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A Note on Ground Vibration Issues Related to the Choice of a Linear Collider Site

by

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Abstract:

Ground motion is a consideration in the construction and operation of a linear collider. Beam based orbit stabilization will be necessary in any type of linear collider at any site. For S-Band and X-Band colliders additional compensation of quadrupole vibration would be required at sites with large levels of ground vibration. Such compensation can be implemented using low price, high precision motion detectors now available. For CLIC and TESLA, beam based orbit stabilization would be sufficient at any site.
Various Linear Collider sites under consideration may differ by an order of magnitude with respect to rms ground vibration, but we conclude that ground vibration considerations are not a key issue in the choice of an appropriate site for any kind of Linear Collider.

Numerous investigations have been published on both ground motion and its effect on the luminosity of a Linear Collider, the most comprehensive include those by Fischer[1], Raubenheimer[2] and Shiltsev[3]. There is a consensus, that the frequency components of the orbit motion which are smaller than a fraction Φ of the linac repetition rate f_{rep} can be compensated using beam based feedback: Low frequency jitter of the beam position at the IP can be measured and compensated for the following bunch train, and very low frequency ground motion along the linac can be corrected using beam based alignment. On the basis of the analysis of typical ground motion spectra and the experience at SLAC, Φ is estimated to be 0.04[4,5]. As a consequence, the critical part of the ground motion spectrum is above $f_{cutoff} = \Phi \cdot f_{rep}$ (see table 1), since compensation at these frequencies requires observation of the mechanical motion of the magnets. There is a tendency that higher values of f_{cutoff} are more favorable since ground motion spectra in general decrease sharply with increasing frequency.

↓ Collider type	linac repetition rate	critical ground vibration frequency f_{cutoff}
TESLA	10 Hz, effectively 1 MHz	40 kHz
S-Band	50 Hz	2 Hz
X-Band	≈200 Hz	8 Hz
CLIC	1700 Hz	68 Hz

Table 1: Lower limit, f_{cutoff}, of vibration frequency spectrum that cannot be stabilized using beam based feedback

For the superconducting collider scheme TESLA, the distance between bunches within a bunch train is long enough (1 μsec), that the correction kick can be applied within the time between the first two bunches of each pulse. Thus, the first bunch (out of a total of 800 per pulse) will be used as a pilot bunch to realign the subsequent 799 bunches. It has been shown that this can be accomplished with present day technology[6]. Consequently, f_{cutoff} is very high and so the compensation of the orbit jitter due to ground motion is not a problem for TESLA. One should avoid, however, not to excessively amplify the ground motion through mechanical resonances of the superconducting quadrupole magnets.

Whether or not the high frequency part of ground motion is tolerable for the other Linear Collider schemes (CLIC, X-Band, S-Band) depends on its magnitude. There is a vast amount of experimental data from all major accelerator centers[7,8,9,10,11,12]. Indeed there are large differences found from site to site, and also as a function of time (e.g. day/night). At frequencies above roughly 1 Hz, so-called cultural noise is a major contribution to the spectrum. This noise is not only due to human activities in settlements close to the location of measurement, but it is, to a large extent, also due to the operation of the accelerator center itself (cooling water, pumps, air conditioning, etc.). This contribution is not easily avoided. Also, one should be careful when comparing data taken in unused tunnels with data taken at operating facilities. Table 2 indicates if mechanical vibration of quadrupole magnets would be tolerable for the respective collider being operated at different locations. Parameters of the respective collider types have been adopted from the LC'93 workshop[12]. Ground motion levels are taken from the cited references. For the estimation of the rms beam vibration σ_y, the following simple formula for uncorrelated quadrupole motion has been used:[2,13]

$$\sigma_y^2 = \frac{\sigma_q^2 \cdot N_q}{\cos^2 \frac{\mu}{2}}$$

σ_q is the rms quadrupole motion as determined by integrating the respective ground motion spectrum from f_{cutoff} to infinity. N_q is the total number of quadrupoles per linac. μ is the betatron phase advance per FODO cell.

