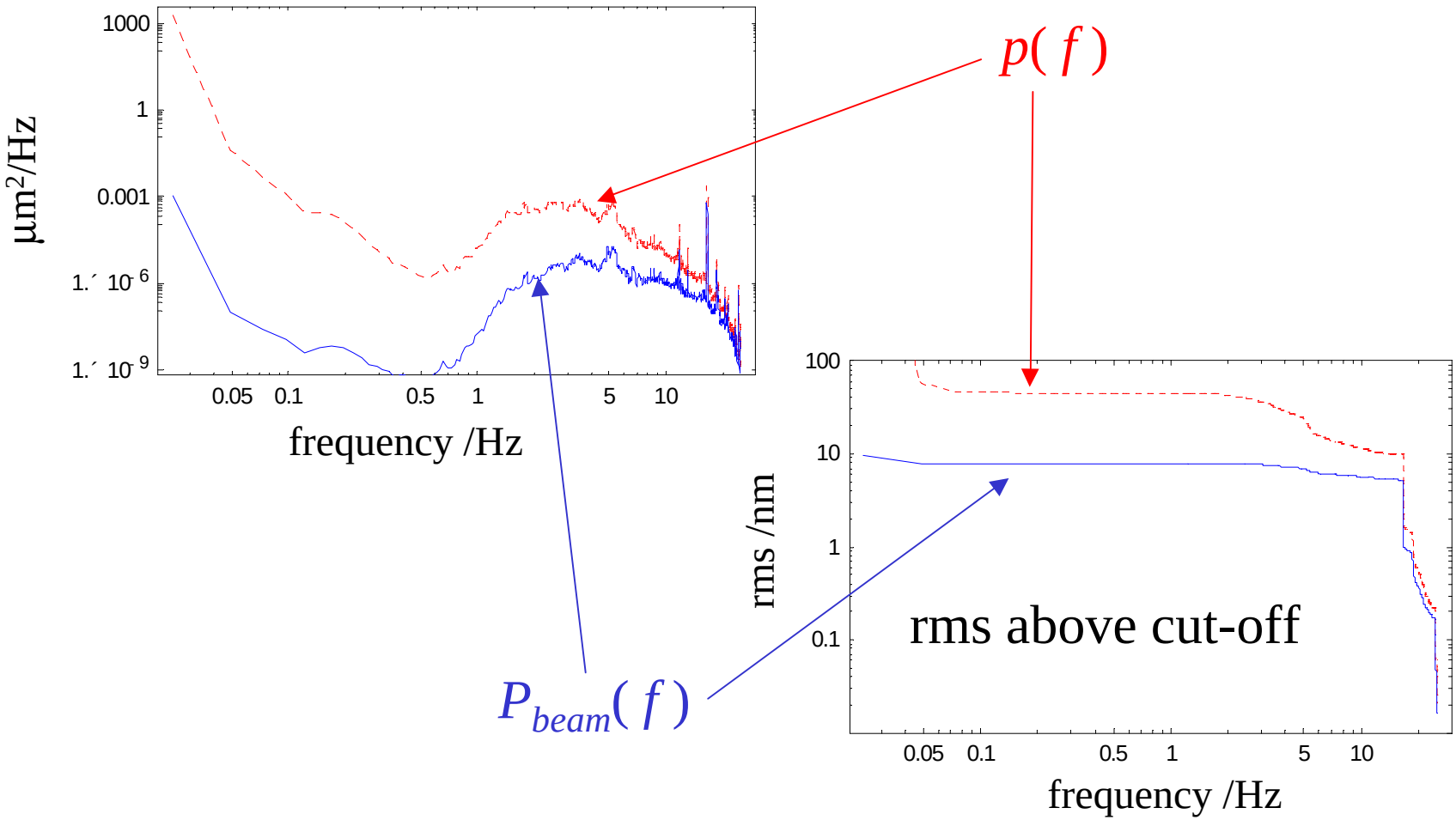
Wave-like motion with phase velocity $v(f) = 450+1900\, e^{-f/2}$

