Magnet Stability (and Reproducibility).

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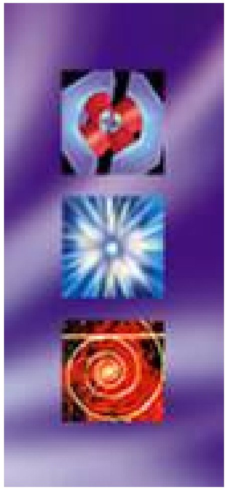


With advice and/or material from:

David Holder, D.L. and University of Liverpool;

Christopher Steier, L.B.L.;

Roberto Bartolini, D.L.S.;

James Kay, D.L.S.;

Hou-Cheng Huang, D.L.S.;

Ian Martin, D.L.S.;

Richard Fielder, D.L.S.;

Jörg Wenninger, CERN;

Nicolas Delerue, U. of Oxford.

Contents

1. Setting the scene - why stability is needed:
   i) beam sizes in: light sources; the LHC; the ILC
   ii) effects of instability and in dipoles and quadrupoles.

2. Observed instabilities:
   i) thermal;
   ii) ground vibration;
   iii) water vibration;
   iv) power supply techniques to minimise instabilities.

3. Performance of a 'state-of-the-art' system (Diamond).

4. Improvement with fast orbit feed-back.

What stability is needed?

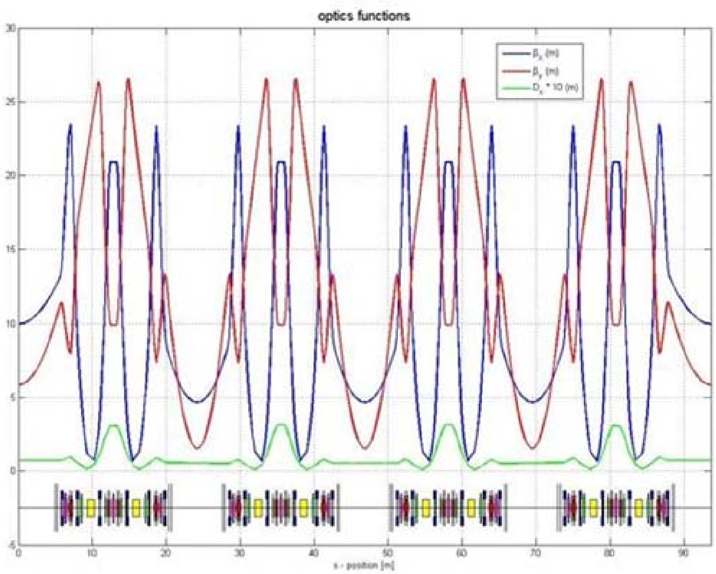
Experiments and other applications demand very small beam cross-sections, fixed with accurately defined positions and angles.

eg: light sources;
circular colliders;
liner colliders;

So the accelerator magnets which control beam position and angle need to be highly stable.

Light source beam dimensions (Roberto Bartolini, DLS, [1])

Diamond (3rd generation S.R. source)



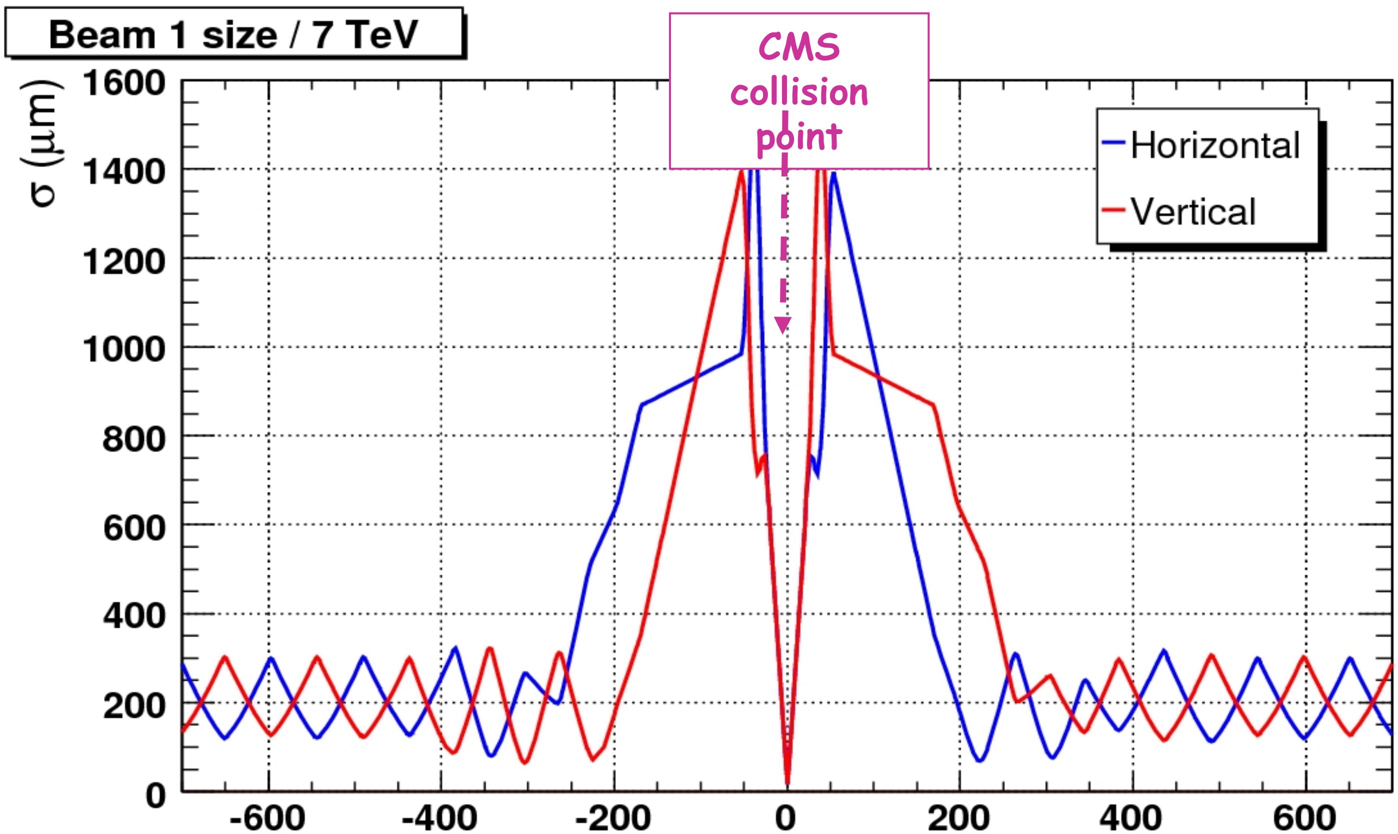
48 Dipoles; 240 Quadrupoles;

Energy	3 GeV
Circumference	561.6 m
No. cells	24
Symmetry	6
Straight sections	6 x 8m, 18 x 5m
Insertion devices	4 x 8m, 18 x 5m
Beam current	300 mA (500 mA)
Emittance (h, v)	2.7, 0.03 nm rad
Lifetime	> 10 h
Min. ID gap	7 mm (5 mm)
Beam size (h, v)	123, 6.4 μm
Beam divergence (h, v) *(at centre of 5 m ID)*	24, 4.2 μrad

Compare with SRS 2:

horizontal emitance at 2 GeV: 0.11 μmrad;
horizonal beam size (fwhm): 2.6 mm;
vertical beam size (fwhm): 0.24 mm;

LHC beam dimensions (Jörg Wenninger, CERN [2])



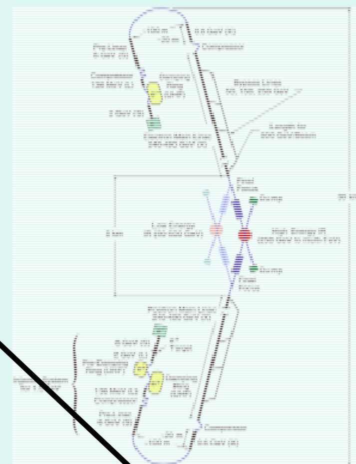
Collision point size (rms):

CMS & ATLAS : 16 μm LHCb : 22 – 160 μm ALICE : 16 μm (ions) / >160 μm (p)

ILC requirements (N. Delerue, U. of Oxford).