It is always assumed that beam based stabilization is applied. It is seen that in a comparatively noisy environment like the HERA tunnel, the vibration level would be intolerably high for both X-Band and S-Band colliders. Also shown are the results if the vibration levels measured on the tunnel floor are multiplied by a factor of three which takes into account the possible amplification of the floor motion through the mechanical resonances of magnet supports.

location →	UNK tunnel (unused)[10]		ISR tunnel (unused)[14]		LEP tunnel (in use)[11]		HERA tunnel (in use)[10]	
↓ Collider type	tunnel floor	× 3	tunnel floor	× 3	tunnel floor	× 3	tunnel floor	× 3
TESLA	yes	yes	yes	yes	yes	yes	yes	yes
S-Band	yes	yes	yes	yes	yes	yes	no	no
X-Band	yes	yes	yes	no	yes	yes	no	no
CLIC	yes	yes	yes	yes	yes	yes	yes	yes

Table 2: *Is the ground vibration level tolerable?* Various locations and, both, just the tunnel motion and an additional enhancement factor of 3 have been taken to determine the expected rms quadrupole motion. Although X-Band colliders require much tighter tolerances (due to the smaller vertical emittance), they are not more critical since their f_{rep} is larger and the vibration spectrum density decreases with frequency.

If the ground vibration level for a collider at a chosen site turns out to be intolerable (**no** in Table 2), then some means of quadrupole magnet stabilization has to be applied. The advantage of an active mechanical stabilization compared to purely passive stabilisation is discussed elsewhere[14]. Simple motion detectors (e.g. geophones) can be used to measure the motion of individual quadrupoles. Their performance is limited mainly by electronic noise. Therefore, inexpensive and very precise detectors have been developed in a collaboration between DESY and industry. In the frequency range above 2 Hz, a noise level of 1 nanometer has been achieved[15]. This is well below the uncorrelated quadrupole jitter tolerance of any type of collider. The price of each detector, including preamplifier, is below DM 5000 if produced on a large scale. Thus, for a collider the total cost of such a system would be below DM 20 million.
Two methods for the vibration compensation are under consideration:

1. compensation of the quadrupole motion by dipole correction magnet
2. direct mechanical stabilization of quadrupole magnets

From the beam optics point of view, the first method seems to be the most straightforward one. It has been successfully demonstrated[16]. Currently at DESY, work is underway to demonstrate the second method at the S-Band Test Linac. A potential advantage of this second method is that the success of stabilization can be monitored for each individual quadrupole magnet.

Finally, slow *dissipative* ground motion is another issue. While slow *elastic* ground motion does not affect the beam orbit due to its large wavelength, dissipative ground motion (described by the term ATL-rule coined by Shiltsev[3]) makes it necessary that beam based alignment[2] and mechanical realignment is regularly performed. The frequencies at which these measures are to be taken is site dependent and is characterized by the constant A of the ATL rule. This constant has been determined by analysis of HERA electron and proton motion over 8 decades of frequency for the DESY site. It is seen that DESY, while being subject to considerable cultural noise, is very stable in this respect[17].

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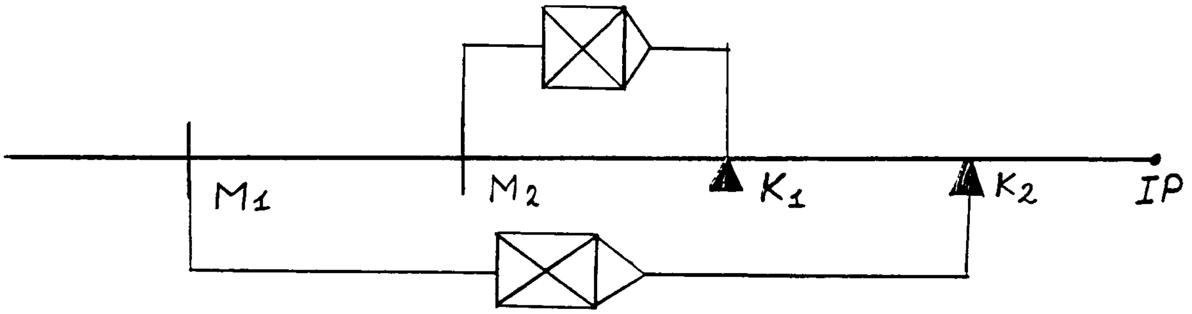
Appendix