$$C_{ij}(f) = J_0\left(\frac{2p\, f \Delta L_{ij}}{v(f)}\right)$$

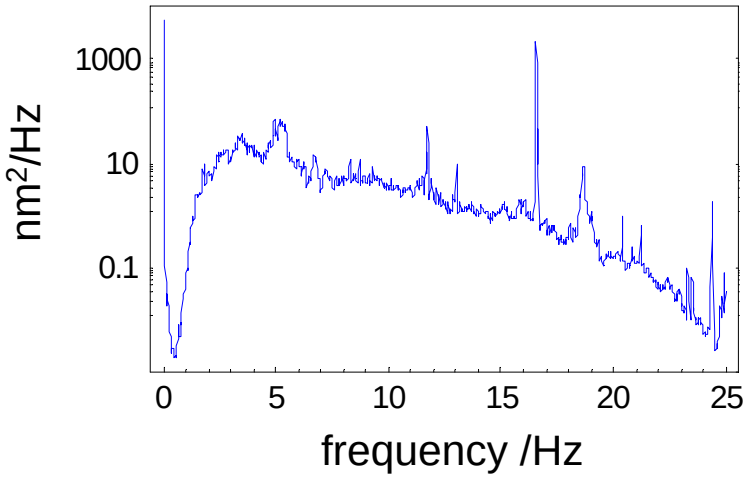
IP Motion Lattice Response

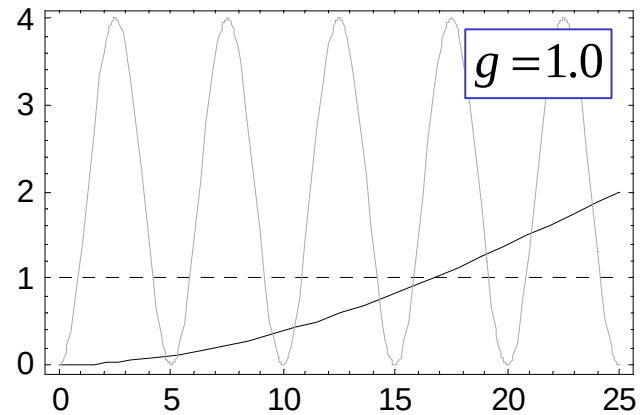


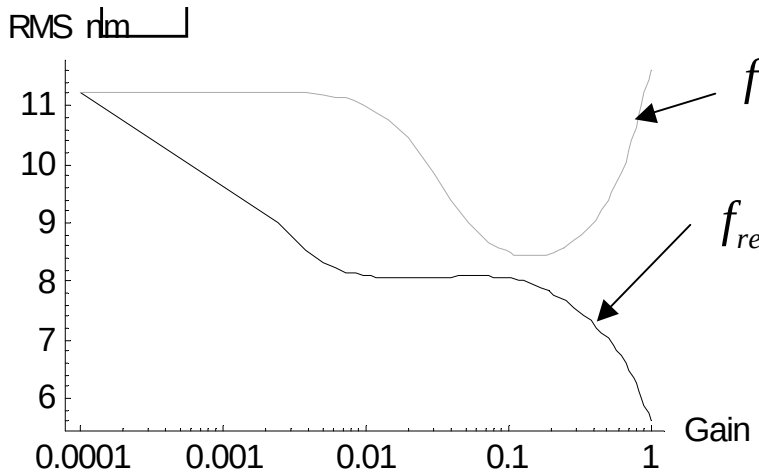
IP Motion (TESLA)

