
Luminosity Stabilisation Issues in Beam Delivery Systems for Linear Colliders

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DESY

CERN, 7th August, 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.

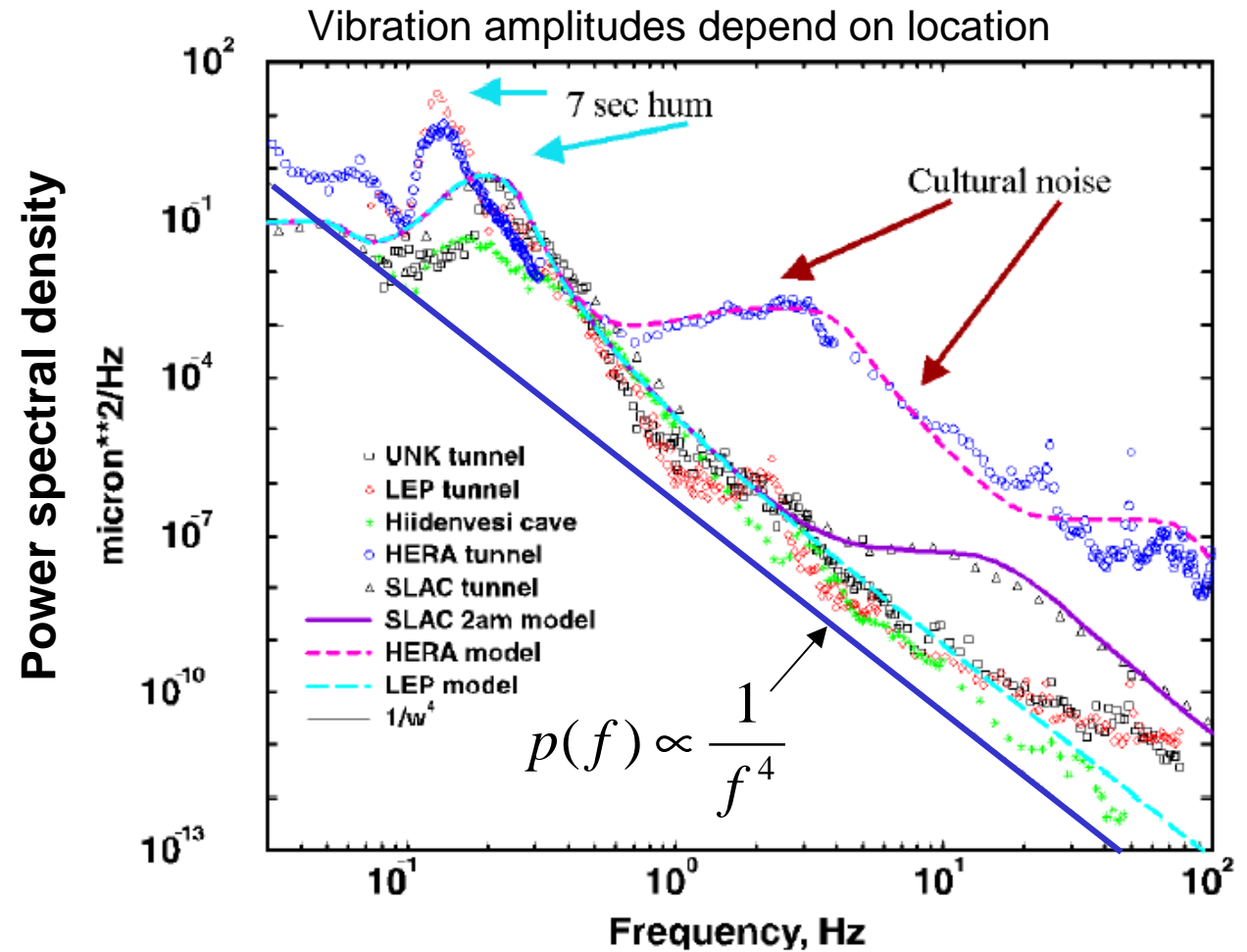
Notes on Beam-Beam Effects

- 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 $\Delta y \sim \sigma_y/10 = 0.5$ nm)
 - so-called “banana” effects should be considered!
- Hence results shown for TESLA are probably optimistic!

$$\approx \frac{\sigma_z}{f_{bunch}}$$

Notes on Ground Motion

Long history of R&D and now relatively well understood



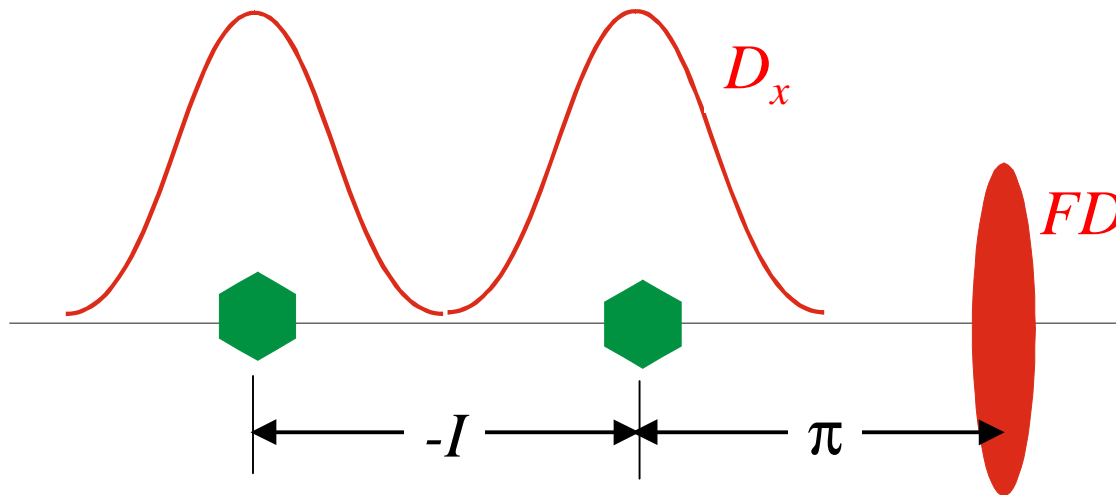
From A. Seryi⁰, SLAC

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

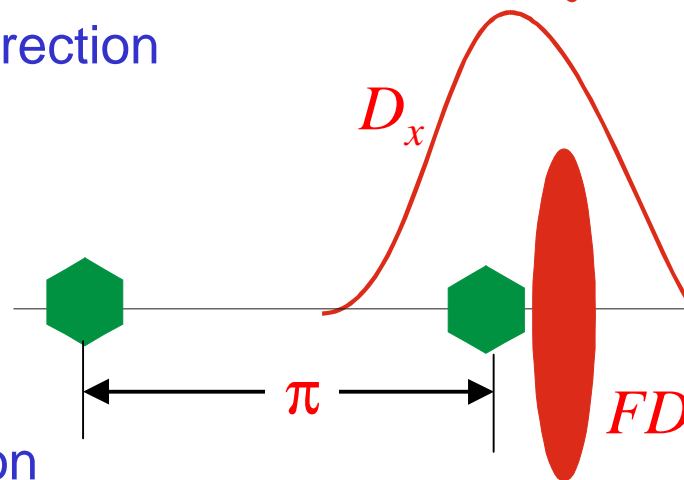
Final Focus Systems

“TRADITIONAL”
(SLC, FFTB, TESLA)



Non-local chrom. correction

IP

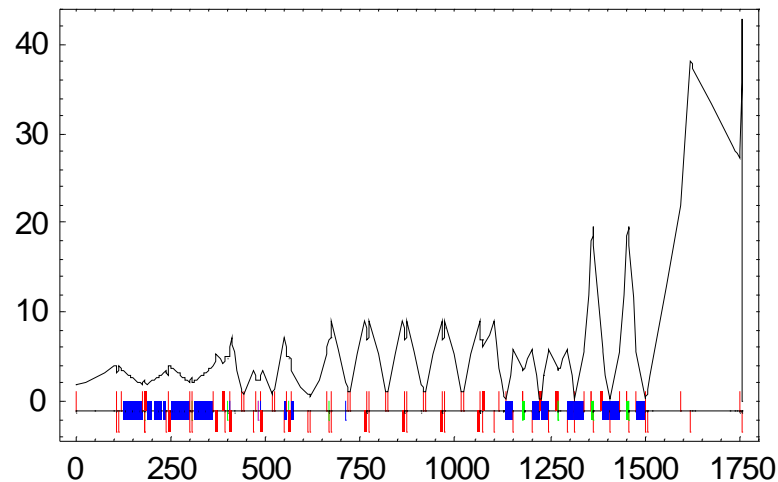


local chrom. correction

“RAIMONDI”
(NLC, CLIC)
8

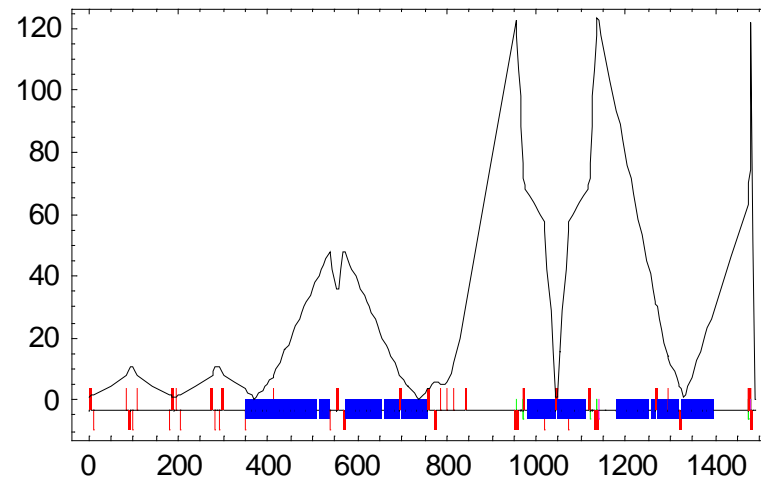
Beam Delivery Systems

TESLA 500 GeV



$$\begin{aligned}\sigma_{x,y} &= 550/5 \text{ nm} \\ \delta_{\text{rms}} &= 0.16\% \text{ (electrons)} \\ &= 0.04\% \text{ (positrons)}\end{aligned}$$