Correction of Beam Motion in the Interaction Region of TESLA

R.Manukian

8.10.93

The suggested scheme for the correction of beam motion in the interaction region is



By chosing orthogonal monitors and kickers it is possible to correct Y and Y' independently. The kicks on the kickers will be

$$K_1 = -\frac{Y'_2}{\sqrt{\beta_1^k \beta_2^m}}, \quad K_2 = \frac{Y_1}{\sqrt{\beta_2^k \beta_1^m}}$$

β^k and β^m are the beta function on the kickers and monitors. If we assume the beta function on the monitors is $\beta^m = 1000m$ the beamsize on the monitors for different TESLA versions will be:

Energy (GeV)	beamsize σ_y (μm)	space between bunches (ns)	number of bunches in pulse	motion to be detected (μm)
250	45	1000	800	~ 4.5
500	7.8	200	4200	~ 1
1000	1.6	92	8690	~ 0.2

The delay time will consist of:

time required for the measurements $\sim 80ns$;
time for the correction kick calculation with dedicated $100MHz$ processor:
  $\sim 100ns$ for reading data and output and $\sim 300ns$ for calculations;
kickers rise time $\sim 50ns$;
time delay im communication line:
  with 0.85c line if the distance between monitor 1 and kicker 2 is $\sim 350m$ the delay will be $\sim 206ns$.

After summing the total time delay will be $\sim 736ns$.For different TESLA versions the number of lost bunches is

Energy (GeV)	number of bunches in pulse	number of lost bunches	relative lose (%)
250	800	1	0.125
500	4200	4	0.095

Since the motion to be detected for $1000GeV$ version is small than $1\mu m$, the possibility of the correction needs further investigations.

Efficiency of beam based feedback
local mechanical resonances and lattice resonance included,
--------extrapolation by cubic splines-----

Mathcad file by
J. Rossbach,
DESY
German version
2.9.93

$m := 8$ 2**m is number of time vector elements

$j_{min} := 1$ jmin*Delta nu is minimum frequency considered

$i_{max} := 2^m - 1 \quad i := 0 .. i_{max} \quad j := 0 .. 2^{m-1} \quad Hz \equiv sek^{-1} \quad nm \equiv 10^{-9} \cdot m$

$f_{rep} := 50 \cdot Hz$ Collider repetition rate

$\Delta t := \frac{1}{f_{rep}}$ time steps $\Delta t = 0.02 \cdot sek$ $\Delta\nu := \frac{1}{i_{max} \cdot \Delta t}$ frequency steps $\Delta\nu = 0.196 \cdot Hz$

$\nu_j := j \cdot \Delta\nu \quad t_i := i \cdot \Delta t \quad k := j_{min} .. 2^{m-1} \quad \nu_1 := 0.17 \cdot Hz \quad \nu_0 := 0.03 \cdot Hz \quad a := 2 \cdot 10^8 \cdot nm^2 \cdot Hz$

Properties of mechanical resonances:

$\nu_{res1} := 3 \cdot Hz \quad \nu_{res2} := 10 \cdot Hz$ resonance frequency

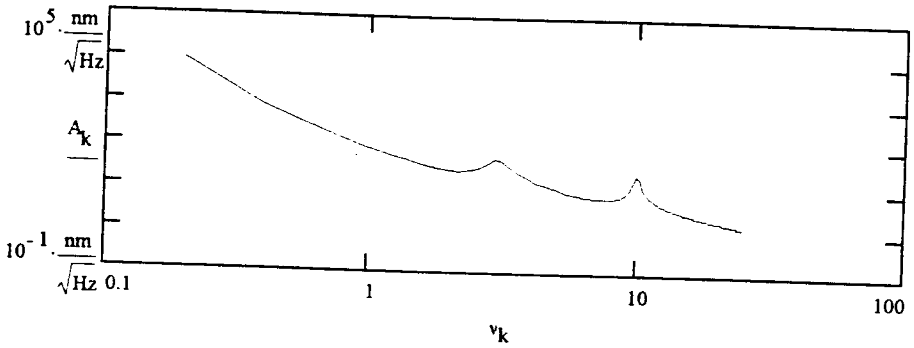
$a_1 := 7 \cdot \frac{nm}{\sqrt{Hz}} \quad a_2 := 1 \cdot \frac{nm}{\sqrt{Hz}}$ resonance amplitude $\Gamma_1 := 0.5 \cdot Hz \quad \Gamma_2 := 0.5 \cdot Hz$ resonance width