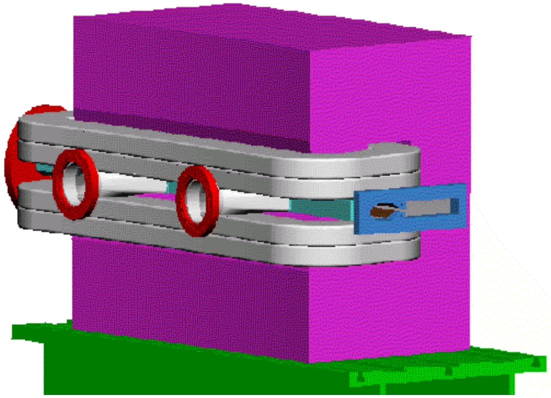
Beam delivery at the ILC

- The ILC will accelerate electrons up to an energy of 250 GeV per beam (upgradable to 500 GeV)
- After acceleration, the beams are not ready to deliver the full luminosity required for the physics studies:
  - – The beam size must be reduced from 1 micrometer at the end of the acceleration unit to just a few nanometers at the interaction point
  - – The beams need to go through several optics correction to allow such strong focusing
- This is done in the beam delivery section of the ILC. This section beam delivery section is a few kilometers long.
- A factor 2 increase in resolution on the beam size in the beam delivery section allows a factor 4 better resolution on the β function and thus helps to reduce the BDS length dramatically.
- No mechanical device can achieve this resolution nor stand the ILC's high currents: a novel beam size monitor is needed.



– The beam size must be reduced from 1 micrometer at the end of the acceleration unit to just a few nanometers at the interaction point

Stability of Dipoles.



Uniform vertical field so:

•small horizontal displacement – negligible effect;

•small vertical displacement – negligible effect;

•longitudinal displacement – some orbit distortion;

•twist about longitudinal axis – vertical steering – must be minimised (*);

•twist about radial axis – axial field – focusing and coupling of horizontal/vertical oscillations – must be minimised (*).

(*) Acceptable values depend on lattice.

Reproducibility of dipoles.

Dipole strength:

$$\int B_y.dz$$

determines the angular deflection produced by each dipole.

Inequalities produce closed orbit distortion which must be corrected.

The tolerance on variation of strengths between dipoles depends on the lattice; a tolerance of $\pm$ 1:10^4 is typical for small machines (the LHC requires one to one and a half orders of magnitude better).

Reproducibility of dipoles (cont.)

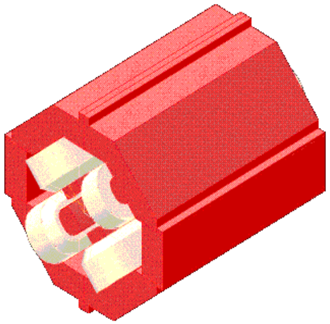
Variations in dipole strength can be produced by:

- variation in magnet geometry during manufacture;
- minimised by choosing the lattice position for the dipoles once their magnetic strengths have been measured after production;

- current leakage from the power circuit;

- where dipole string is separated into separate circuits, inequality of the output current from different power converters;

Stability of Quadrupoles.



Horizontal and vertical displacements of the magnetic centre ($B_y = B_x = 0$) result in movement of the closed orbit.

The beam displacement depends on the lattice '**amplification factor**' - the ratio of the orbit displacement to the quadrupole movement.

For a simple FODO lattice (such as the SRS) this factor is between 10 to 20;

For a complex lattice (Diamond) it is:

horizontal amplification factor: 60;

vertical amplification factor: 45.

Stability of Quadrupoles (cont)

So displacements **in quadrupoles** are **critical**.

Diamond's target for **beam** stability is 10% of the e^- beam dimensions.

Beam sizes in Diamond:

horizontal:	~ 123 μm;
vertical	~ 6.4 μm.

Defined **beam stability** requirements (*):

$\Delta x \leq 12.3$ μm; $\Delta x' \leq 2.3$ μrad;

$\Delta y \leq 0.6$ μm; $\Delta y' \leq 0.4$ μrad.

So quadrupole magnet stability needs to be:

horizontal	$\leq$	**0.2**	**μm;**
vertical	$\leq$	**0.015**	**μm.**

(*) Bartolini, Huang, Kay and Martin, WEPC002, Proc of EPAC08, Genoa.

Reproducibility of quadrupoles

Variations in quadrupole strength:

- static variations (ie as built) in gradient strength distort the beta values around the lattice – need to be corrected during manufacture and measurement;
- dynamic variations in strength (eg by power supplies) also change the beta values; sometimes this is useful – in light sources for eg different straights (containing 'insertion device' – the main s.r sources) need different beta values and seaparate power supplies are used for each quadrupole;
- dynamic variations of all magnets in a family (Fs or Ds for example) result in changes to the 'tune' – the number of betatron oscillations per revolution; this is BAD – affects beam stability (cause beam loss!), change beam size, etc.; must be minimised to an acceptable level.

Magnet stability – summary.

So magnet stability is:

- important in all accelerators;
- critical in many.

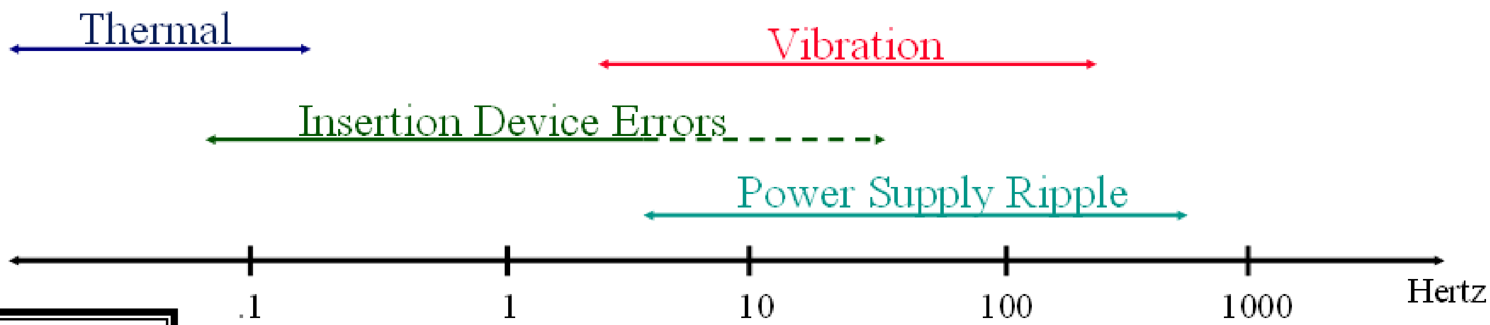
But:

- static displacements are corrected during installation;
- uniform displacement of all accelerator components by the same amount is NOT a problem;
- technical methods of correcting for dynamic instability exist (increasingly difficult for higher frequency disturbances).

So: independent (magnet to magnet), dynamic (time varying), instabilities are the major concern

– with **quadrupoles** being the biggest problem.

Beam instabilities and causes - in light sources (Chris Steier [3])



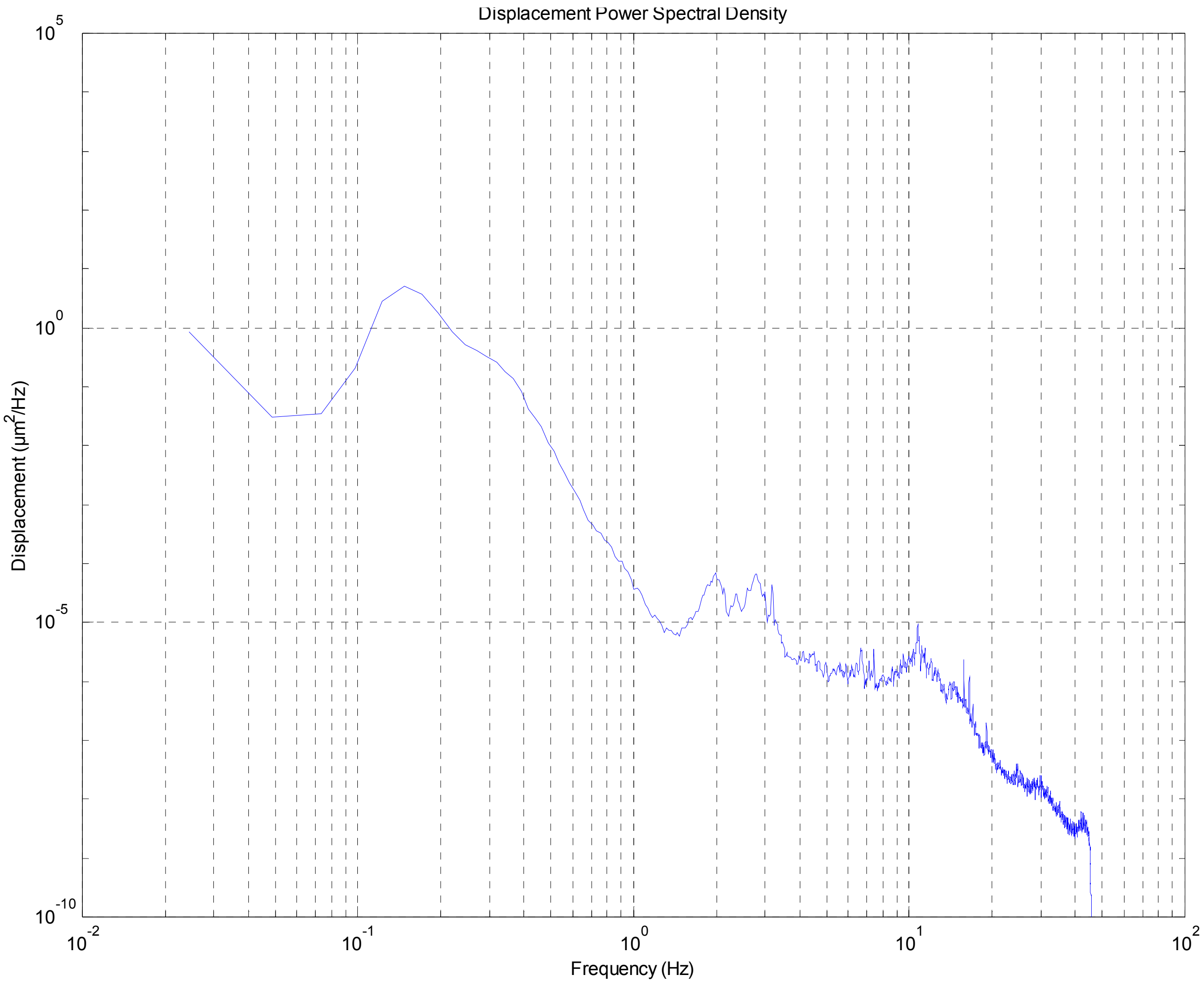
We shall look at:

- ground vibration;
- thermal instabilities
- water vibration;
- power supply instabilities and ripple.

Frequency	Magnitude	Dominant Cause
Two weeks (A typical experimental run)	±200 µm Horizontal ±100 µm Vertical	1. Magnet hysteresis 2. Temperature fluctuations 3. Component heating between 1.5 GeV and 1.9 GeV
1 Day	±125 µm Horizontal ±50 µm Vertical	Temperature fluctuations
8 Hour Fill	±50 µm Horizontal ±20 µm Vertical	1. Temperature fluctuations 2. Feed forward errors
Minutes	1 to 5 µm	1. Feed forward errors 2. D/A converter digitization noise
.1 to 300 Hz	3 µm Horizontal 1 µm Vertical	1. Ground vibrations 2. Cooling water vibrations 3. Power supply ripple 4. Feed forward errors

Beam Stability in straight sections w/o Orbit Correction, w/o Orbit Feedback,

Vibration – spectrum of ground motion. (David Holder [4])



Called 'Power Spectral Density'

Note Axis:

displacement**:**

$(\mu m)^2 (Hz)^{-1}$

frequency**: (Hz)**;

This will vary site to site – data is from bedrock on the DL site;

Ground motion cont. (David Holder, DL [4])

- Peak at 0.1 to 0.25 Hz is the ‘microseismic peak’, due to ocean waves on the coast – present at all sites;
- higher frequencies are ‘technical and cultural noise’;
- the amplitudes of these frequency vary substantially from site to site;
- over-flying aircraft depress the ground by up to 4 μm!

The actual ground motion (z_{rms}) is the square root of the integration of the curve between f_1 and f_2:

$$z_{rms}(f_1, f_2) = \sqrt{\int_{f_1}^{f_2} S_x(f)\,df}$$

The ground motion is transmitted to the magnets through the **mounting girders – critical components.**

Wavelength of ground motion (David Holder, DL [4]).

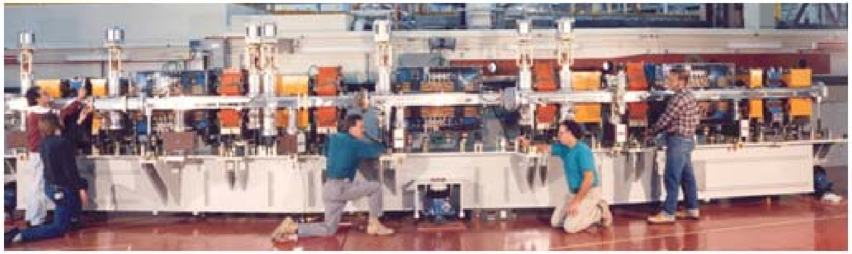
Is the ground movement 'coherent' across the accelerator?
(eg – the 'earth tide', 0.57m peak to peak, is!);

Complex problem:

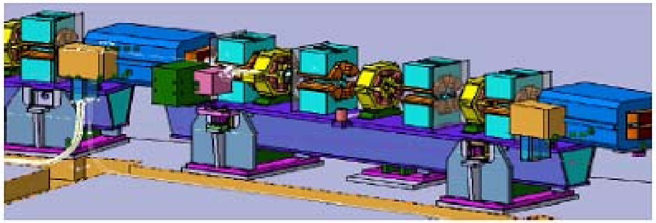
- 2 types of bulk wave;
- 2 types of surface wave;
- underlying rock and sub-soil determine wave velocity and wavelength;

Holder concludes for the Diamond facility (diameter 150m) that:
'ground waves with wavelengths of more than 300 m will not be a problem' .... 'the low frequency limit, below which the lattice will move coherently, is about 1.5 Hz' .... 'above this limit particularly important frequencies exist that give ground wavelengths that are the same as the betatron wavelengths and therefore cause resonant beam excitations'.

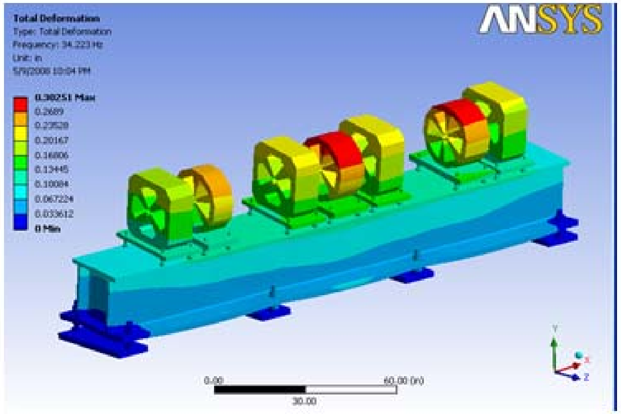
Girder design debate (Chris Steier, LBL [3])



ALS



Soleil



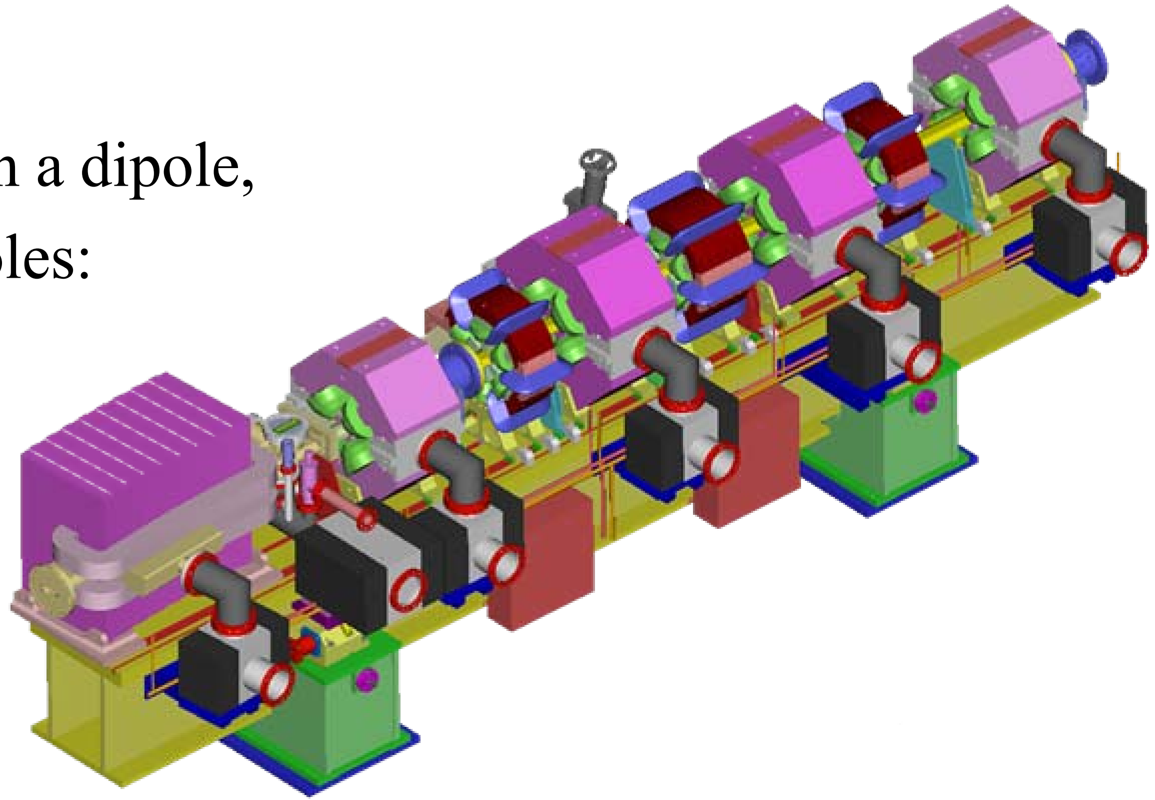
NSLS-II: courtesy S. Sharma

- Some early 3rd generation sources had massive girders (low resonance frequencies – sampling larger ground oscillation amplitudes)
- Later ones had girders with higher resonance frequencies but movers, that significantly lowered them
- Latest designs (Soleil, NSLS-II) avoid this caveat – smaller vibration transmission to beam