NLC 500 GeV

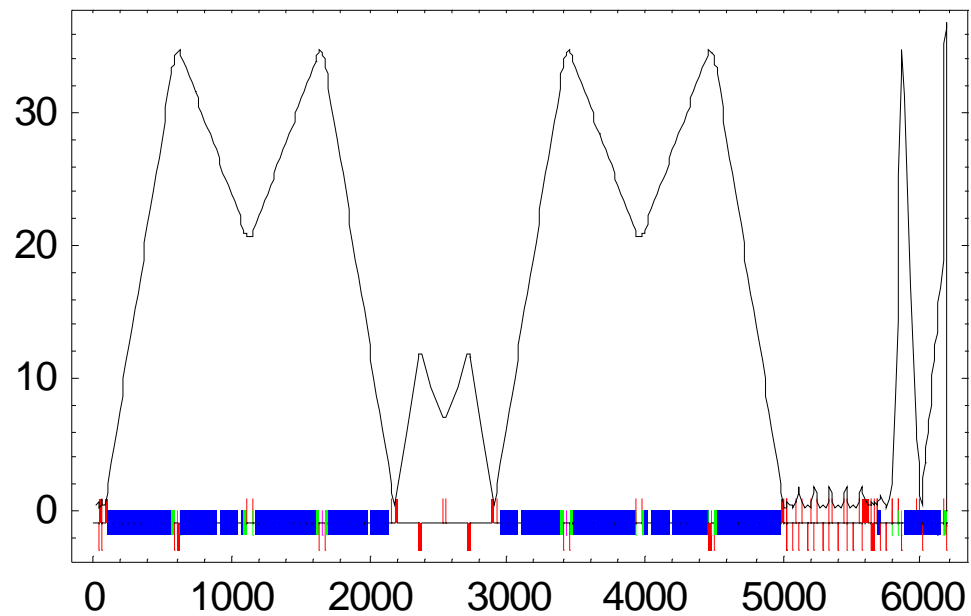


$$\begin{aligned}\sigma_{x,y} &= 243/2.7 \text{ nm} \\ \delta_{\text{rms}} &= 0.23\% (\pm 0.4\%)\end{aligned}$$

BDS = Final Focus + Collimation System

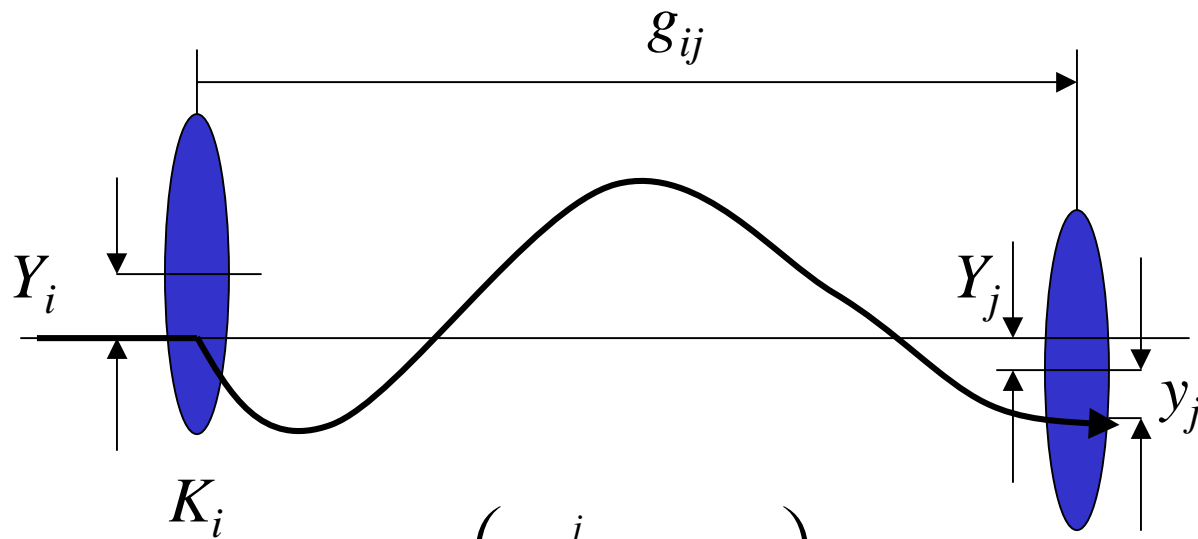
Beam Delivery Systems

CLIC 3TeV



$$\begin{aligned}\sigma_{x,y} &= 43/1 \text{ nm} \\ \delta_{\text{rms}} &= 0.28\% (\pm 0.5\%) \end{aligned}$$

Analysis of Magnet Motion



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

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*:

$$\mathbf{Q} = \mathbf{G} \cdot \mathbf{diag}(\mathbf{K}) + \mathbf{I}$$

Hence beam offset becomes

$$\mathbf{y} = -\mathbf{Q} \cdot \mathbf{Y}$$

Covariance of beam motion

$$\langle y_i y_j \rangle = \mathbf{V}_y = \mathbf{Q} \cdot \mathbf{V}_Y \cdot \mathbf{Q}^T$$

\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)
- $\mathbf{V}_Y = \sigma^2 \mathbf{I}$

$$\left. \begin{array}{l} \bullet V_{ij} = 0; i \neq j \\ \bullet V_{ii} = \sigma^2 \text{ (for all } i) \\ \bullet \mathbf{V}_Y = \sigma^2 \mathbf{I} \end{array} \right\} \mathbf{V}_y = \sigma^2 \mathbf{Q} \cdot \mathbf{Q}^T$$

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

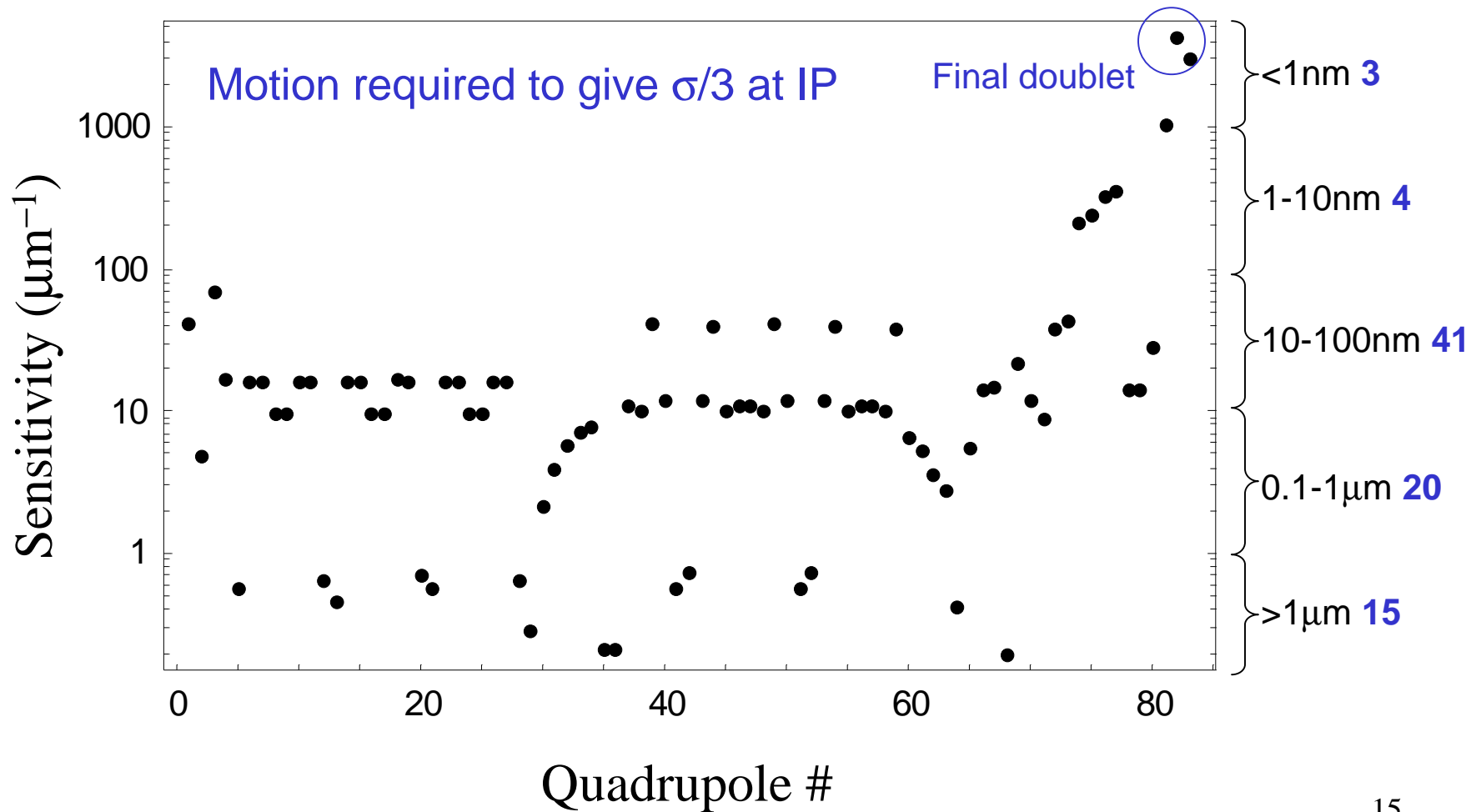
IP Vertical Motion due to Uncorrelated Magnet Motion

	Entire Lattice		No Final Doublet	
	factor	$\sigma/3$ motion	factor	$\sigma/3$ motion
CLIC 3TeV	1.77	0.24 nm	0.39	1.1 nm
NLC 500 GeV	1.96	0.46 nm	0.33	2.7 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 Stabilisation 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)¹⁶