model of power spectrum density, including two mechanical resonances of a support (or so). The somewhat peculiar expression nu(res)xnu(j) guarantees that only frequencies in the vicinity of nu(res) are enhanced.

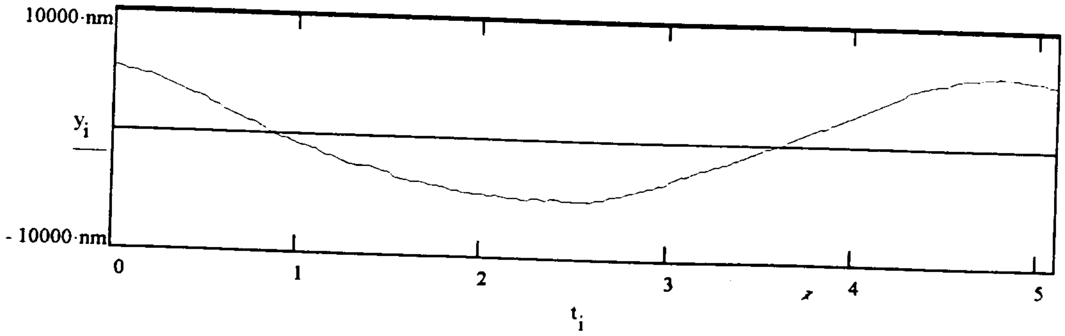
$$A_j := \mathrm{wenn}\left[j<j_{min}, 0 \cdot \frac{nm}{\sqrt{Hz}}, \frac{\nu_0}{2 \cdot \pi \cdot \nu_j} \cdot \sqrt{\frac{a}{\nu_0^2 + (\nu_j - \nu_1)^2}} + \frac{a_1 \cdot \nu_{res1} \cdot \nu_j}{\sqrt{\left[(\nu_j)^2 - \nu_{res1}^2\right]^2 + \Gamma_1^2 \cdot (\nu_j)^2}} \ldots \right. \\ \left. + \frac{a_2 \cdot \nu_{res2} \cdot \nu_j}{\sqrt{\left[(\nu_j)^2 - \nu_{res2}^2\right]^2 + \Gamma_2^2 \cdot (\nu_j)^2}} \right]$$

model of Fourier spectrum according to above power spectrum density: $F_j := A_j \cdot \sqrt{\frac{f_{rep}}{2}} \cdot \exp(i \cdot (-\pi + \mathrm{rnd}(2 \cdot \pi)))$ $\quad y := \mathrm{usft}(F)$

Model spectrum of ground motion considered



sample time signal



$\sqrt{\frac{1}{i_{max}} \cdot \left[\sum_i (y_i)^2\right]} = 3.855 \cdot 10^3 \cdot nm$

rms amplitude of ground motion

$\sqrt{\Delta\nu \cdot \left[\sum_k (A_k)^2\right]} = 3.855 \cdot 10^3 \cdot nm$

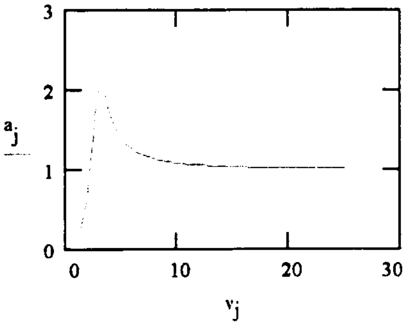
Dto, from power spectrum

Response of beam at interaction is suppressed for ground wavelengths larger than the betatron wavelength. Resonance enhancement is for sure smaller than 3. Note that this response function is arbitrarily scaled, i.e. it does not reflect the real beam demagnification at the IP. For the purpose of this investigation, however, only the relative changes are of interest.