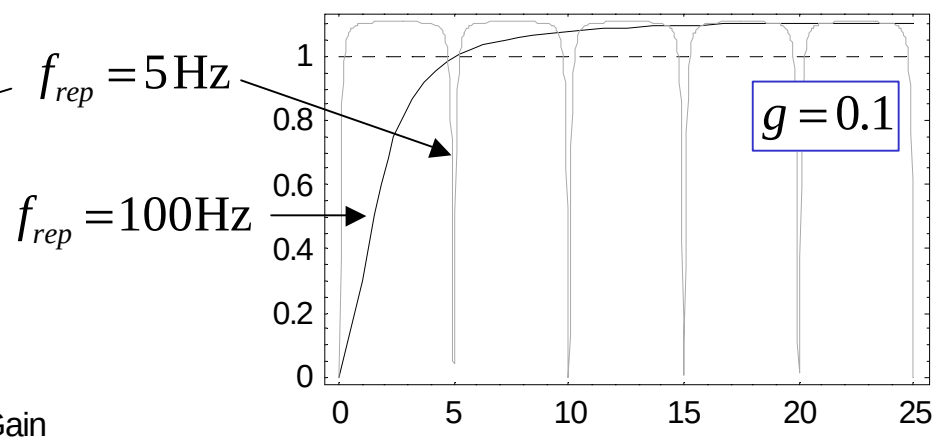


Feedback and Rep. Rate



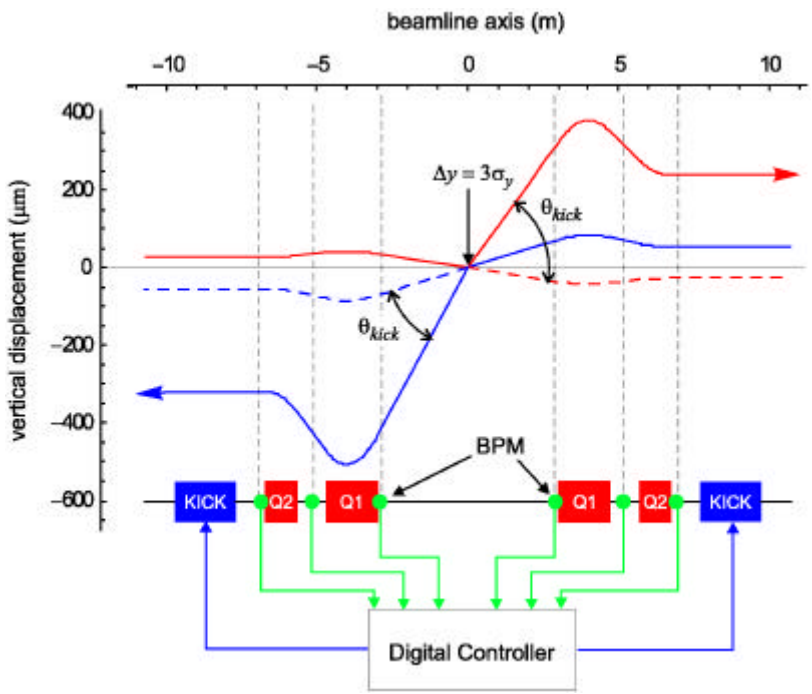






Beam-Beam Feedback

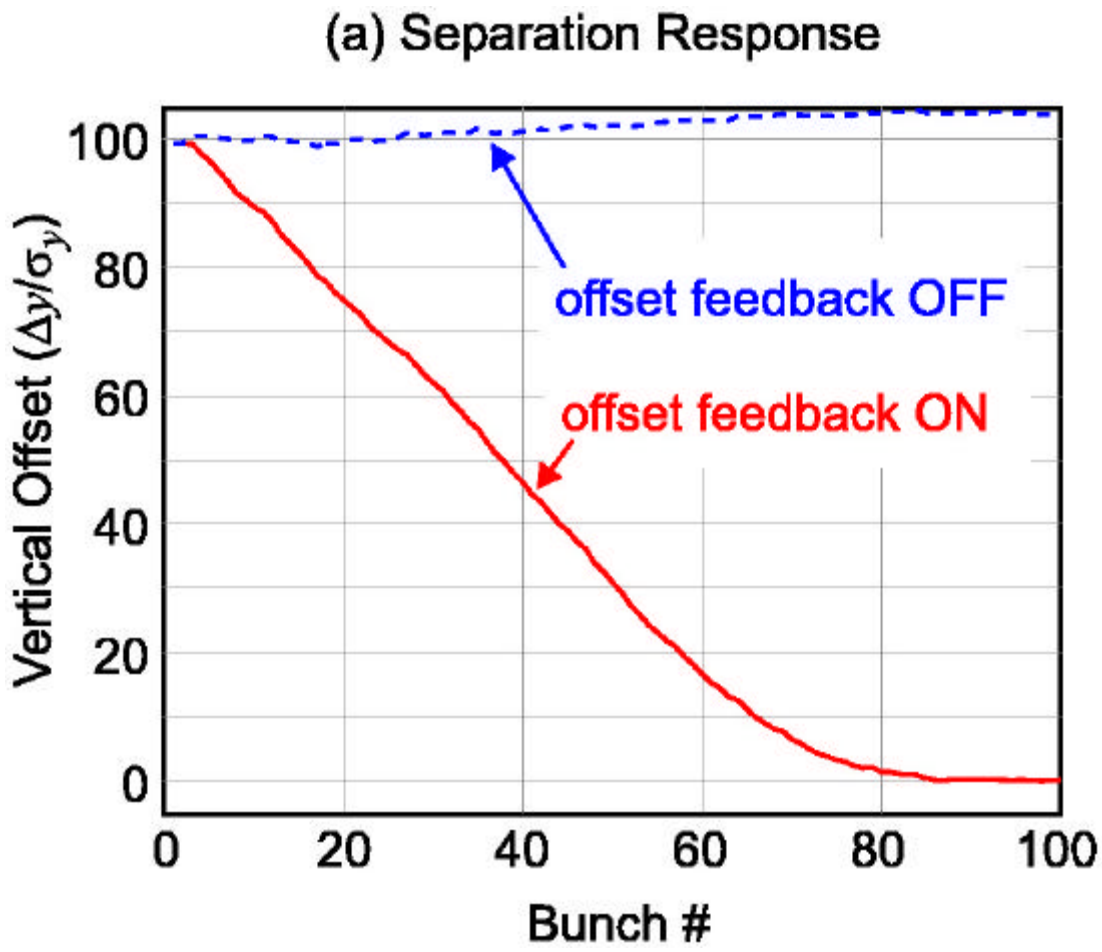
- Use beam-beam kick as offset signal
- Two types:
  - feedback ≤ f_{rep} (cf SLC)
  - intra-bunch-train (fast) feedback



TESLA:
2820 bunches in 950μs bunch train (τ_b = 337 ns)

TESLA IP Feedback

- Fast (>300KHz) IP FDBK
- Forget tolerances based on Δy^*
- Tolerances set *only* by $\Delta\sigma_y$ considerations