Emittance Dilution

Magnet	Type	RMS σ_y aberration
Quadrupole	Linear Dispersion	$R_{34} K \delta_{rms} y$
Sextupole	x-y coupling	$R_{12} R_{34} S \theta_x^* y$
	Linear dispersion	$R_{34} S D_x \delta_{rms} y$
Skew-sextupole	Waist shift	$R_{34}^2 S \theta_y^* y$

- y = beam offset wrt magnetic centre
 K, S = integrated strength (quad, sextupole, octupole resp.)
 δ_{rms} = RMS energy spread
 θ^* = IP beam divergence

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 $D_y = \mathbf{D} \cdot \Delta \mathbf{y}$
- Hence

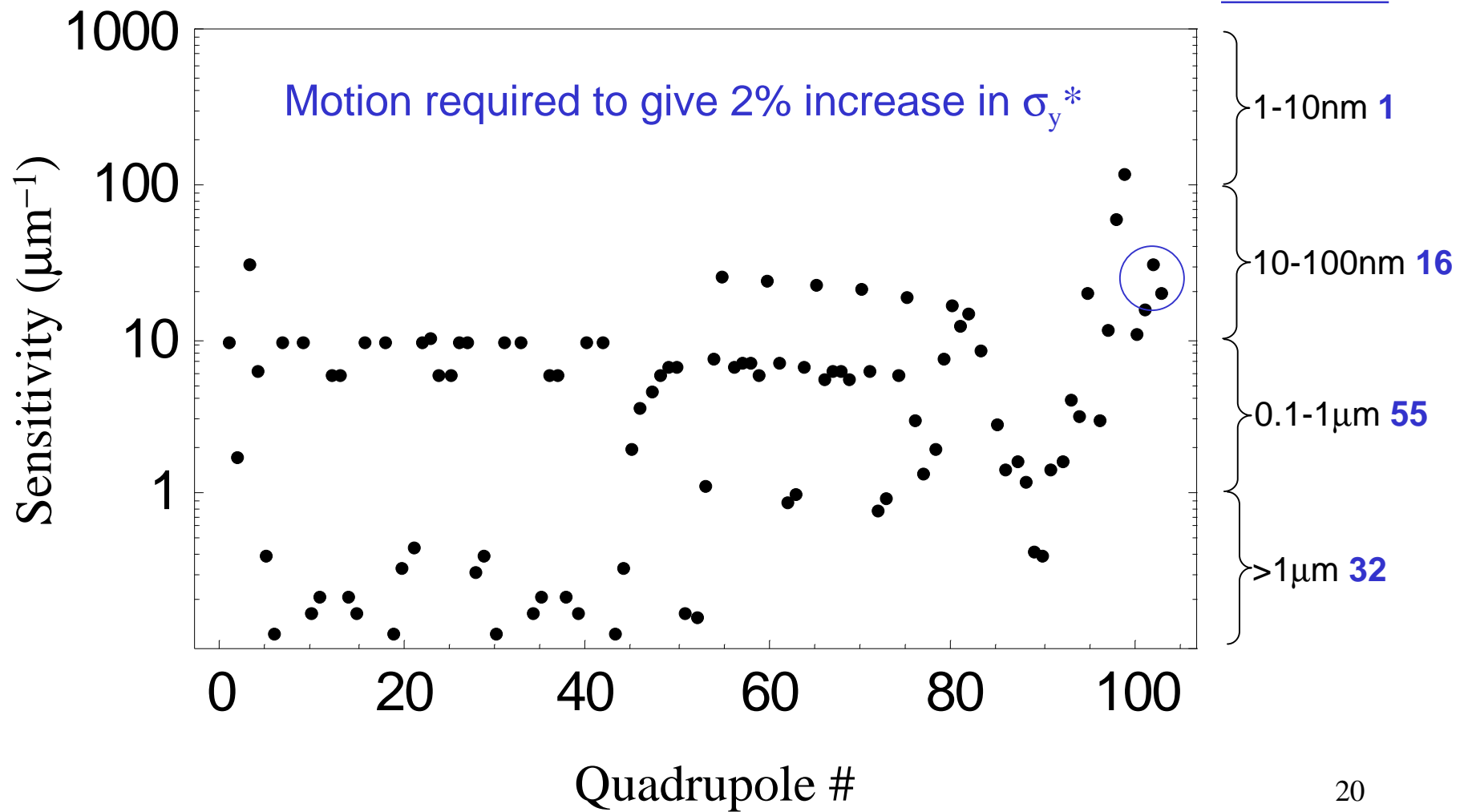
$$D_y = -\mathbf{D} \cdot \mathbf{Q} \cdot \mathbf{Y}$$
$$\langle D_y^2 \rangle = (\mathbf{D} \cdot \mathbf{Q}) \cdot \mathbf{V}_Y \cdot (\mathbf{D} \cdot \mathbf{Q})^T$$

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

similar expressions for coupling, waist shift *etc.*

		Lattice Factor	RMS motion for 2% tolerance (nm)
	dispersion	32	19
TESLA 500GeV	x-y coupling	544	49
	2 nd -order dispersion	8198	33
	dispersion	2.8	80
NLC 500 GeV	x-y coupling	1093	16
	2 nd -order dispersion	104	1007
	dispersion	11	8
CLIC 3TeV	x-y coupling	4990	9
	2 nd -order dispersion	1007	36

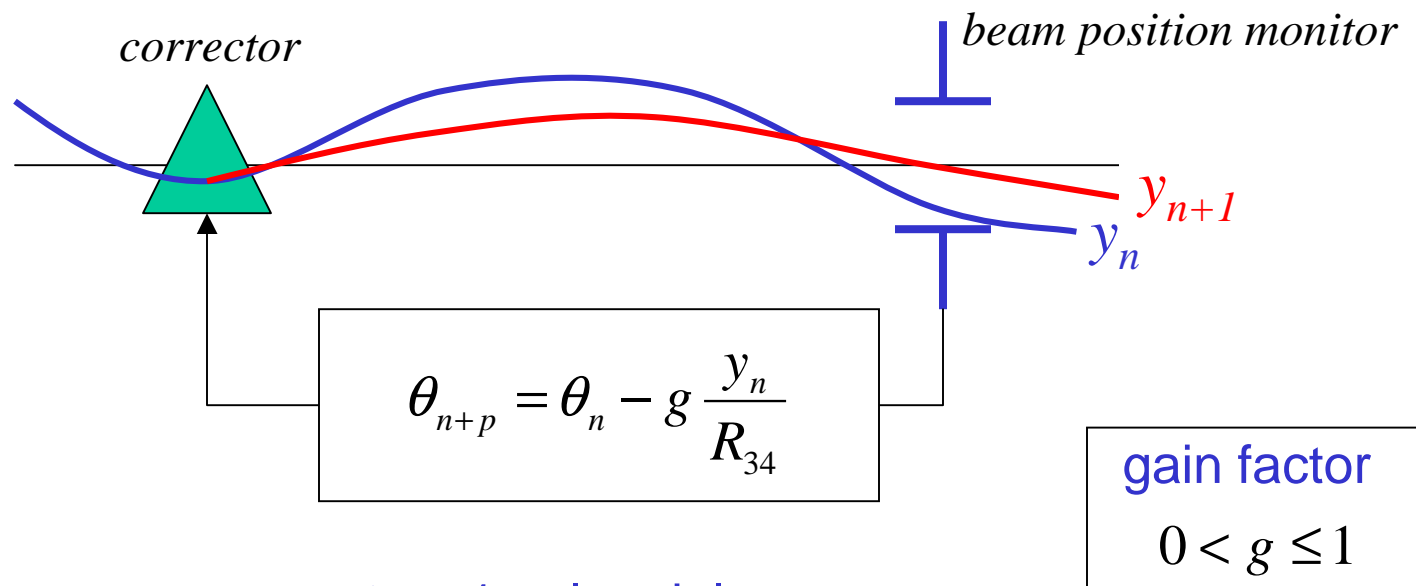
CLIC Quadrupole Tolerances



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 $f_{\text{rep}} = 100$ Hz

Beam-Based Feedback (orbit correction)