$v_p := 300 \cdot \frac{m}{sek}$ $\quad \lambda_\beta := 100 \cdot m \quad \nu_{reslat} := \frac{v_p}{\lambda_\beta} \quad \Gamma_{lat} := 1.5 \cdot Hz$

$$a_j := \frac{(\nu_j)^2}{\sqrt{\left[(\nu_j)^2 - \nu_{reslat}{}^2\right]^2 + \Gamma_{lat}{}^2 \cdot (\nu_j)^2}}$$

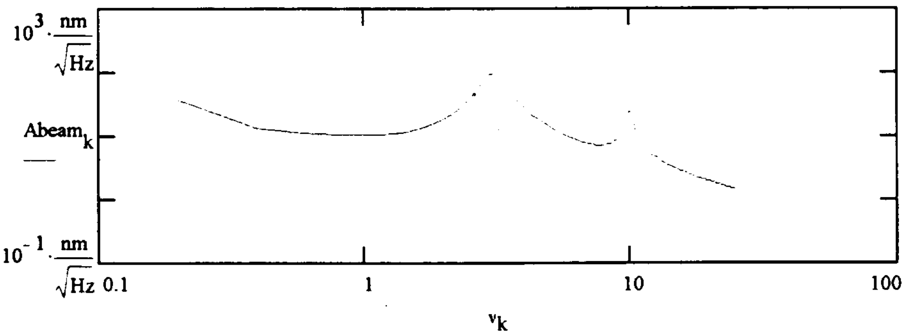
This is the filter function that models the optics lattice response to ground motion



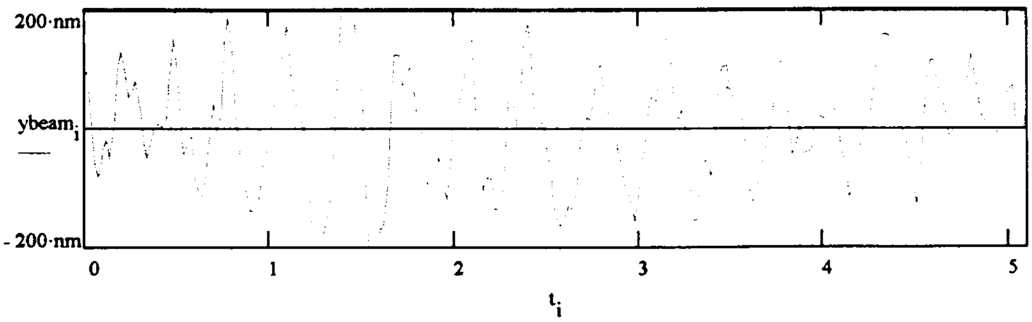
Spectrum of beam motion at IP is

$\text{Abeam}_j := \overrightarrow{(a_j \cdot A_j)} \quad \text{Fbeam}_j := \overrightarrow{(a_j \cdot F_j)} \qquad \text{ybeam} := \text{usft}(\text{Fbeam})$

model spectrum of beam motion



sample time signal of beam



$\sqrt{\frac{1}{i_{max}} \cdot \left[\sum_i (\text{ybeam}_i)^2\right]} = 93.348 \cdot nm \qquad \sqrt{\Delta\nu \cdot \left[\sum_k (\text{Abeam}_k)^2\right]} = 93.349 \cdot nm$

rms amplitude of beam motion

Dto, from power spectrum

Extrapolation of beam motion for the next time step: simple approach using cubic spline coefficients