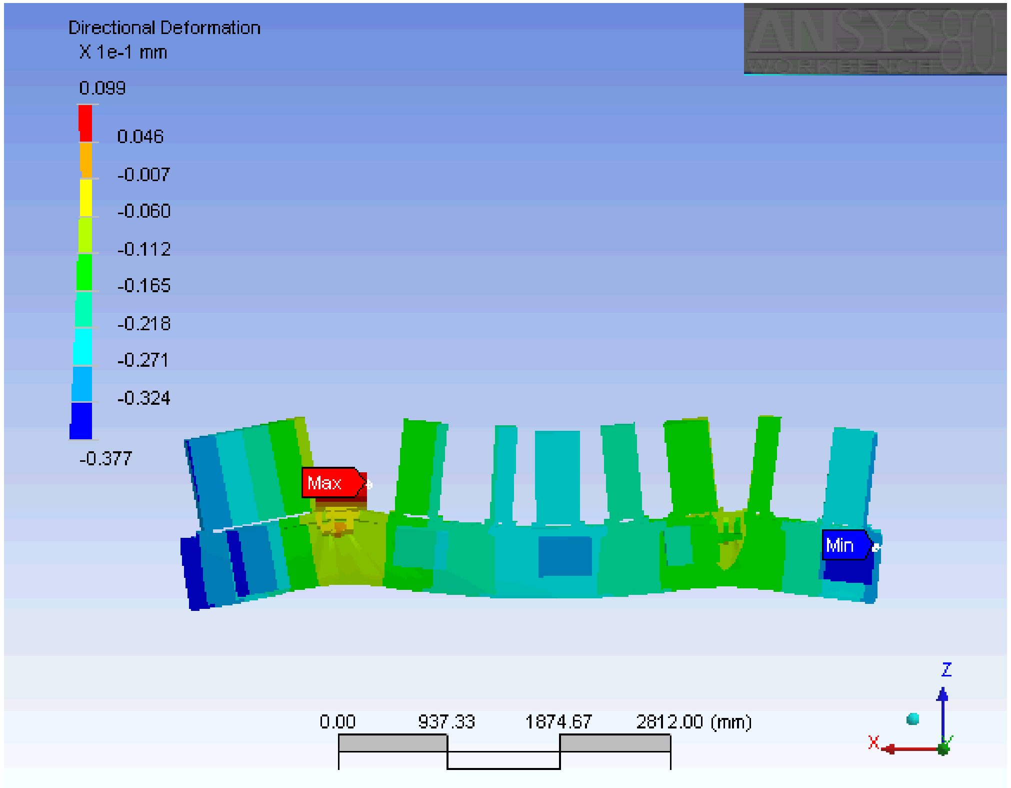
Diamond Girder design (Hou-Cheng Huang , DLS [5]).

So the object of girder design is to move the resonant frequencies to as high a value as possible, where the ground motion spectrum is smaller.

A diamond girder with a dipole,
4 quads and 3 sextupoles:



Diamond F.E.A. Static deflections; (Hou-Cheng Huang , DLS [5]).



Final girder design;

calculated static deflection shown in diagram - maximum is 48 μm.

Storage ring set-up:

circumference 561.2m;

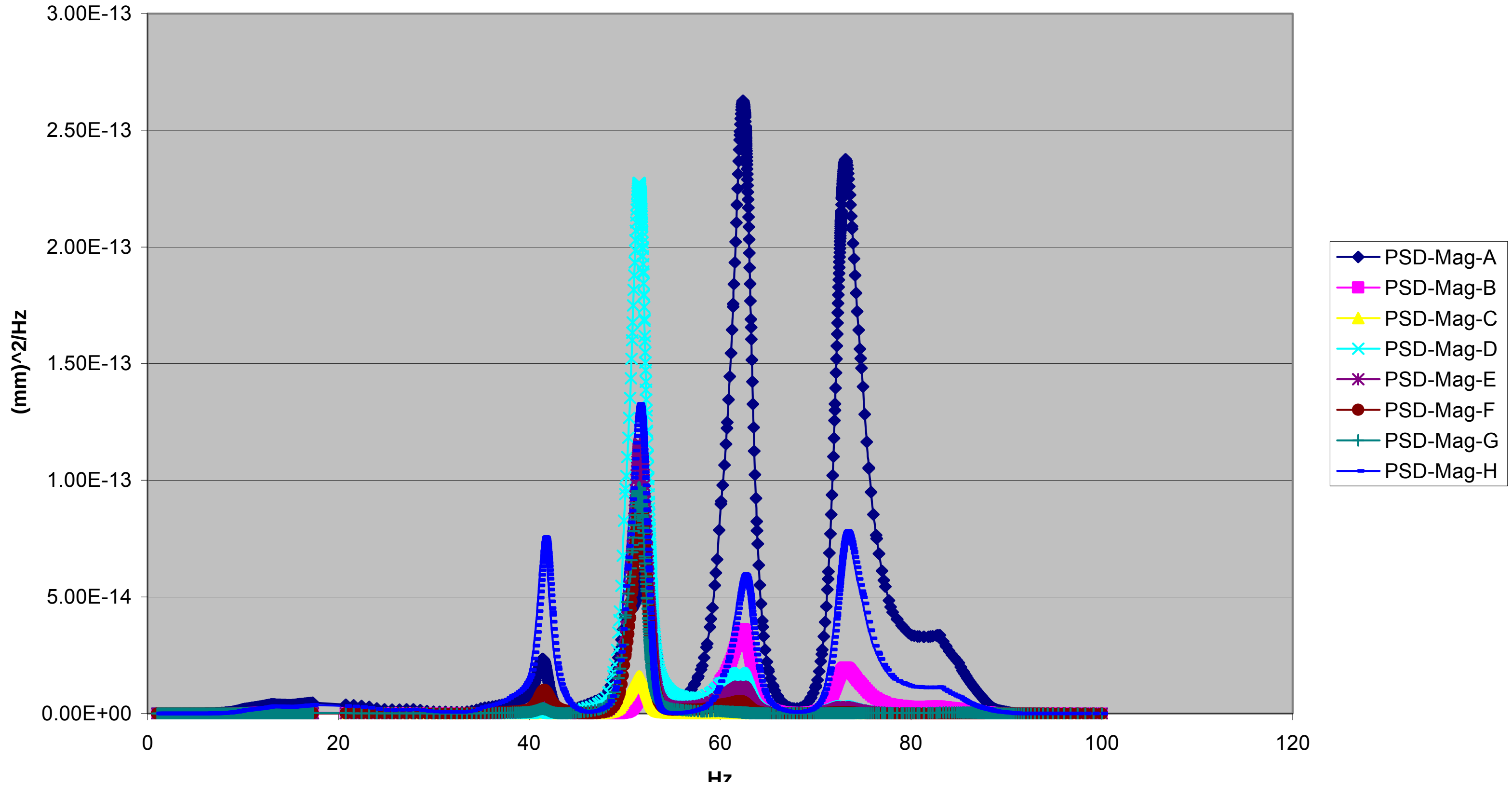
72 magnet support girders level between 2 planes, 1mm apart;

average height difference between adjacent girders approximately 0.1mm;

annual variation in level approximately 0.4mm.