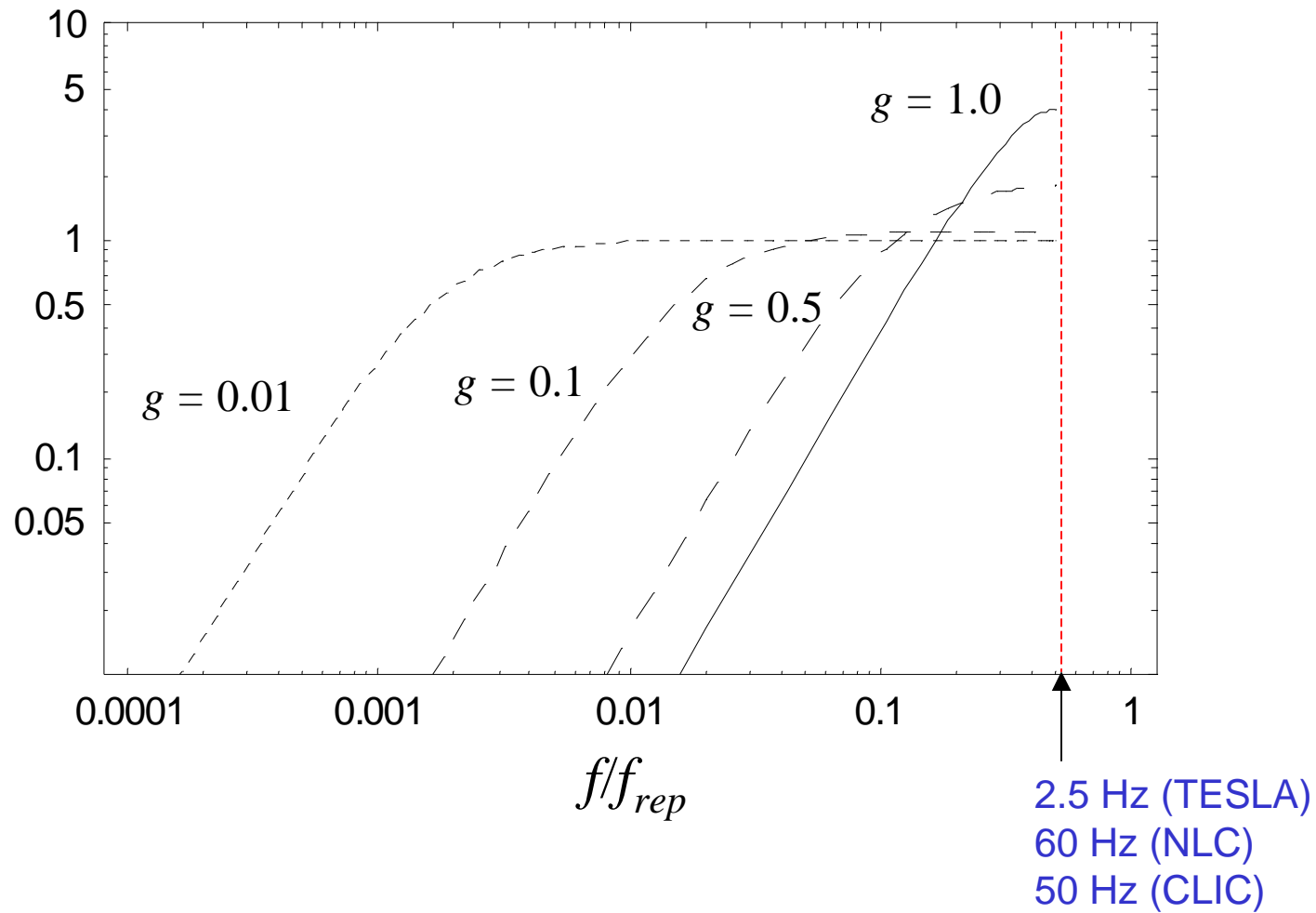


$p = 1$ 1 pulse delay

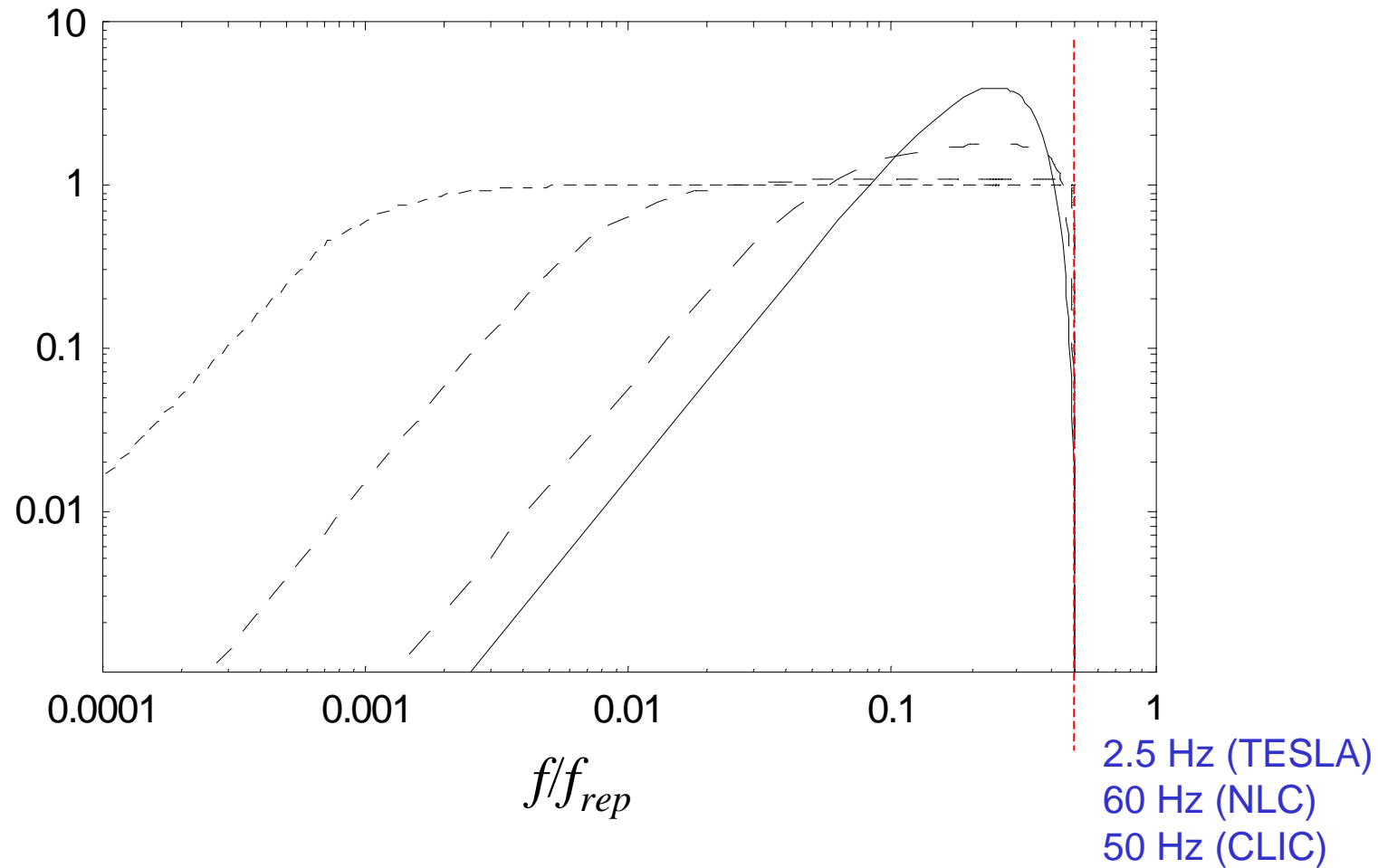
$p = 2$ 2 pulse delay etc.

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

$p = 1$ Frequency Response



$p = 2$ Frequency Response



Frequency Spectrum

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

$$\langle y_i y_j \rangle = \int_{-\infty}^{\infty} F\{y_i(t)\} F^*\{y_i(t)\} df$$

mutual (or cross) power spectrum

For Ground Motion:

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

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

absolute power spectrum

correlation function

Frequency Spectrum

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

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

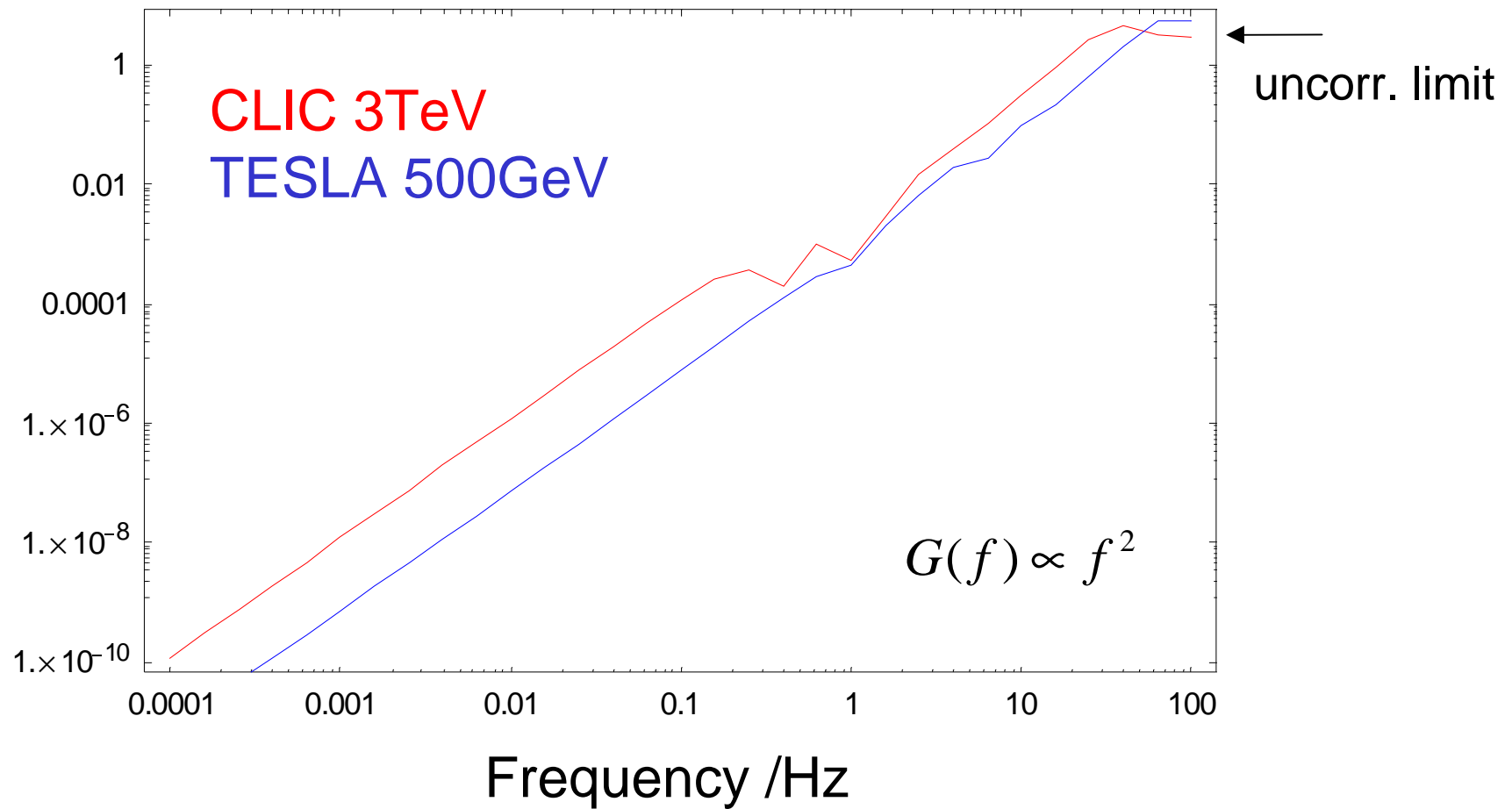
Lattice Response
("filter")