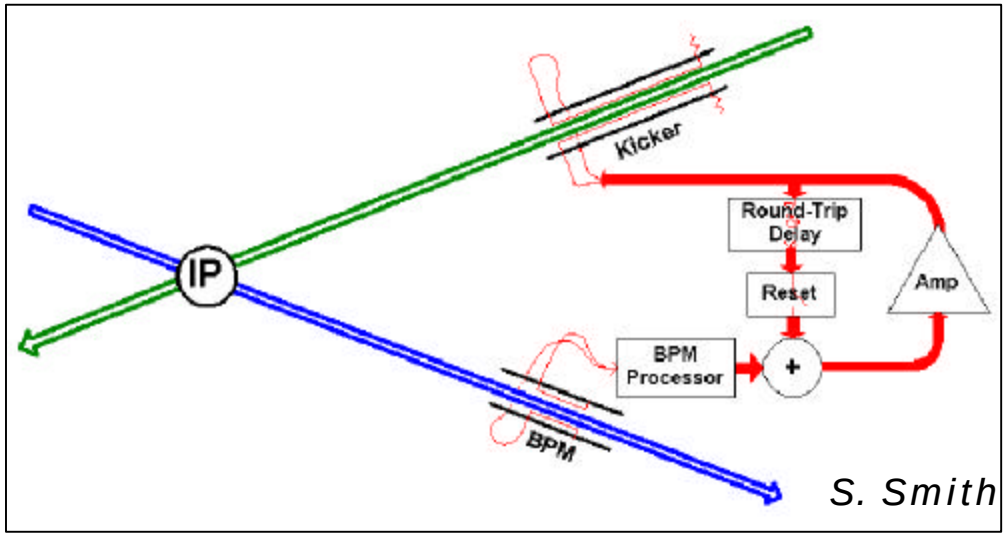


Feedback On NanoSecond Time Scales (FONT)

NLC bunch spacing:	1.4 ns	Vertical spot size:	2.7 nm	
Number of bunches:	190	Bunch train length:	266 ns	*(100 ns for CLIC)*

Status of NLC fast (intra-train) feedback

(reported by Philip Burrows and Glen White, 10/5/01, CERN, see also note LCC – 0056 03/01, Steve Smith)



Initial offset	Start of steering	Full luminosity	
8 nm (3 σ_y)	after 36 ns	after 42 ns	(16 % of bunches)
100 nm (37 σ_y)	after 36 ns	after 120 ns	(45 % of bunches)

Beneficial for NLC and CLIC as well but not sufficient.

ATL

Slow diffusive ground motion: $\sigma^2 = A \times T \times L$

$$\left\langle y_i y_j \right\rangle = \left[\mathbf{Q} \cdot \mathbf{V}_Y \cdot \mathbf{Q}^{\mathrm{T}} \right]_{ij}$$

$$\mathbf{V}_Y = A \cdot T \cdot \begin{pmatrix} z_1 & z_1 & z_1 & \cdots \\ z_1 & z_2 & z_2 & \cdots \\ z_1 & z_2 & z_3 & \cdots \\ \vdots & \vdots & \vdots & \ddots \end{pmatrix} \equiv A \cdot T \cdot \mathbf{Z}_{ATL}$$

assuming $z_i > 0$

$$\left\langle y_n^2 \right\rangle = A \cdot T \cdot \underbrace{\left[\mathbf{Q}_n \cdot \mathbf{Z}_{ATL} \cdot \mathbf{Q}_n^{\mathrm{T}} \right]}_{\text{effective ATL length}}$$