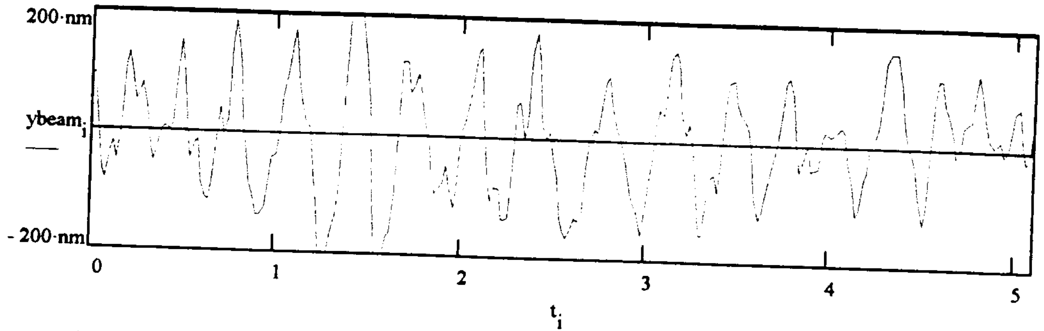
$r_{max} := 6$ $\quad r := 0..r_{max}$ number of time steps considered for spline

$s := 0..\left(i_{max} - r_{max} - 1\right)$

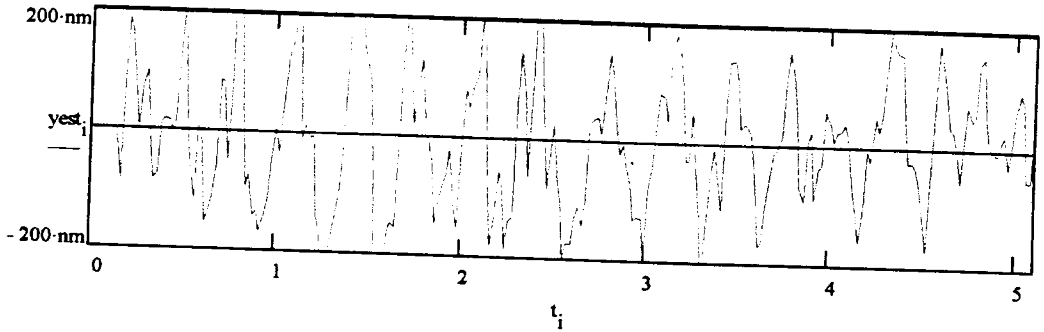
$ypast_{r,s} := ybeam_{s+r}$ $\quad T_{r,s} := t_{r+s}$

$vs^{<s>} := lspline\left(T^{<s>}, ypast^{<s>}\right)$

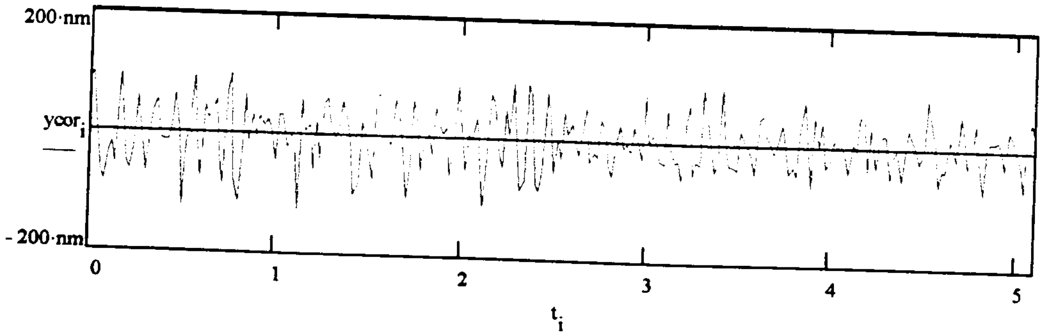
$yest_{r_{max}+s+1} := interp\left(vs^{<s>}, T^{<s>}, ypast^{<s>}, t_{r_{max}+s+1}\right)$ $\qquad ycor := ybeam - yest$