SLAC Ground Motion Model:

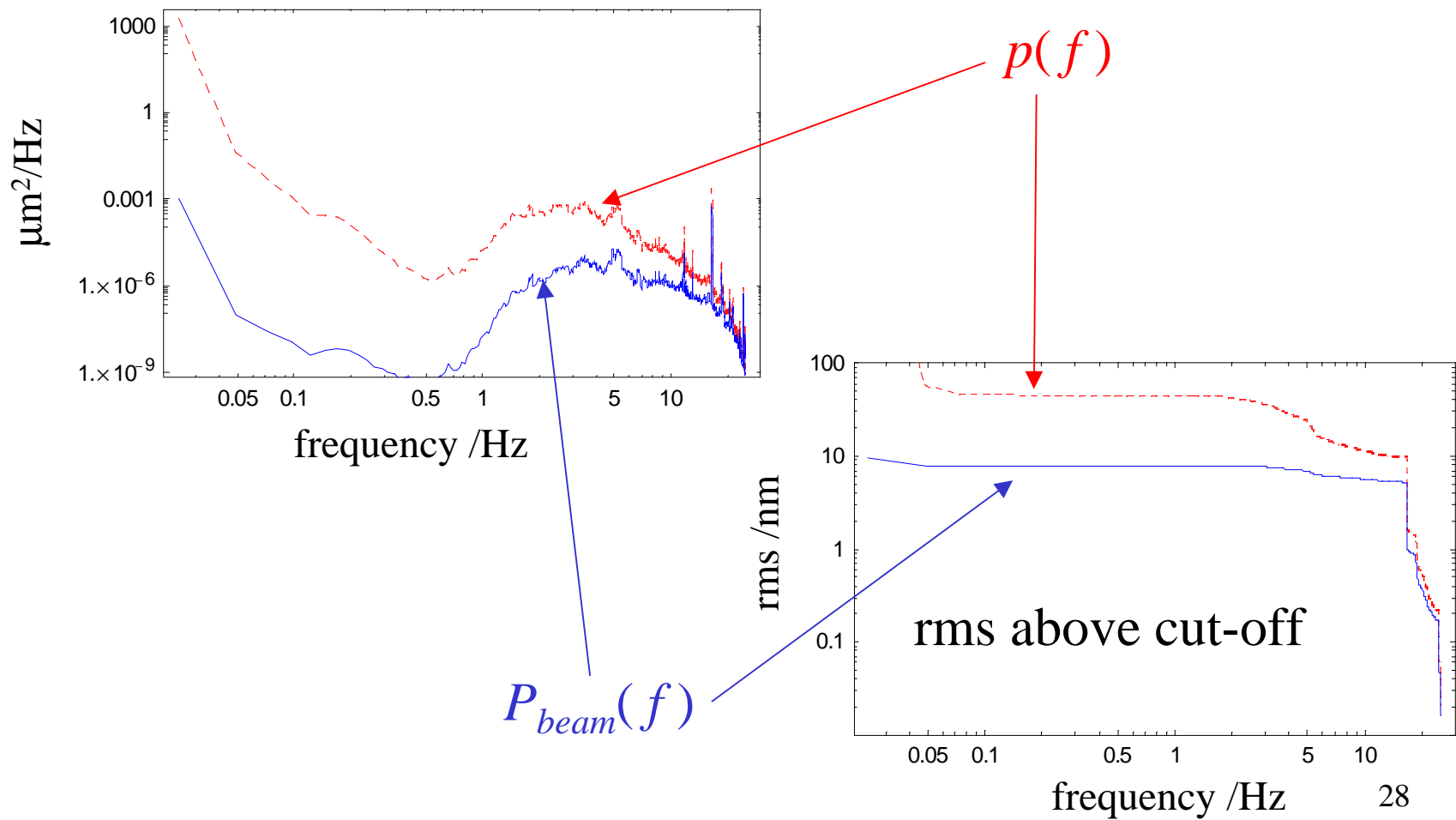
Wave-like motion with phase velocity $v(f) = 450 + 1900 e^{-f/2}$

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

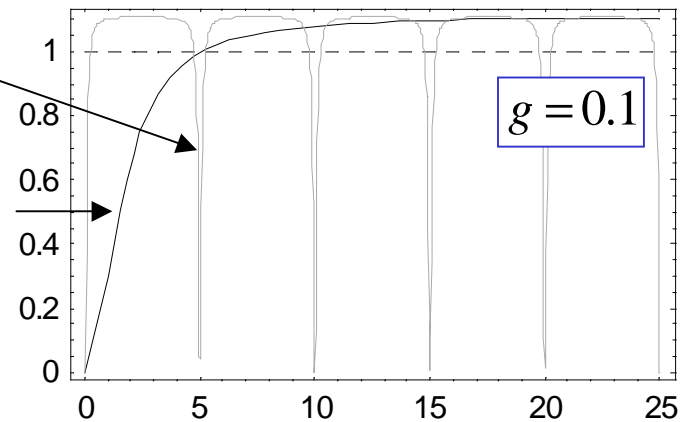
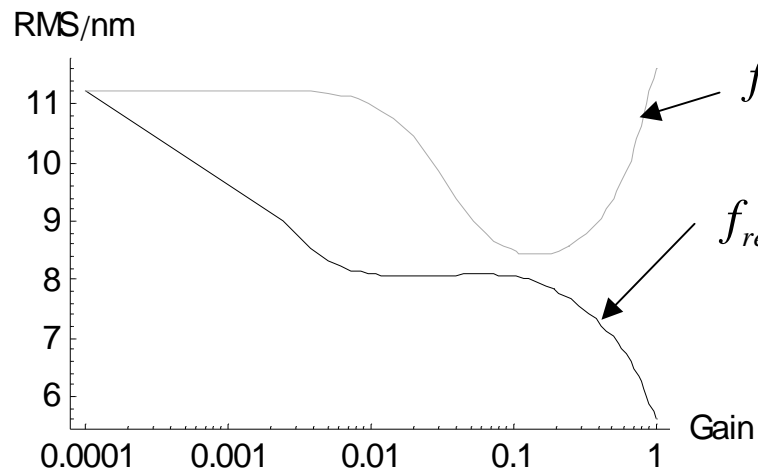
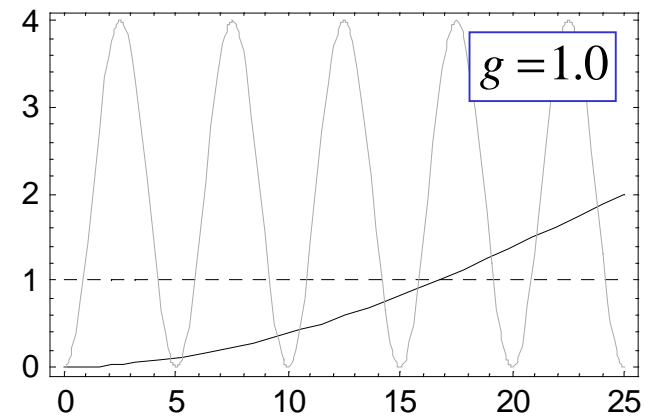
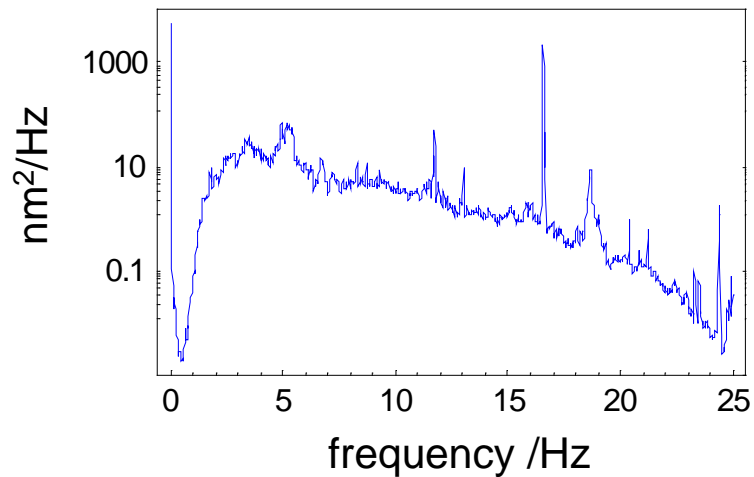
IP Motion Lattice Response



IP Motion (TESLA)