TESLA 500 GeV	15 m
CLIC 3TeV	28 m

ATL Lattice Factors

Define

$$\left\langle \Delta y^2 \right\rangle = \Delta Y \cdot A \cdot T$$

$$\left\langle D_y^2 \right\rangle = D \cdot A \cdot T$$

etc

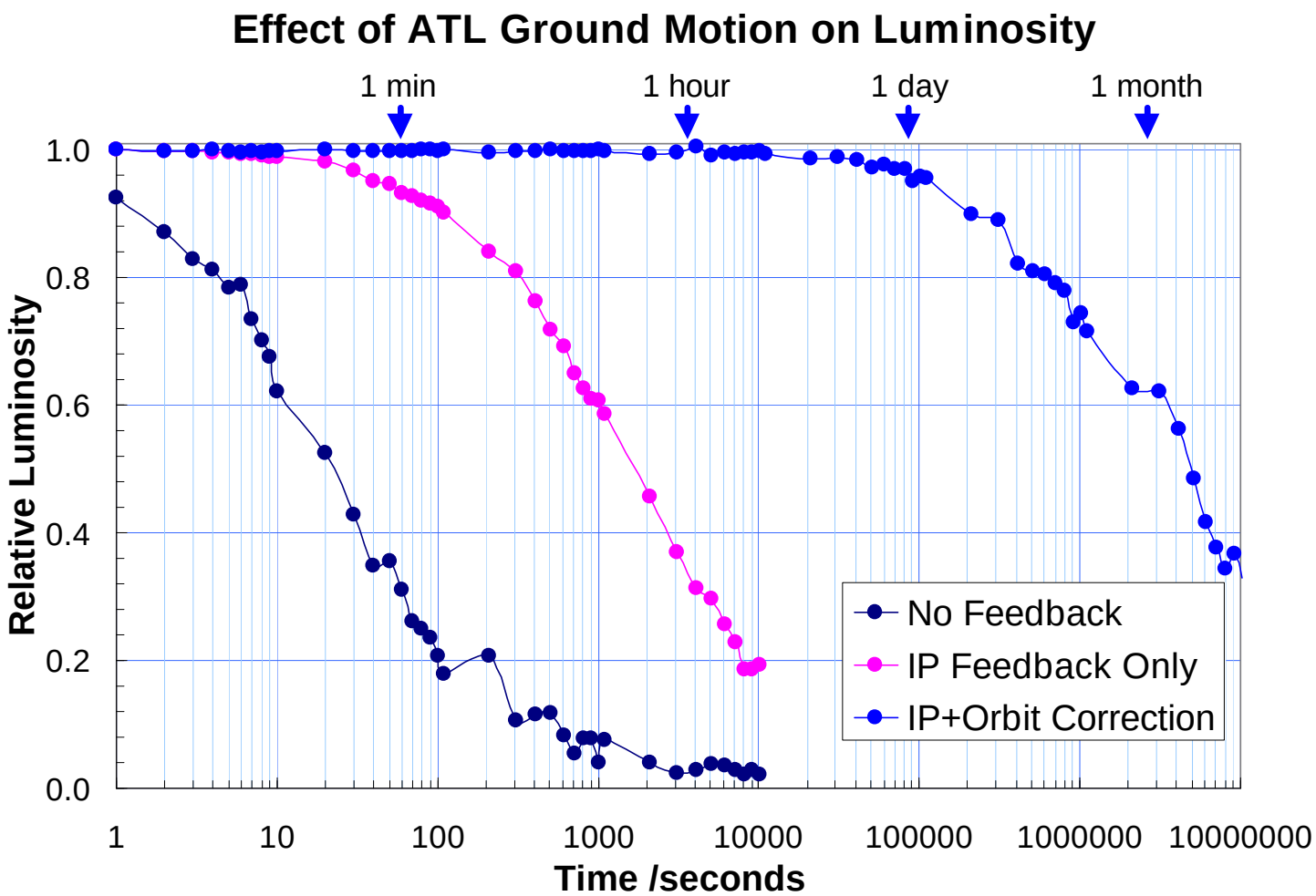
Where:

ΔY	beam-beam offset (effective length)
D	Dispersion
C	x-y Coupling ($\Delta y \propto \theta_x$)
D_2	2nd-order dispersion ($\Delta y \propto \delta^2$)

Two "Extremes"

