Vibration studies for SiD

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Sub-nanometric stability of the focusing system is required to maintain the luminosity to within a few percent of the design value.

Ground motion is a source of vibrations which would continuously misaligning the focusing elements.

The design of the support of the QD0 is a fundamental issue.
Two Luminosity Feedback systems are implemented in ILC:

- A 5 Hz to control the orbit in the BDS (low frequency)
- A Intra-train system to address ground motion and mechanical disturbances (high frequency ~1000 Hz)

The mechanical stability requirements of the QD0 are set by the capture range of the IP fast feedback, as written in the “Functional Requirements” document, ILC-Note-2009-050

"The QD0 mechanical alignment accuracy and stability after beam-based alignment and the QD0 vibration stability requirement are set by the capture range and response characteristics [8] of the inter-bunch feedback system.

- QD0 alignment accuracy: ± 200 nm and 0.1 μrad from a line determined by QF1s, stable over the 200ms time interval between bunch trains
- QD0 vibration stability: Δ(QD0(e+)-QD0(e-)) < 50 nm within 1ms long bunch train"
Ground vibration measurements are available for all the major accelerators sites in form of Power Spectrum Densities. Datasets available at [http://vibration.desy.de](http://vibration.desy.de)

Main features:

- Separation at ~few Hz between geology and human induced noise (pretty much the separation between the slow and fast luminosity feedback)
- Some sites are quiet and some are noisy
- Motion falls as $1/\omega^4$

For a given a ground motion time history $x(t)$, the PSD is defined as:

$$P(f) = \lim_{T \to \infty} \frac{1}{T} \left| \int_{-T/2}^{T/2} x(t)e^{-i2\pi ft} dt \right|^2$$

i.e. PSD is the Fourier transform of the autocorrelation function $R(0)$ of the signal $x(t)$.

The main property of the PSD is that the variance of $x(t)$ is given by:

$$\sigma^2 = \langle x^2 \rangle = \int_{f_i}^{f_f} P(f) df$$

![Graph showing power spectral density of vertical ground motion](image)
Simplified PSD Models

$P(f) \approx \frac{A}{f^4}$

$\sigma^2 = \left\langle x^2 \right\rangle = \int_{f_i}^{f_s} P(f) df$

Integrated r.m.s.

25 nm
Random vibrations model

Ground Motion PSD \( S_y(t) \)

Frequency Response Function

Modulus of FRF \( |H(f)| \)

Response power spectrum \( S_y(f) \)

FRF for one d.o.f. \( |H(f)| = \frac{1}{m(2\pi f_n)^2 \sqrt{(1 - \Omega^2)^2 + (2\gamma\Omega)^2}} \)

\[ S_y(f) = |H(f)|^2 P(f) \]

The FRF of multi degree-of-freedom system, like QD0 and SiD, is obtained a FEM (e.g. ANSYS)
QD0 supports for ILD and SiD

QD0

Pillar

Barrel

Platform

PSD ground

PSD

IP

wall

QD0

door

PSD ground

Cavern

platform

ILD

SiD
QD0 integration and movement as in SLD
Random Vibration effects Metric

Ground motion effects are usually accounted as perturbation of the lattice elements through the girders, the magnetic cells assumed point-like (rigid body).

Final Focusing element deforms along the full length under random vibration effects.

How define the metric of the net effect of the displacement at the IP?

\[ \delta_{\text{r.m.s.}} = u_y \text{ r.m.s.} + (\text{rot.x} \times L^*) \text{ r.m.s.} \]
QD0 supported on the door

Rot.x Harmonic analysis response for two different cryostat wall thickness: t=6 mm (ILC Nominal), t=25 (SLD), t=50 mm

Cryostat wt = 6 mm, stat. sag 1 mm

Cryostat wt = 25 mm, stat. sag 0.4 mm

Cryostat wt = 50 mm, stat. sag 0.3 mm
PSD response

\[ \langle u_{tot}^2 \rangle = \left( \langle u_y + \alpha \cdot L^* \rangle \right)^2 = \left( \langle u_y \rangle \right)^2 + \left( \langle \alpha \cdot L^* \rangle \right)^2 + 2 \langle u_y \rangle \alpha \cdot L^* \]

\[ \langle u_y^2 \rangle = \int_{f_1}^{f_2} S_{u_y} df, \quad \langle \alpha^2 \rangle = \int_{f_1}^{f_2} S_{\alpha} df, \quad \langle \alpha^2 \rangle = FRF(f) \cdot \langle u_y^2 \rangle, \]

\[ \langle u_y \alpha \cdot L^* \rangle = 2 \cdot L^* \int_{f_1}^{f_2} (S_{u_y} \cdot \text{Re}[FRF(f)]) df \]
QDO cantilevered + spring suspension from the barrel