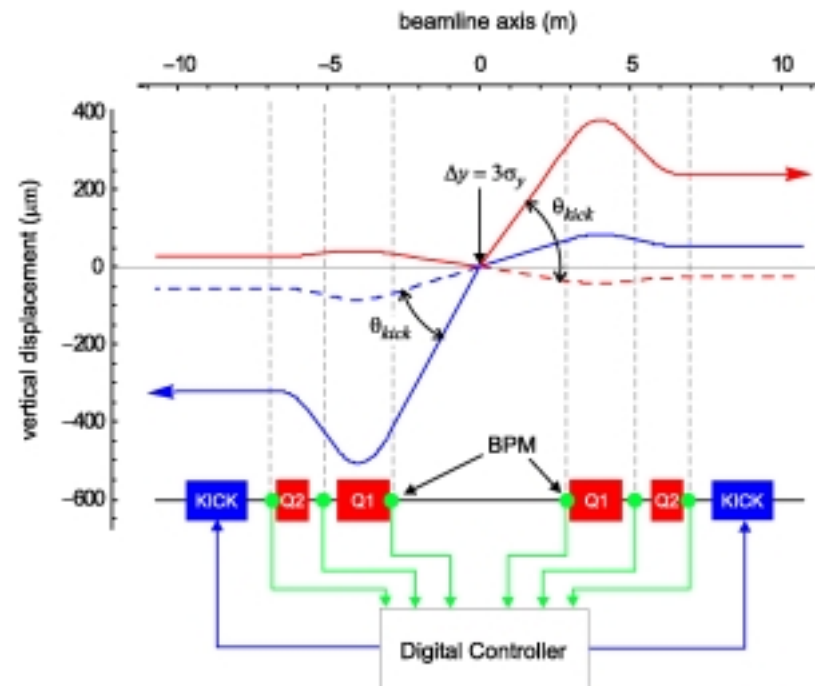


Feedback and Rep. Rate



Beam-Beam Feedback

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

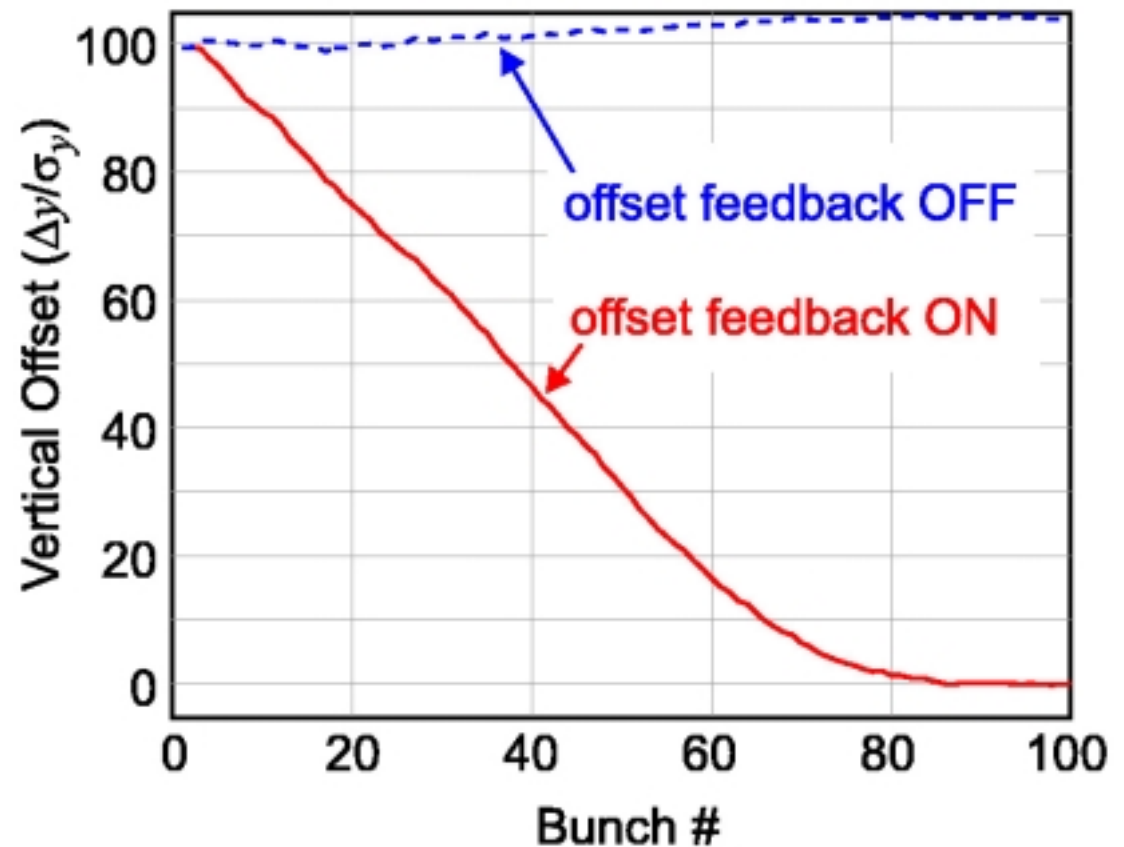


TESLA:
2820 bunches in 950 μs bunch
train ($\tau_b = 337$ ns)

TESLA IP Feedback

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

(a) Separation Response

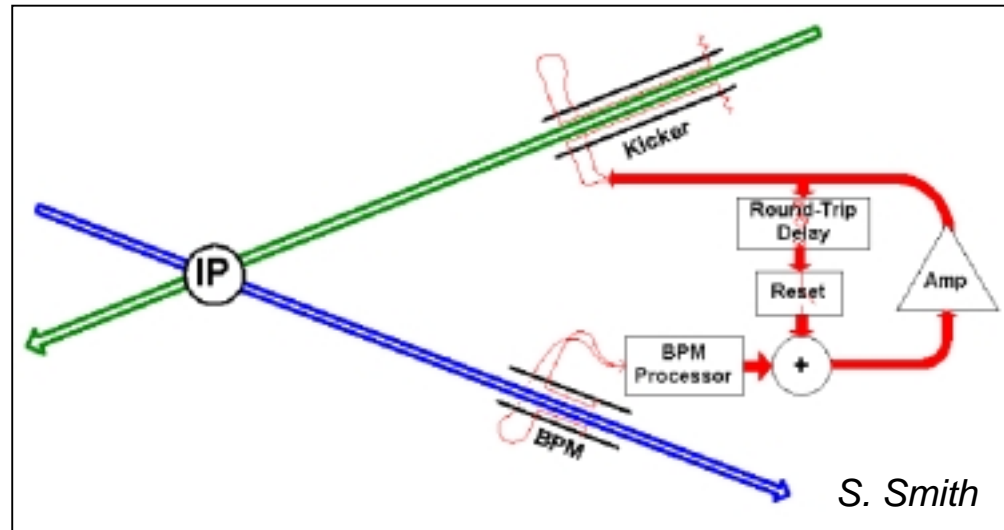


Feedback On NanoSecond Time Scales (FONT)

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 ($3 \sigma_y$)	after 36 ns	after 42 ns (16 % of bunches)
100 nm ($37 \sigma_y$)	after 36 ns	after 120 ns (45 % of bunches)

Beneficial for NLC and CLIC as well but not sufficient.

ATL

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

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

$$\mathbf{V}_Y = A \cdot T \cdot \begin{pmatrix} z_1 & z_1 & z_1 & \cdots \\ z_1 & z_2 & z_2 & \cdots \\ z_1 & z_2 & z_3 & \cdots \\ \vdots & \vdots & \vdots & \ddots \end{pmatrix} \equiv A \cdot T \cdot \mathbf{Z}_{ATL} \quad \text{assuming } z_i > 0$$

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

effective ATL length

TESLA 500 GeV	15 m
CLIC 3TeV	28 m

ATL Lattice Factors

Define

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

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

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
$A \cdot T = 10^{-4} \mu\text{m}^2/\text{m}$	nm		% increase in σ_y	
TESLA 500 GeV	36	2	0.82	0.16
CLIC 3TeV	53	34	0.00	0.49