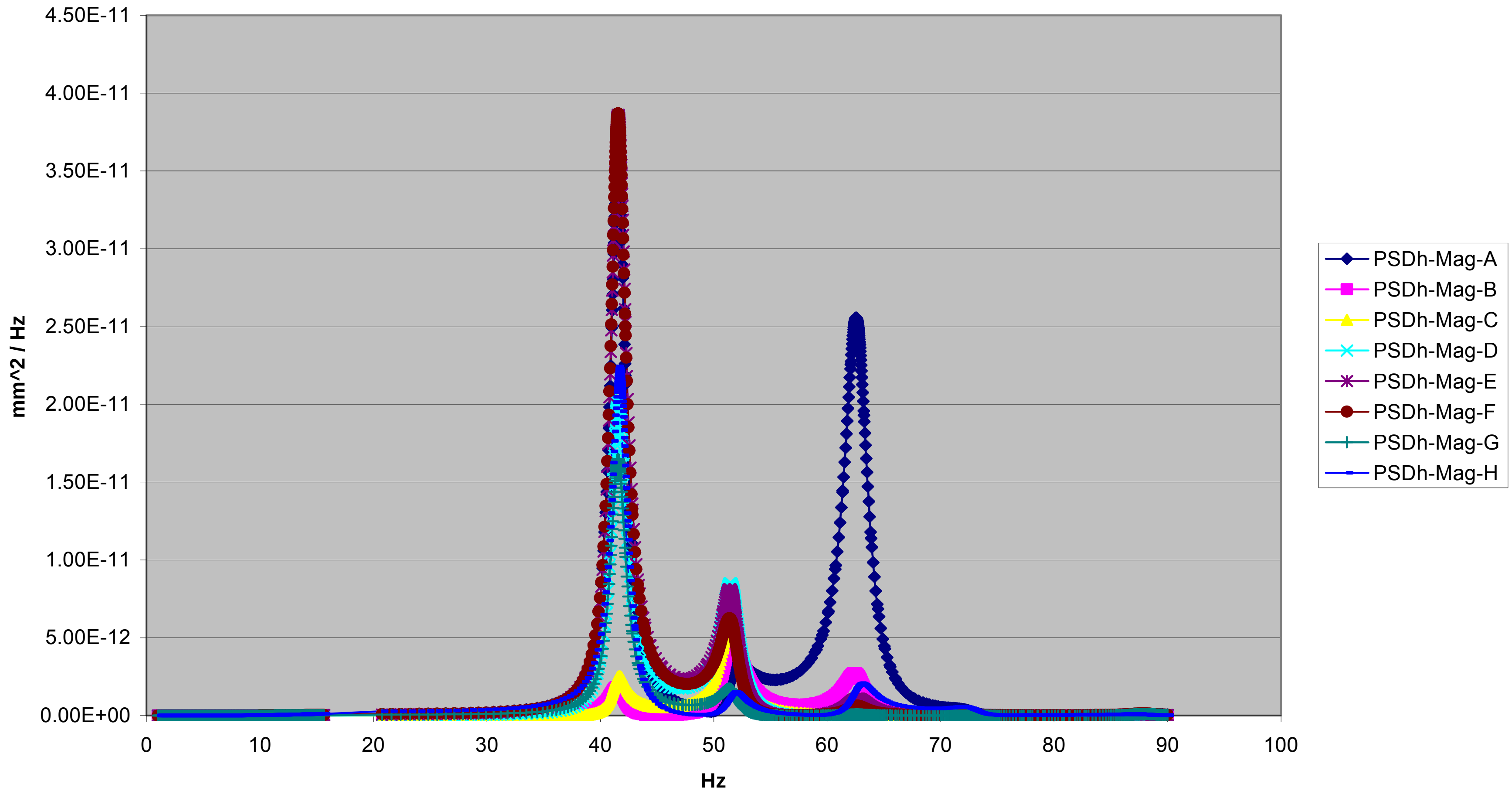
Diamond Resonance Calculations (Hou-Cheng Huang [5]).

Ground motion spectrum applied to the FEA model of the loaded girder predicts the vertical resonance spectrum for the 8 magnets;
predicted resonances are at: 41, 51, 53, 63, 73, and 88 Hz.



Diamond Resonance Calculations (Hou-Cheng Huang [5]).

Horizontal resonance spectrum:



Thermal effects – low frequency

Linear coefficient of expansion of steel is ~ 13 x 10^{-6} /°K;

Some examples:

- quadrupole with radius R = 40mm, pole length = 100mm;

strength change (due to expansion of poles):

0.007% per ˚K;

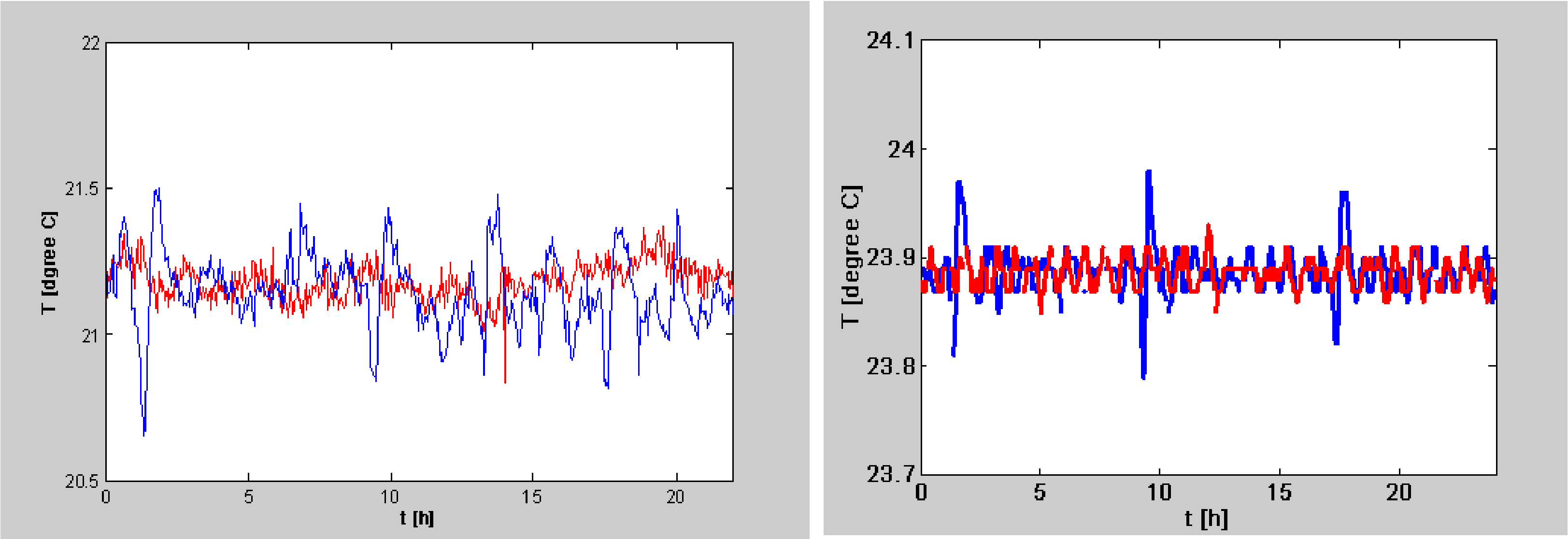
poles could increase temperature by ~ 10 ˚K during power up!

- quadrupole with magnetic centre 200 mm above support feet;

movement of magnetic centre due to yoke expansion:

~ 2.5 μm/ ˚K

Air/water temperature stability at LBL. (Chris Steier [3])



Left: ALS LCW temperature, Right: Tunnel air temperature (red – with top-off)

- Stable environmental conditions are extremely important
- State of the art is water and tunnel air temperature stability on the order of 0.1 degree C
- Stable power supply controllers, invar rods for BPM mounts, … also help, but it is always best to also keep the conditions constant

Air/water temperature stability at Diamond. (James Kay [6])

- Tunnel air temperature:

  22.0 +/- 0.1 C;

- Demineralised water supply:

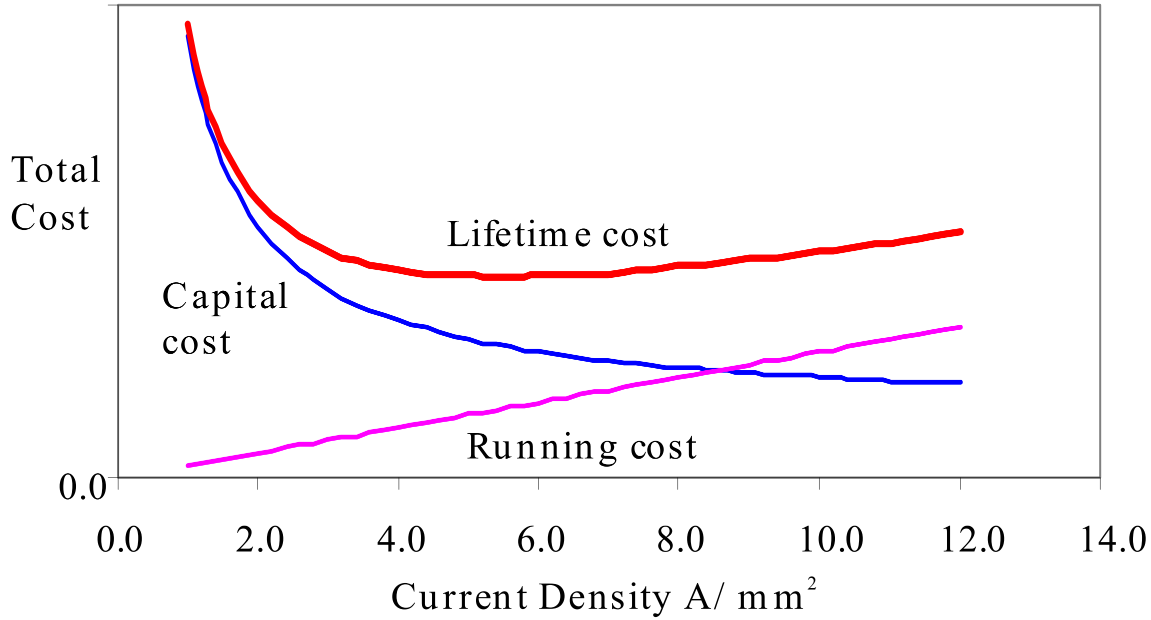
  22 +/- 0.3˚C.

Minimising magnet temperature rise

Object - keep coil current density (j) low to minimise magnet temperature rise:

Chosen value of j is an optimisation of magnet capital against power costs:

So a value of j below the optimum will be selected.



Diamond quads had j of ~2.5 A/mm^2 and max temp rise of 10˚C – perhaps too high!

Water vibration.

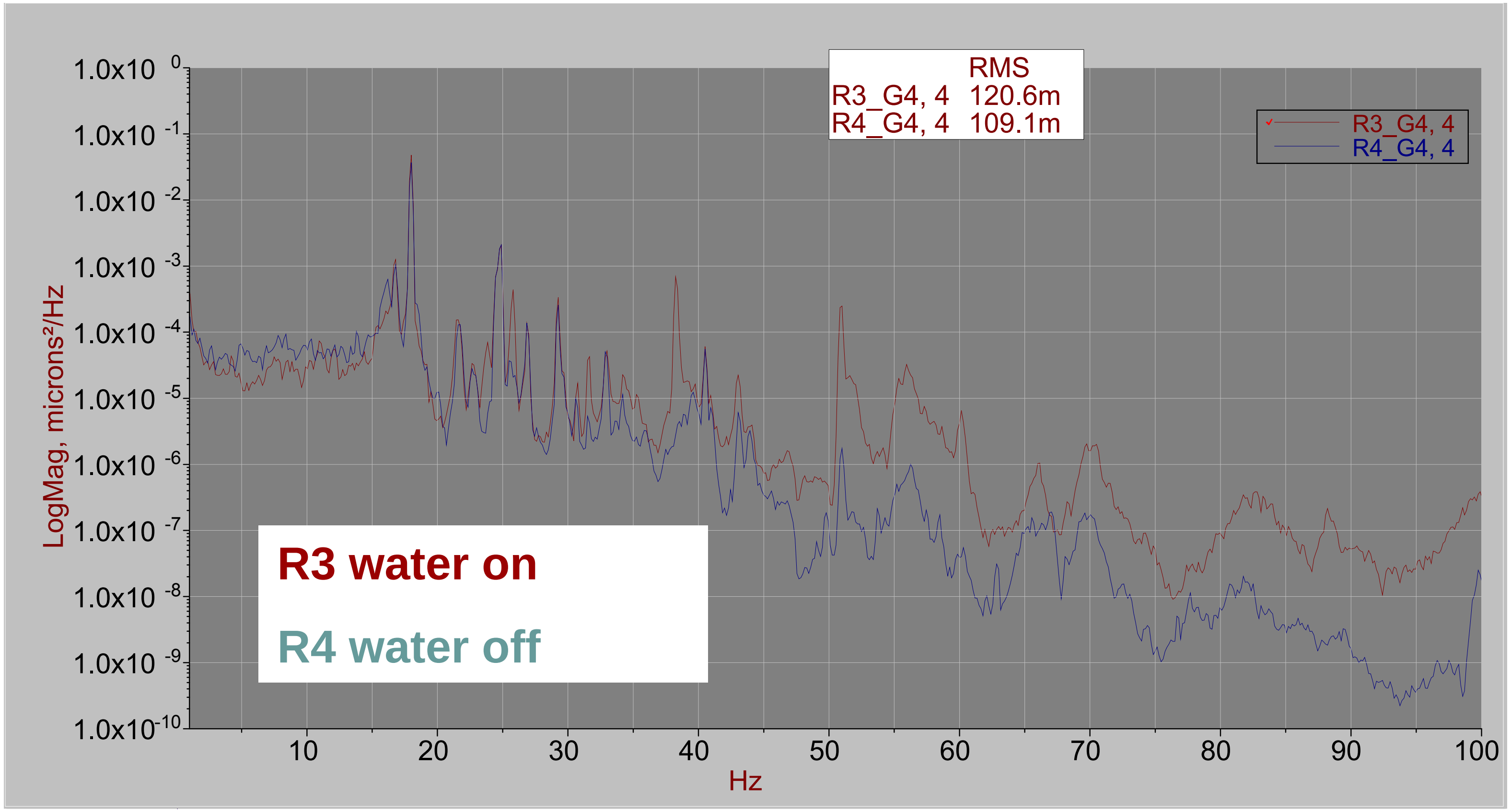
Magnet coils are usually cooled by pumping water through a central channel in the conductor:

- the rate of flow determines the temperature rise in the conductor;
- the water velocity must produce turbulent flow – laminar flow does not break the boundary layer at the tube walls and therefore does not efficiently remove the dissipated heat;
- the water pumps have rapidly moving mechanical parts!

The turbulent flow and the pumps produce vibrations.

Effect of water turbulence at Diamond (Hou-Cheng Huang [7])

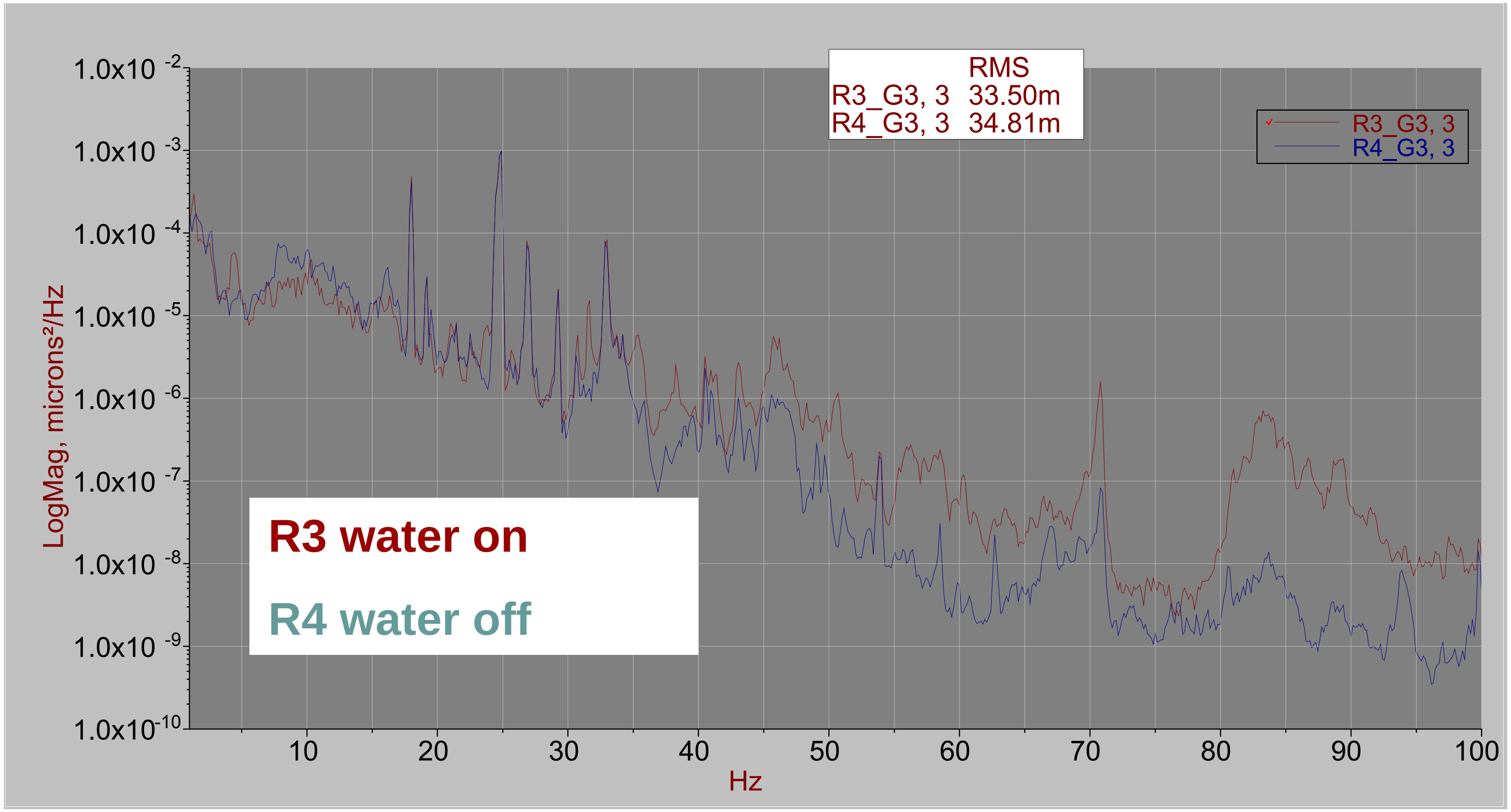
Horizontal spectrum of girder instabilities with water on and off.