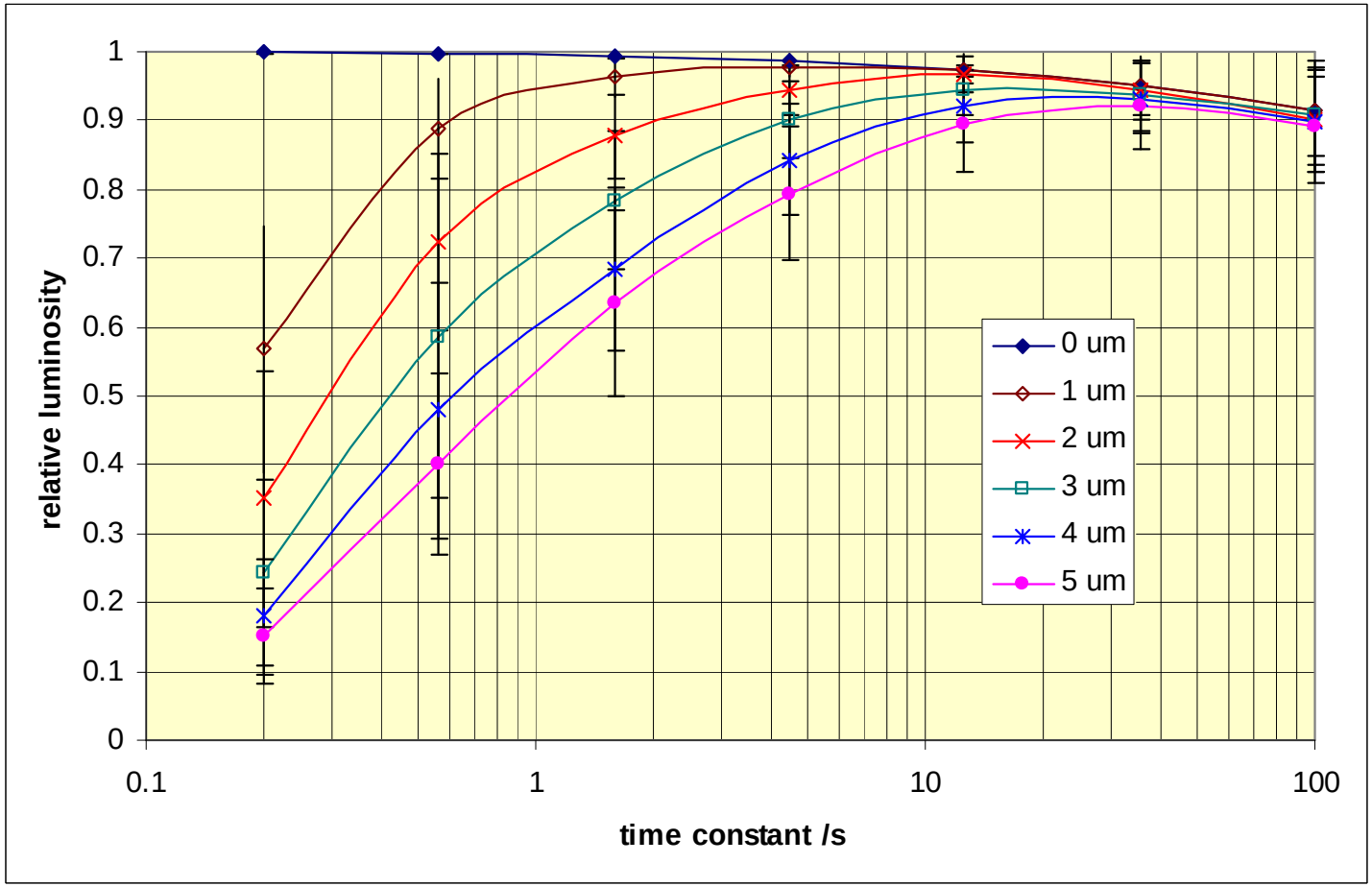
	ΔY	D	C	D_2
TESLA 500 GeV	15	4477	3×10^6	6×10^7
CLIC 3TeV	28	878	5×10^8	2×10^6
$A*T=10^{-4}$ $\mu m^2/m$	nm	% increase in σ_y		
TESLA 500 GeV	36	2	0.82	0.16
CLIC 3TeV	53	34	0.00	0.49