ATL Lattice Factors

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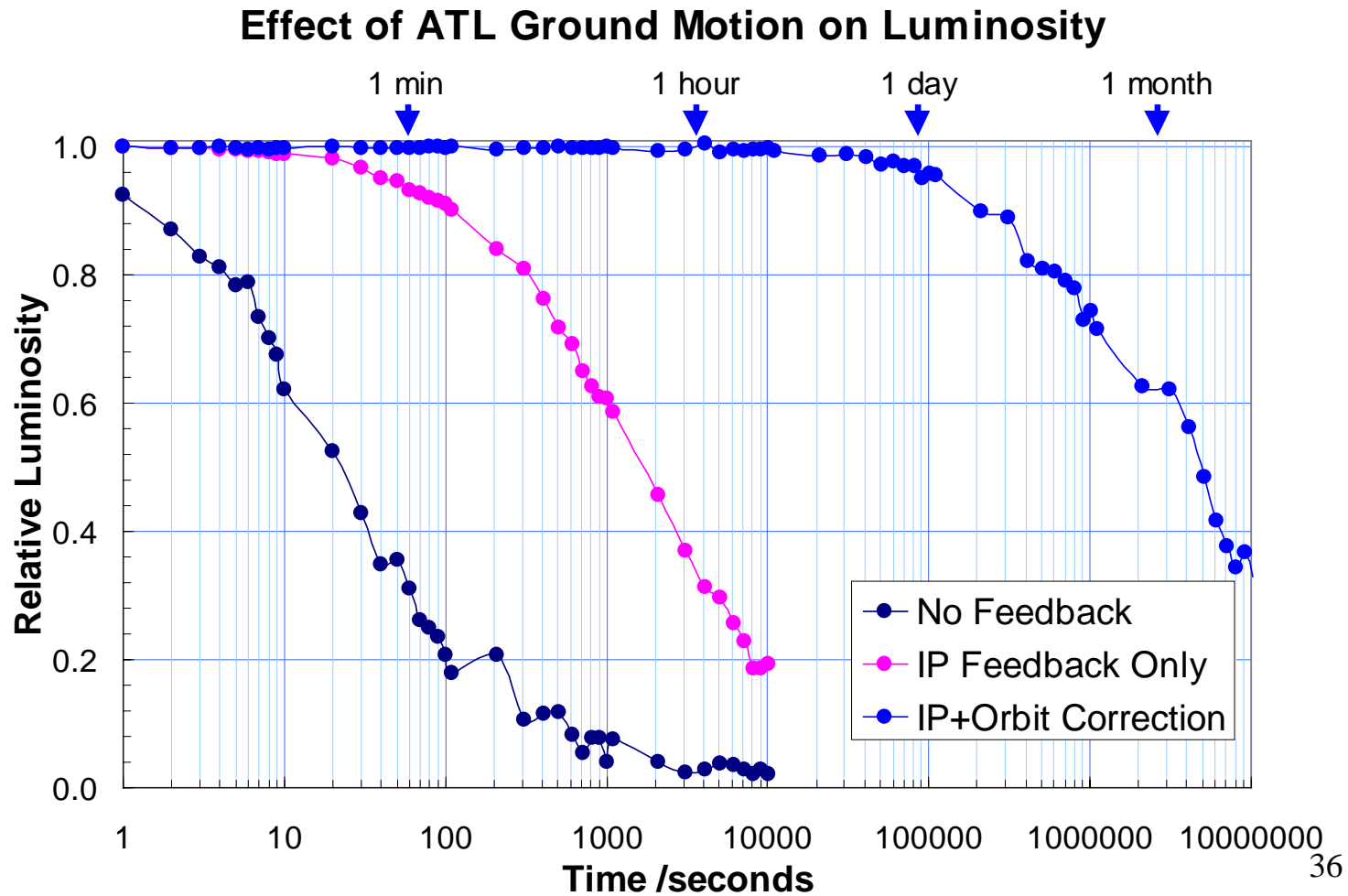
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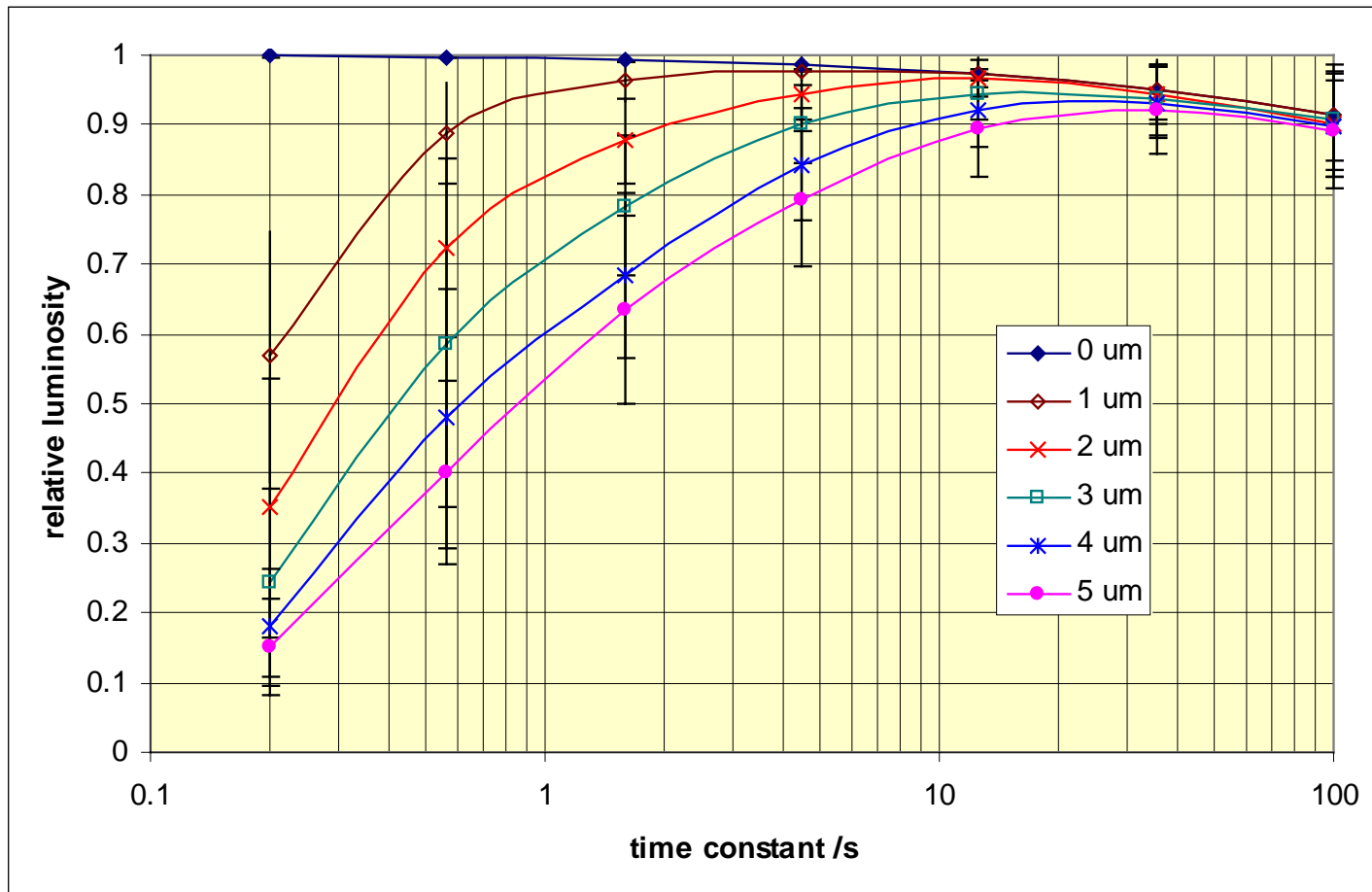
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ATL Simulation Results for TESLA