detected beam motion



predicted beam motion



beam motion after beam based correction

$q := r_{max}..i_{max}$

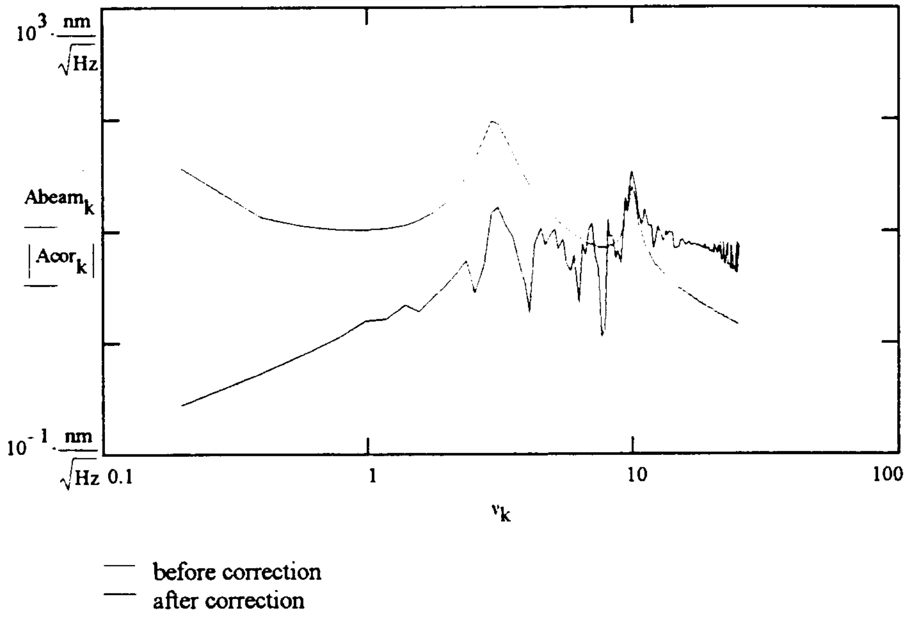
rms amplitude of motion after correction:

$$\sqrt{\frac{1}{i_{max} - r_{max}}\cdot\left[\sum_q \left(ycor_q\right)^2\right]} = 45.395\cdot nm$$

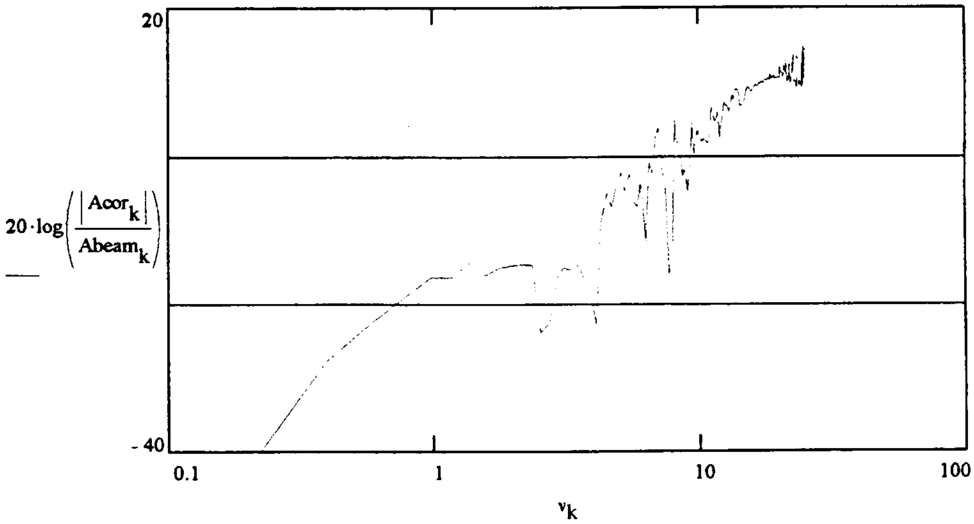
NOTE: This is **not** the beam motion at the IP, it only reflects the change of beam motion due to feeback!

spectrum density of beam motion after correction:

$$\mathrm{Acor} := \frac{\mathrm{sft}(\mathrm{ycor})}{\sqrt{\frac{f_{rep}}{2}}}$$



feedforward gain (dB):



$$\frac{\sum_k \mathrm{Abeam}_k\cdot\nu_k}{\sum_k \mathrm{Abeam}_k} = 6.24\cdot\mathrm{Hz}$$

Equivalent bandwidth of beam motion