RMS (ie integrated) displacements – R3 is 120 x 10^{-9} m, R4 is 109 x 10^{-9} m

Effect of water turbulence at Diamond (Hou-Cheng Huang [7])

Vertical spectrum of girder instabilities with water on and off.



RMS (ie integrated) displacements – R3 is 33.5 x 10^{-9} m, R4 is 34.8 x 10^{-9} m

Power supply instabilities and ripple.

These can be attenuated and controlled by using state of the art power supplies.

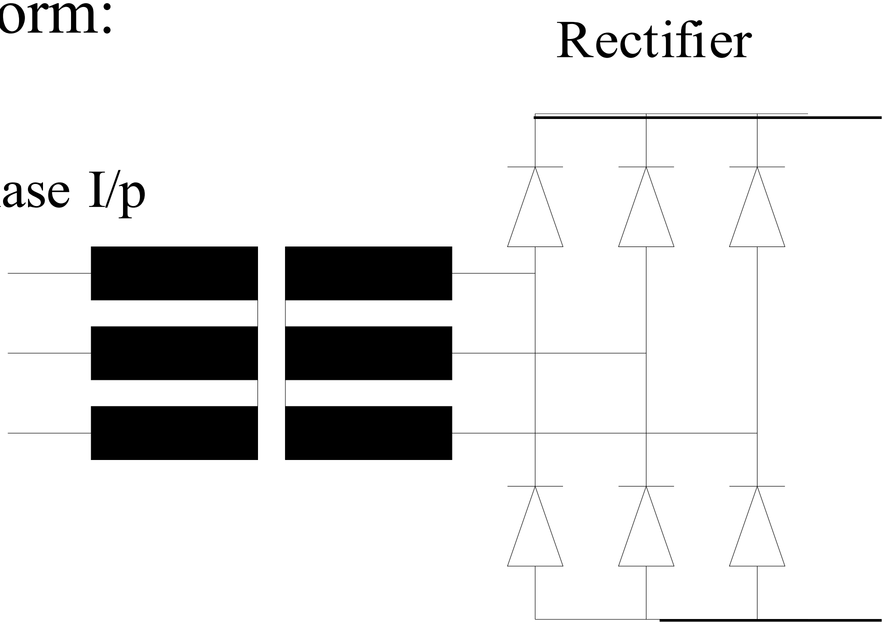
In 1960s, the best stability that could be achieved was $\sim 1{:}10^4$;

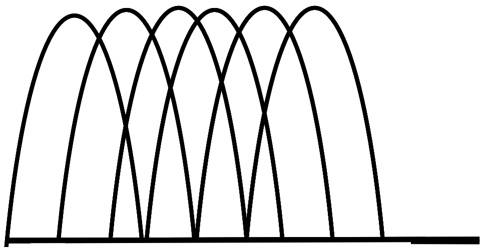
Today $1{:}10^5$ is close to standard and, if necessary (such as in the LHC), stabilities can approach 1 part per million.

This is now possible using the state of the art ‘switch mode’ power converter technology.

Power Supplies – from the 1960s to state of the art systems

The standard 6 pulse diode rectifier of the 1960s and output waveform:





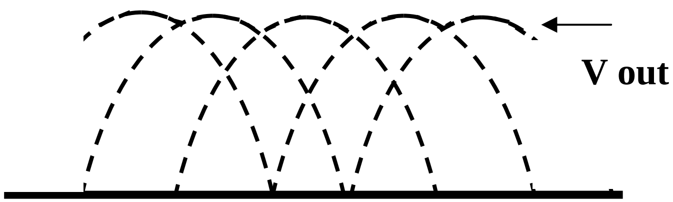
This is a three phase, six pulse system:

•no amplitude control;

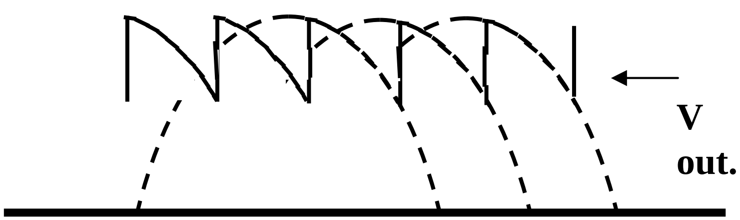
•ripple is ~ 12% 6th harmonic ie 300 Hz a low-pass filter is needed.

Power Supplies – from the 1960s to state of the art systems

Replace diodes with thyristors - amplitude of the d.c. is controlled by retarding the conduction phase but ripple increases:

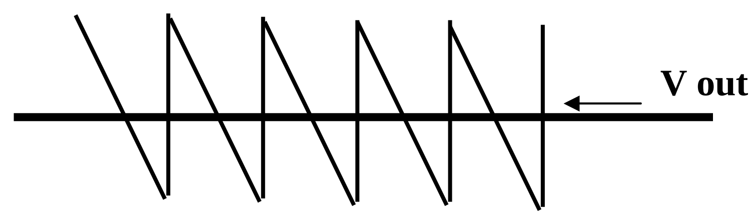


Full conduction – like diode

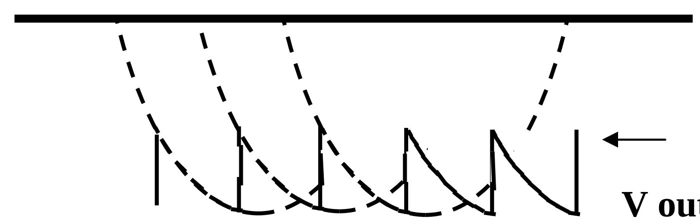


Half conduction

Zero output

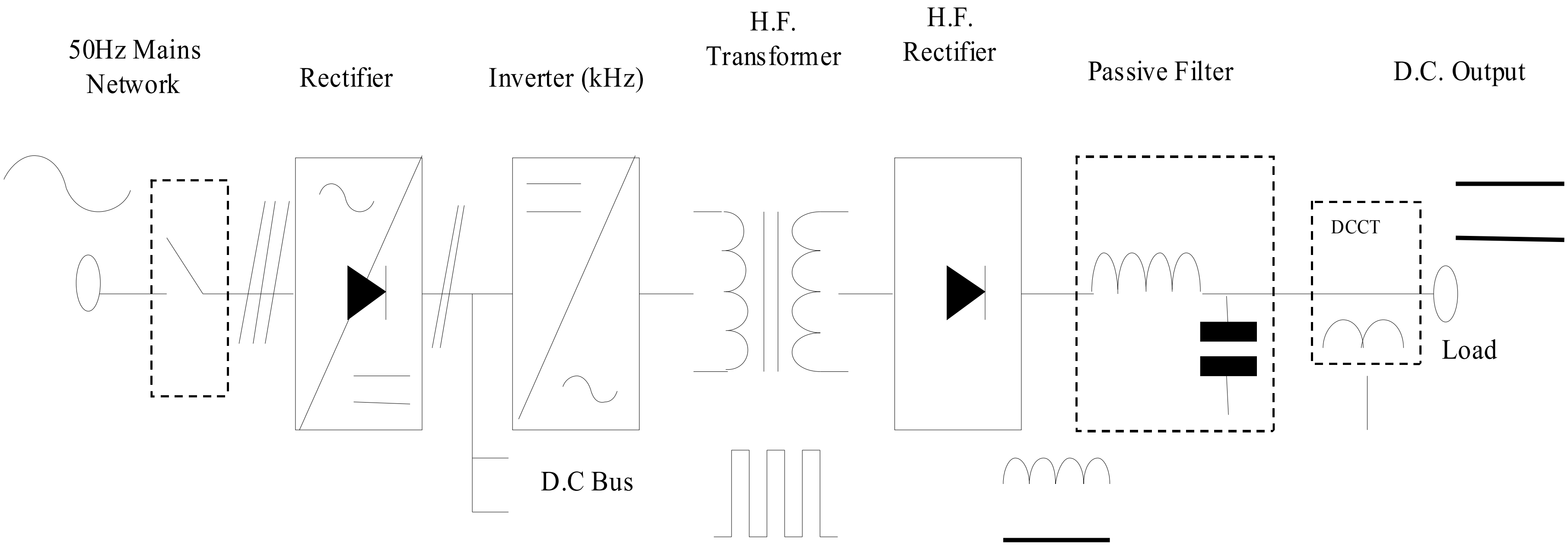


negative output – ‘inversion’ (but current must still be positive).