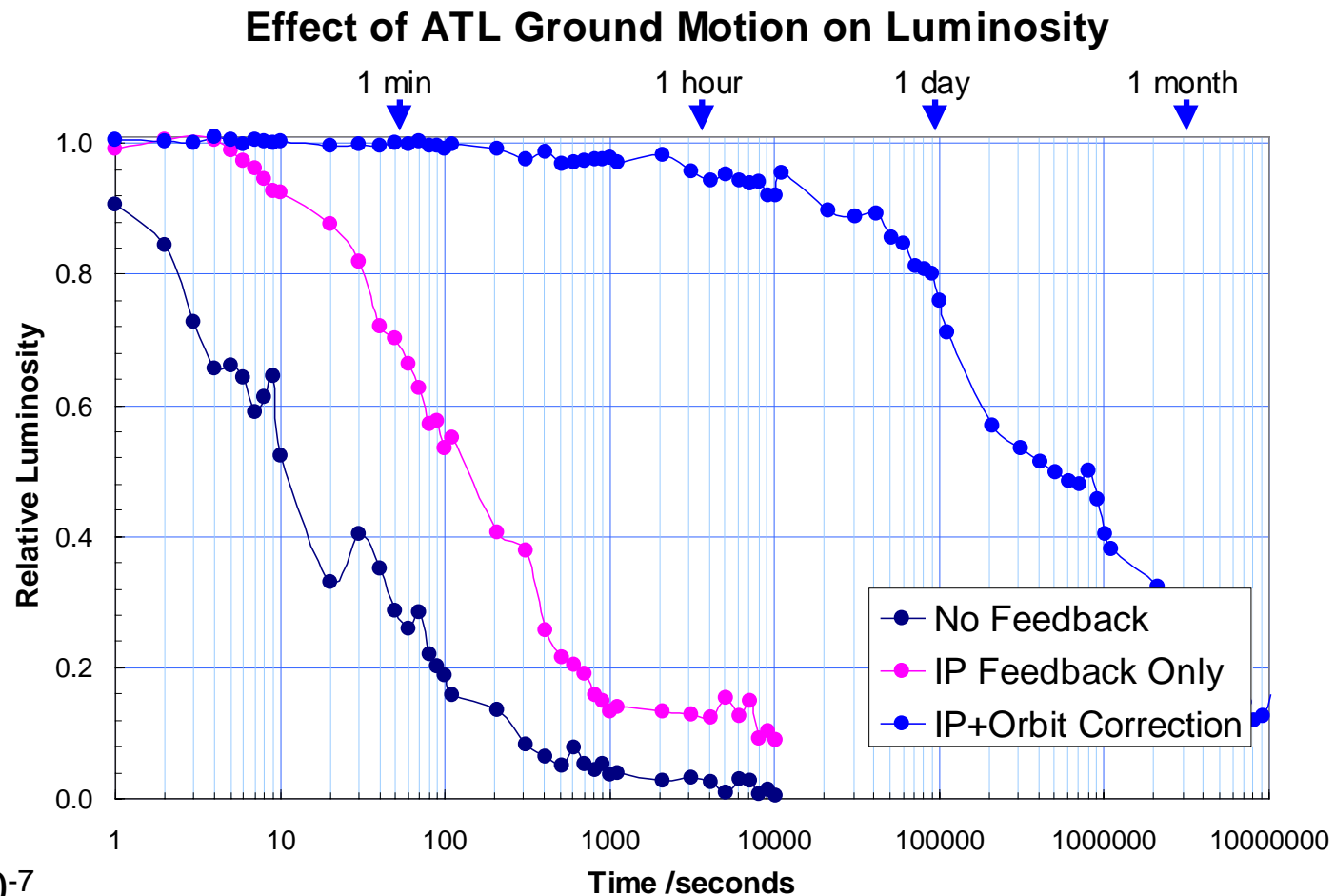
$$A = 4 \times 10^{-6}$$

ATL Simulation Results for TESLA



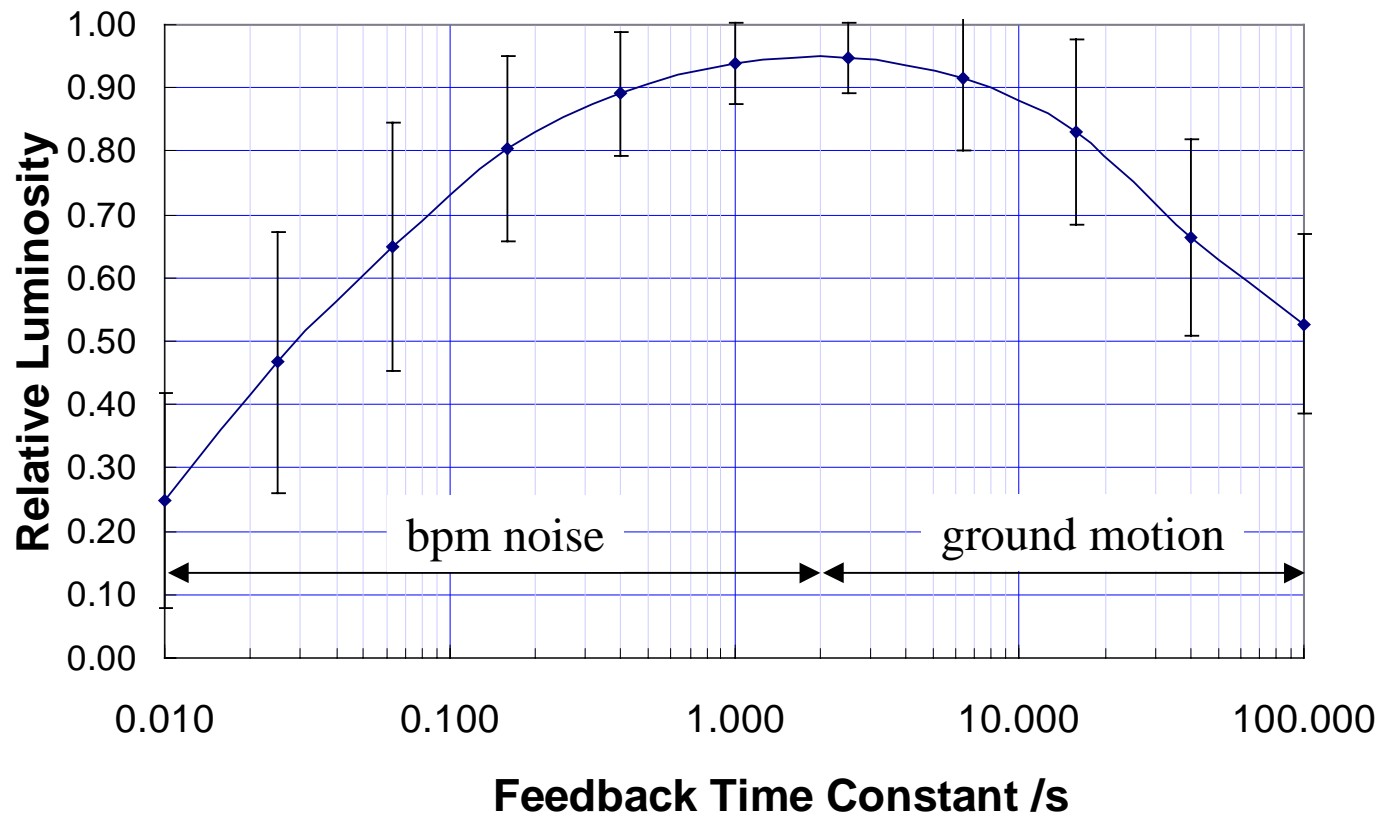
$$A = 4 \times 10^{-6}$$

ATL Simulation Results for CLIC



$$A = 5 \times 10^{-7}$$

ATL Simulation Results for CLIC

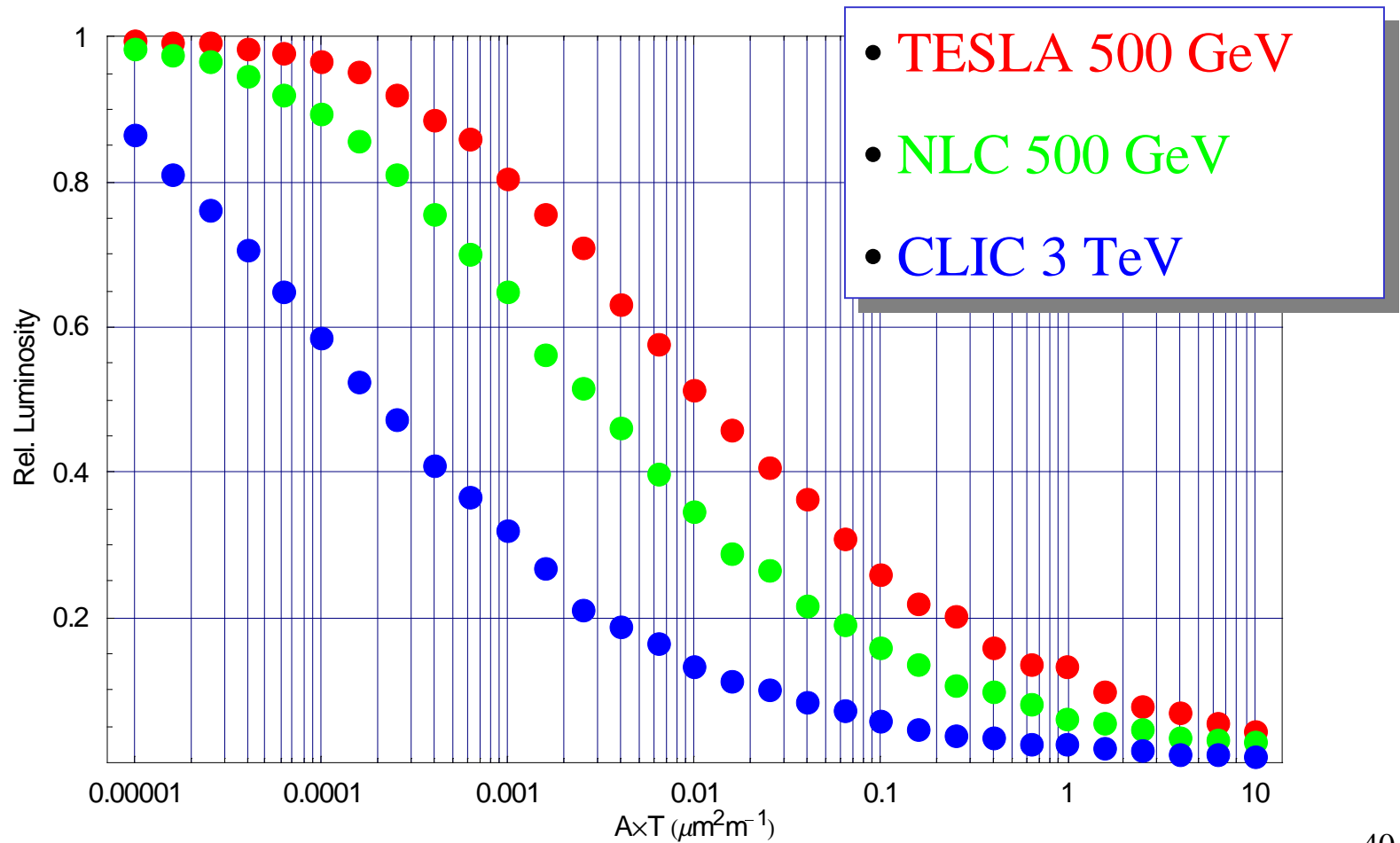


$$A = 5 \times 10^{-7}$$

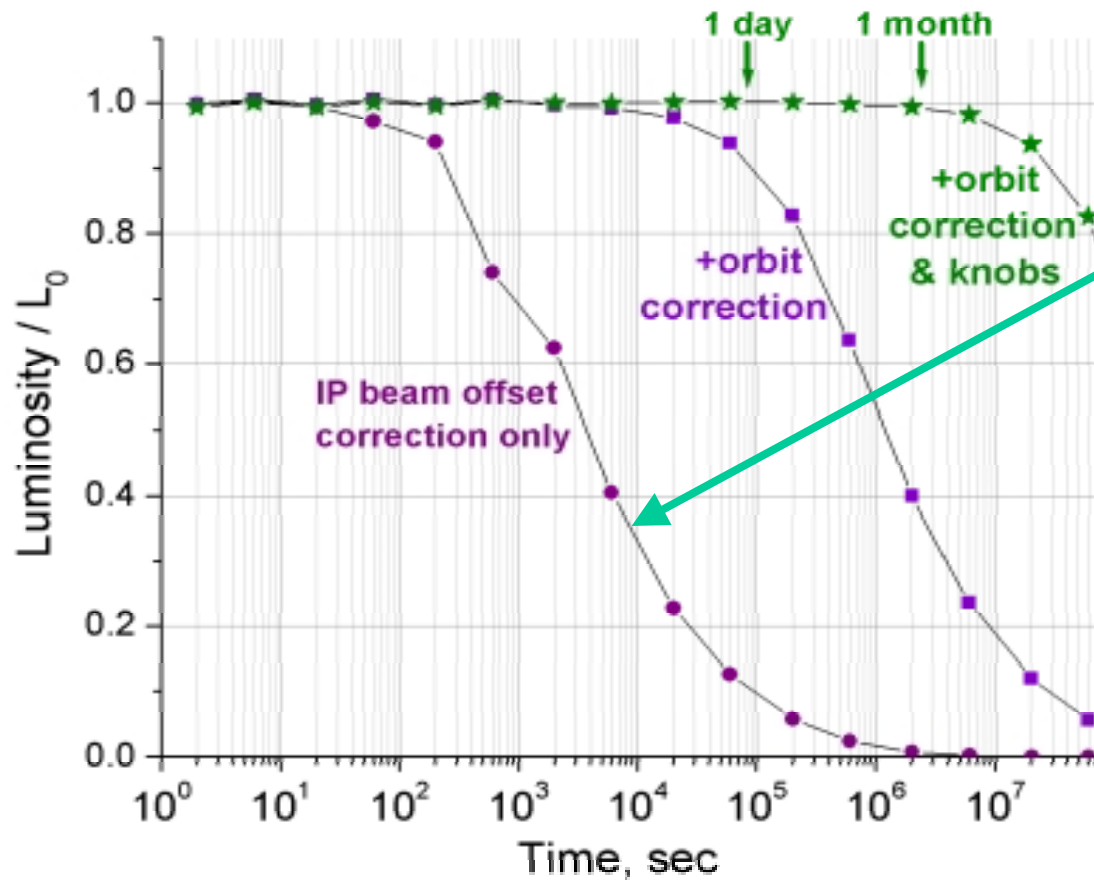
$$A = 5 \times 10^{-7} \mu\text{m}^2/\text{m}/\text{s} \quad 39$$

$1 \mu\text{m}$ BPM noise

Effect of ATL on σ_y^* (luminosity) based on analytical estimates



NLC



assuming dispersion dominates:

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

suggests:

$$C_{NLC} \approx 2 \times C_{TESLA}$$

$$A = 5 \times 10^{-7}$$

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*)