ATL Simulation Results for TESLA



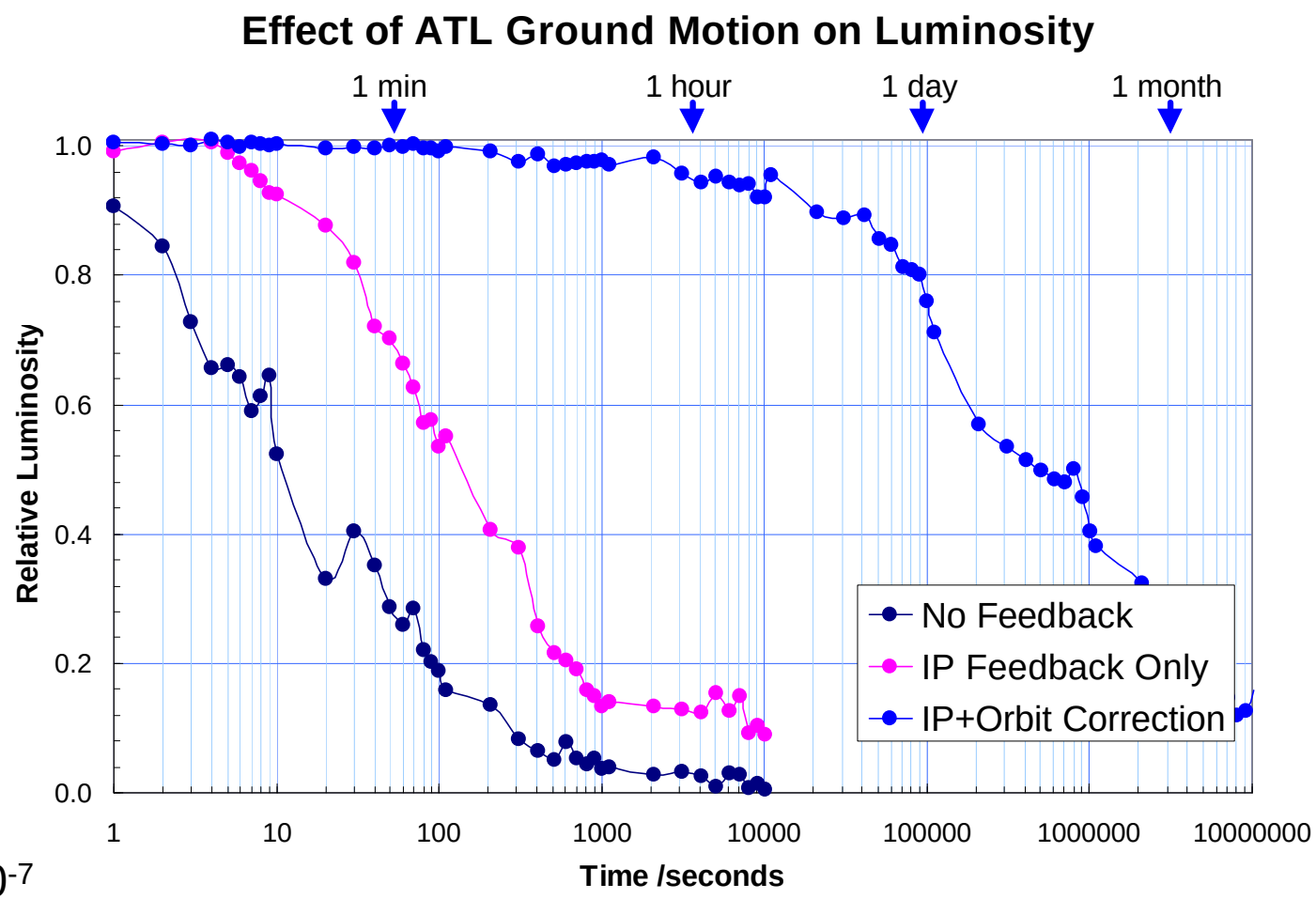
$A = 4\times10^{-6}$

ATL Simulation Results for TESLA



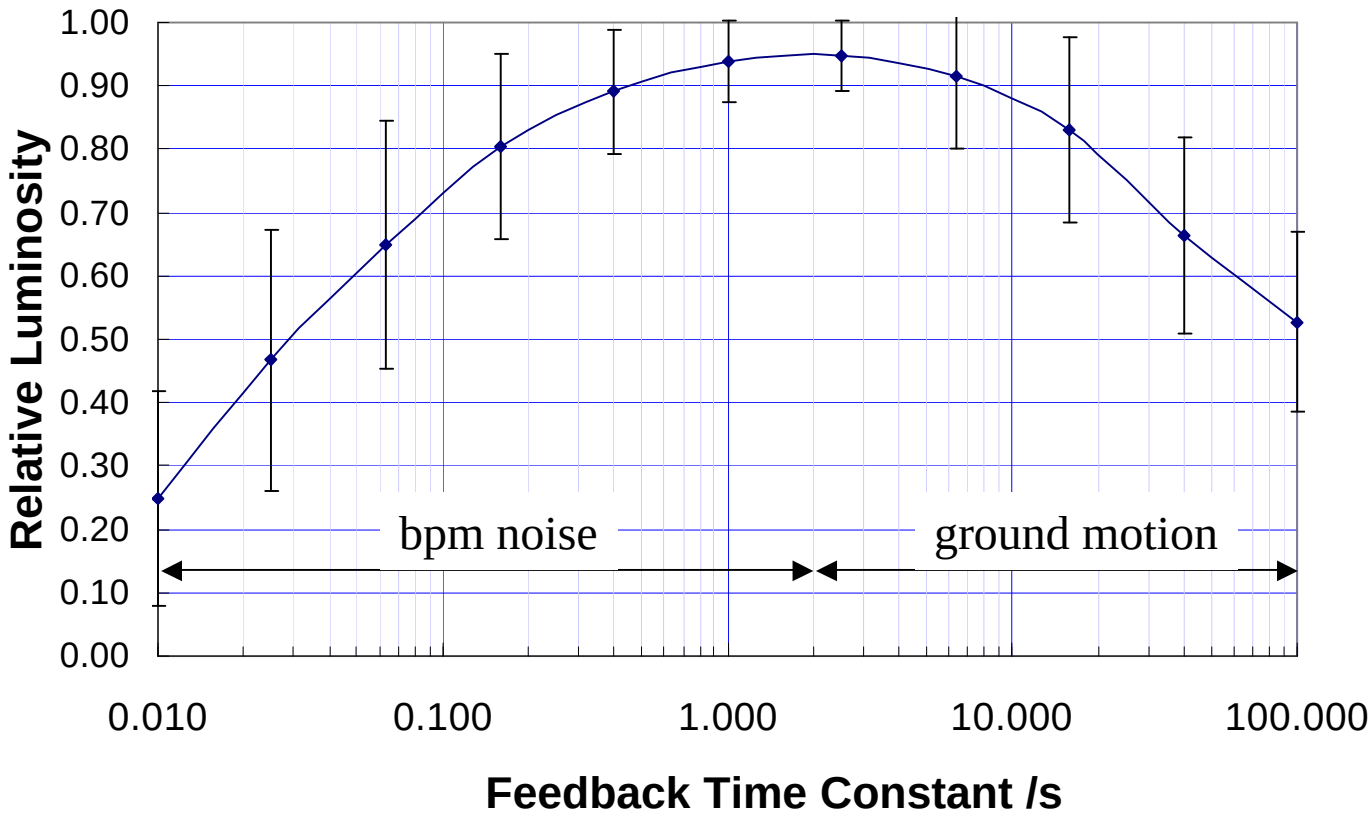
$A = 4\times10^{-6}$

ATL Simulation Results for CLIC



$A = 5\times10^{-7}$

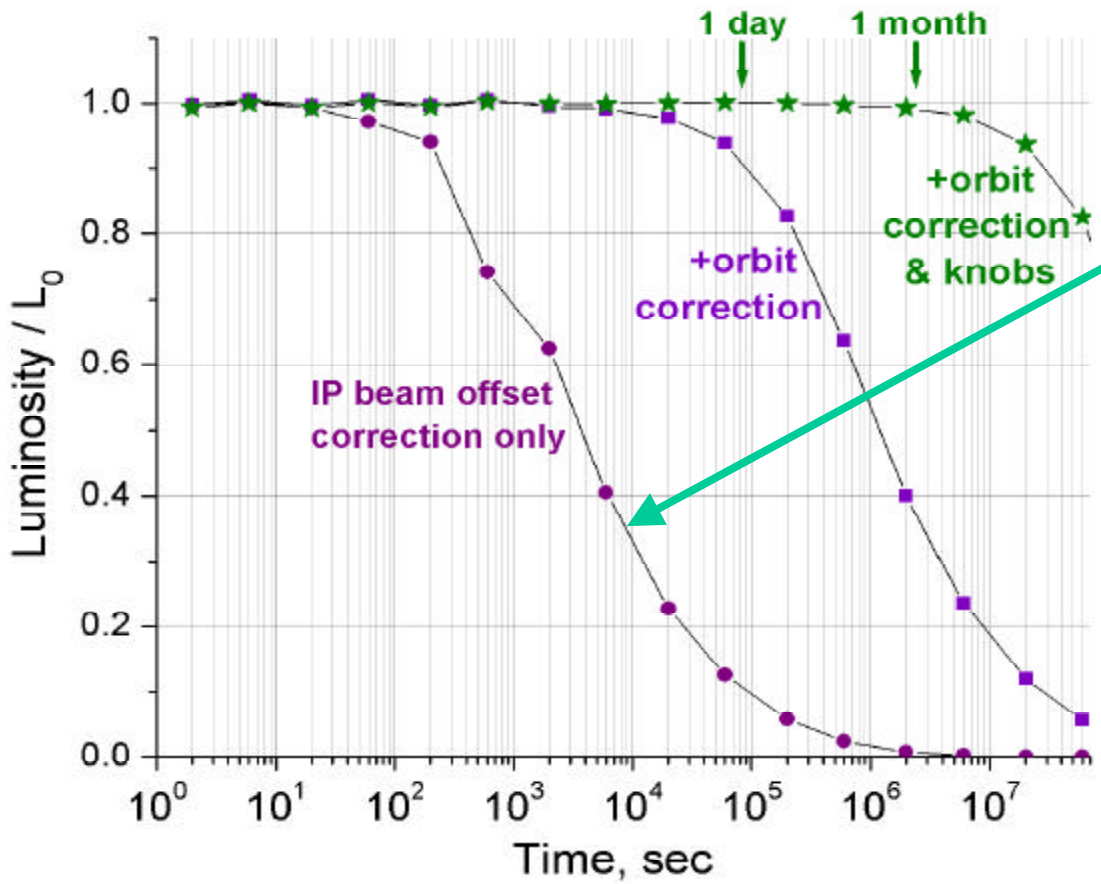
ATL Simulation Results for CLIC



$A = 5\times10^{-7}$

$A = 5\times10^{-7}\ \mu m^2/m/s$
$1\mu m$ BPM noise

NLC



A = 5×10^{-7}

assuming dispersion dominates:

$$\frac{\Delta L}{L} \propto C_{lattice} A T \left(\frac{d_{RMS}}{s_y^*} \right)^2$$

suggests:

$$C_{NLC} \;\text{»}\; 2 \acute{} C_{TESLA}$$

taken from the NLC Snowmass Report

Summary

- Response of Lattices of all machines are similar
  - “Raimondi” style FF seems better wrt dispersion, but worse wrt X-Y coupling (sextupoles)
- Performance (tolerance to magnet motion) dominated by beam parameters (ε_y, δ)
- Low rep. rate (5Hz) of TESLA is disadvantage
  - fast IP feedback solves beam-beam offset problem, BUT
  - optical aberrations are still an issue
- Improved simulations with more ‘realistic’ models
  - better ground motion simulation (at least for TESLA/CLIC)
  - effects of supports *etc*
  - Cultural noise sources *etc*
- Continued R&D on stabilisation techniques
  (*fc CLIC study*)