Cavern
PSD ground
Girder
PSD ground

Shift of the 1st mode

k

k=0

25 nm

Salt Mine Ass
Hera
FNAL

0 137 550 2200

rot.x

rot.x
From this…... to this

Ground motion through the feet
Lumped Mass element
Solenoid + Hcal + Ecal = 700t

Global FE Model

3D Solid Elements for the Iron Yoke, 9000 t

3D Shell Elements for the Arch, thickness 50mm
Free Vibration Mode

1\textsuperscript{st} Mode, 2.38 Hz

2\textsuperscript{nd} Mode, 5.15 Hz

3\textsuperscript{rd} Mode, 5.45 Hz

4\textsuperscript{th} Mode, 6.53 Hz

5\textsuperscript{th} Mode, 10.42 Hz

6\textsuperscript{th} Mode, 13.7 Hz

Vertical motion
Harmonic Analysis

Frequency Response Function

Resonance at 10 Hz (5th mode)

To mitigate the r.m.s. response, the resonance mode must be as high as possible

PSD response (mm²/Hz)

Integrated r.m.s. response (mm)

25 nm
The vertical mode of resonance depends on the elasticity of the feet

To increase the resonance frequency one can:

- Reduce the detector mass -> less iron -> more stray field
- Select a more rigid material -> SSteel \(\sim 210\text{GPa}\)
- Lower the height the foot -> lower the center of gravity \(\sim\) factor 2
- Increase the cross section area of the foot -> thicker plate \(\sim\) factor 2
- Additional supports to reduce the specific mass per foot \(\sim\) factor 2

\[ f \approx 10 \text{ Hz} \]

\[ M = \frac{1}{4} \text{ of SiD mass} \]

\[ f = \frac{1}{2\pi} \sqrt{\frac{k}{M}} \]

\[ k = \frac{\text{Young Mod} \cdot \text{Area}}{\text{height}} \]

- \(M = 2500\) tons
- \(E = 210\) GPa
- Height = 3 m
- Plate thickness = 30 mm

\[ f \approx 28 \text{ Hz} \]
Shift of the resonance mode from 10 to 28 Hz
~ factor 2 on the r.m.s. amplitude at low freq.
~ wider range at higher freq.

Comparison for the HERA ground motion spectrum
One of main concerns that triggered the stabilization studies of the final focus system is the effectiveness of a platform concept versus the shielding of the ground motions:

- Is a detector on a platform experiencing amplified, reduced or same levels of ground motion?

The question is subordinate to the availability of an the engineering design of the platform and how the detector and the QD0s are secured on board.
Total mass 1800 t

Reinforced concrete Slab

2 m
18 m
20 m

Steel plate 30 mm at the bottom

Steel re-bars 16mm$^2$

Four support lines for 4’000 tons each

10kt Anti-seismic supports
Modal analysis

- Static deformation, 1 mm
- Normal mode, 43 Hz
- Normal mode, 58 Hz
Random vibrations

Frequency Response Platform

PSD response Platform

Integrated r.m.s. (mm)

Integrated r.m.s. (mm)
The global effect

Gfy(f) transfer function through the cavern wall
Gs(f) transfer function through SiD

\[ S_y(f) = |G_{fy}|^2 \cdot S_f + G_{fy} \cdot G_{sy} \cdot S_{sf} + G_{fy} \cdot G_{sy} \cdot S_{fs} + |G_{sy}|^2 \cdot S_s \]

and finally:

\[ S_y(f) = |G_{fy}|^2 + G_{fy} \cdot G_{sy} \cdot G_s + G_{fy} \cdot G_{sy} \cdot G_s + |G_{sy}|^2 \cdot |G_s|^2 \cdot S_f \]
Ground Motion Coherence

Final Focus system vibrations would not be a problem, if there were a coherent ground motion.

Measurement at different sites show large uncorrelated ground motions for $f > 1$ Hz, between sensors placed in the cavern and at the final focus systems.
Summary

We started the process to produce a model to quantify the vibration effects on SiD.

Preliminary results shows that supporting the QD0s from the doors in combination with the cavern wall is viable solution (proven in SLD).

For a random vibrating QD0, it is need to quantify the net effect of the random vibrating magnetic field on the final path of the beam.

The progress of mechanical design of the QD0 would allow to model the internal vibration of the cold mass inside the cryostat.

We have the estimation of the resonance modes of SiD alone which helps in optimizing the detector supports.

Preliminary calculations of a platform show that more engineering design would be required to confirm the resonance modes range.

We aim to agree on the use of a common set of PSD spectra to benchmark the results.

More work required on the implementation in the dynamic simulation of the not coherent ground motions.