Power Supplies – from the 1960s to state of the art systems

The insulated gate bipolar transistor allows a new, revolutionary system to be used: the **‘switch-mode’** power supply:



The 'Switch Mode' power supply.

- Stages of power conversion:
- incoming a.c. is rectified with diodes to give 'raw' d.c.;
- the d.c. is 'chopped' at high frequency (> 10 kHz) by an inverter using i.g.b.t.s;
- a.c. is transformed to required level (transformer is much smaller, cheaper at high frequency);
- transformed a.c. is rectified – diodes;
- filtered (filter is much smaller at 10 kHz);
- regulation is by feed-back to the inverter (much faster, therefore greater stability);
- response and protection is very fast;
- ripple much smaller;
- stability improved.

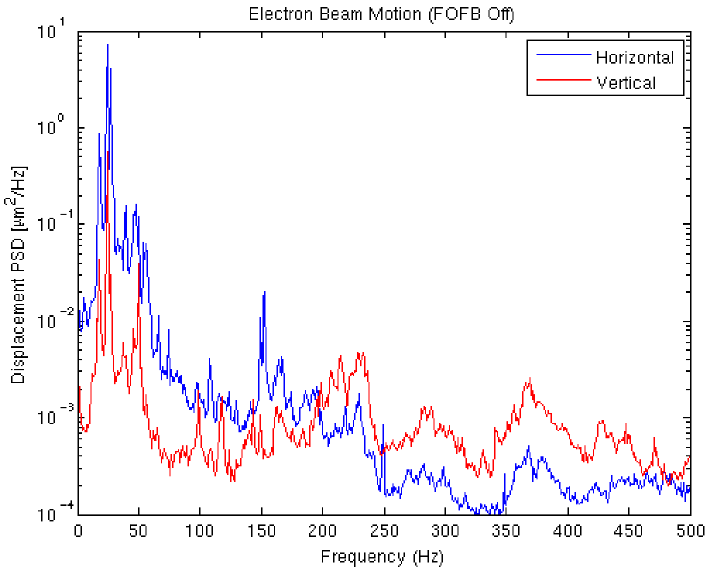
Minimising magnet instabilities

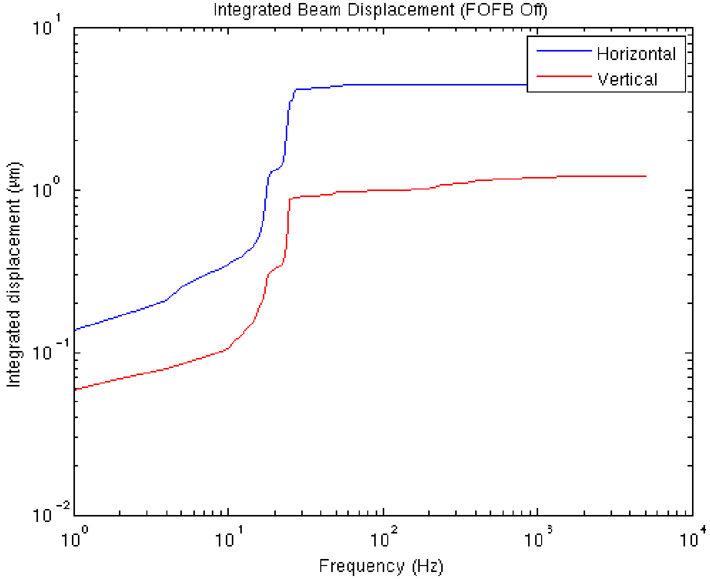
Due diligence in engineering:

- choose site with low ground vibration – low ‘technical and cultural’ noise (is this really possible?);
- design girders to have high resonant frequencies;
- design for highly stable temperature control in the accelerator tunnel;
- minimise magnet temperature rise by using low current densities (particularly quadrupoles);
- use as low water velocity as possible (but sufficient to cool magnets!)
- mechanically insulate magnets from water pumps, feed-lines, etc.;
- use best quality, low ripple, highly stable, state-of-the-art power supplies.

And when you have done all that, what do you get??? (see next slide!)

Electron Beam Uncorrected Vibrations at Diamond (I.M.Martin [8]).





Horizontal and vertical electron beam displacement power spectral density (left) and corresponding integrated spectra (right) with the 'fast orbit feed-back' switched off.

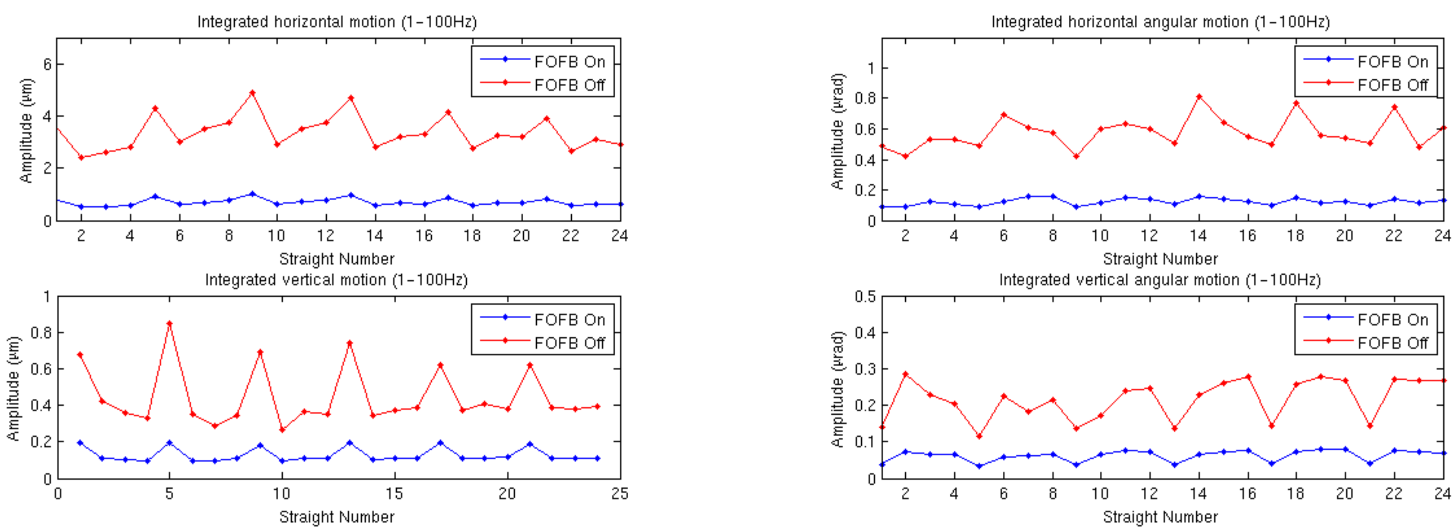
Note amplitude (r.m.s.) of integrated vibrations:

horizontal	4 μm	(target is 12.3 μm);
vertical	1 μm	(target is 0.64 μm).

Fast Orbit Feedback - F.O.F.B. (I.M.Martin [8]).

So horizontal vibration is within specification, but vertical needs improvement by a factor of x 0.5.

This is achieved by orbit feed-back systems; see below:



Integrated motion in the 1-100Hz bandwidth in each straight section of Diamond with FOFB on and off.

Conclusion

By using best practice and modern techniques for the design, construction and operation of magnets (and power supplies) beam disturbance due to magnet instability and poor reproducibility can be minimised.

But beam position feed-back systems will probably be needed as the final stabilising influence on the beam - now extensively used in light sources, colliders and other facilities.

These are outside the scope of this lecture – they are possibly sufficiently complex to require a complete CAS just devoted to this topic!

References.

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6. J.Kay, DLS, private communication;
7. H-C Huang, Proc.Vibration Workshop 1 April 08, DLS;
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