

Alignment and Stability of Future Machines

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Abstract

We overview briefly current status of alignment and stability issues at future accelerators.

1 INTRODUCTION

Leading accelerator laboratories mount serious efforts in alignment and vibration studies concerning stability of future accelerator facilities such as photon and meson factories, future linear colliders (LCs), and hadron supercolliders (HCs). Some 200 publications covered the topic since late 80s, following pioneering works of G.E.Fischer [1]. Four International workshops on accelerator alignment were held since 1989 at SLAC, DESY, CERN and KEK. The SSCL hosted the workshop on vibration control and dynamic alignment (1992).

This article briefly covers some present achievements and issues in the field. We discuss major effects and tolerances for the future accelerators, results of measurements up-to-date, correction techniques and make some conclusions.

2 MACHINES' TOLERANCES

Let us start with “present time” and “near future” projects such as comparatively low-energy $e^- (e^+)$ storage rings with high current (photon or meson factories): the 3rd generation synchrotron light sources (e.g. APS at ANL), and B -factories currently under construction at SLAC and KEK. Table 1 presents their major parameters and tolerances. As the main goal of the factories is high luminosity or brightness, then their requirements on beam stability are rather tight: orbit jitter of 5% beam size is caused by as small as tenths of micron uncorrelated quads vibrations in the rings. Fortunately, measured vibration amplitudes are some 2-5 times less if some efforts are made to avoid mechanical resonances of supports and technological noises due to power supplies and cooling water turbulence in magnet coils. Nevertheless, certain measures of active local or global orbit stabilization at interaction points or in insertion devices are included into the designs.

The factories have to have small closed orbit distortions (COD) which are important for free aperture and polarization maintainance. One can see from Table 1 that the alignment goals – about 100 μm neighbor quads positioning (at

Table 1: Stability of Factories

Parameter	APS	PEP-II
Energy/beam E , GeV	7	9/3.1
Circumference C , km	1.1	2.2
Emittance ϵ_V/ϵ_H , nm	1/10	$\sim 2/50$
5%-jitter σ_V/σ_H , μm	0.1/0.3	0.3/1.5
Measured jitter, μm	0.06	0.05
Alignm. goal, μm	~ 100	~ 150

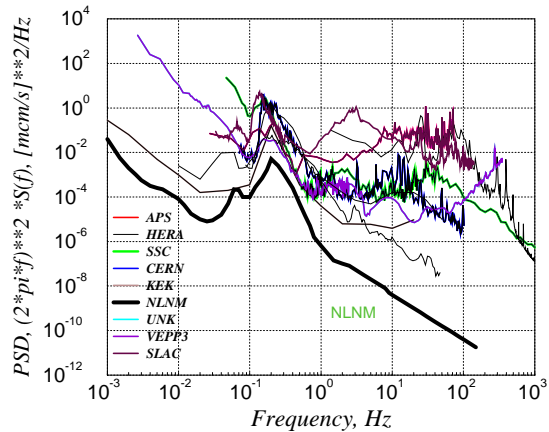


Figure 1: Spectra at different sites.

distances about 10 m) – are quite easy and far within abilities of modern tools.

Next class of future accelerators is e^+e^- linear colliders (LCs). Three projects are compared in Table 2 [2]: TESLA (coordinated by DESY), NLC (SLAC), and “next-step” 2-TeV c.m. energy collider. Their beams are flat, so one should care mostly about vertical dynamics. There are two major concerns: first, in a poorly aligned linac beam trajectory does not follow centers of quadrupoles and accelerating sections, and therefore, due to the dispersive and wakefield effects the beam emittance grows. The second effect is beam-beam separation at the interaction point where the bunches have nanometer-scale sizes.

If disturbances (e.g. quads vibrations) are slow then the beam can be used in a feedback loop to keep the bunches colliding using steering magnets. This technique is routinely used at the SLC (SLAC) where it was found that at frequencies above $f_{rep}/20$ (f_{rep} is the linac repetition rate)

* Operated by the Universities Research Association Inc., under contract with the U.S. Department of Energy

Table 2: Stability of Linear Colliders

Parameter	TESLA	NLC	2-TEV
Energy/beam, TeV	0.25	0.25	1
f_{RF} , GHz	1.3	11.4	11-30
Tot. Length L , km	32	21	22
Rep. rate f_0 , Hz	10	180	300
Linac jitter σ_q , nm	100	9	4
FFS jitter, nm	50	4	1
FD jitter, nm	10	1	0.3
Measured jitter, nm	5-80	1-3	0.2-4
Alignment of quads, cav., μm	500	100	~ 50
BPM align., μm	100	100	10
BPM resol., μm	10	2	0.2
FF BPM resol., μm	1	1	0.3

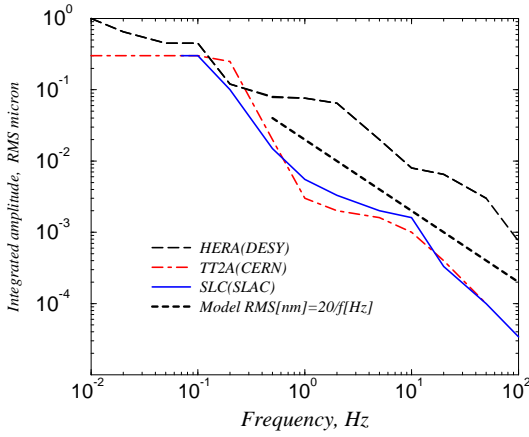


Figure 2: Integrated rms amplitude vs frequency.

the feedback does not work effectively. This fast motion (called jitter) has the tightest tolerances – see Table 2. If the motions of N_q linac quads are uncorrelated, then the rms beam centroid vibrations σ_y relates to quads vibration as $\sigma_y^2 \sim 2N_q\sigma_q^2$. As long as beam dimensions are tiny and number of quads is large, then due to the dilution some 10-20% emittance increase can be caused by 9 nm jitter in NLC and about 4 nm in 2-TeV machine. Very dangerous are movements of quadrupoles of the final focus system (FFS) and especially of the final doublet (FD), which lead to immediate beam-beam separation – tolerances are about or less the measured ground vibrations for all three LC projects! The tolerances on initial alignment for neighbor quads, accelerating structures and BPMs are not very tight, while the resolution of BPMs is challenging, because it limits precision of beam-based alignment which is the only way to keep high luminosity of LCs (about $6 \cdot 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$ for TESLA and NLC, and $\sim 10^{35} \text{ cm}^{-2} \text{ s}^{-1}$ for 2-TeV machine).

The last group of machines is hadron colliders like LHC(CERN), SSC(terminated) and so-called Megatron [3]

Table 3: Stability of Hadron Colliders

Parameter	LHC	SSC	Mega
Energy E , TeV	7	20	100
Circumference C km	26.7	87.1	1000
Emittance ϵ_N , μm	4	1	1
L -lifetime τ , hrs	10	20	5
$\Delta\nu f_0$, Hz	3100	760	66
Quads jitter σ_q , nm	0.15	0.1	0.2
Measured jitter, nm	0.01-0.1	0.2	0.1-50
$\Delta B/B$, 10^{-9}	~ 1	~ 1	~ 0.1
5mm COD align., μm	100	60	30
Realign. time, days	~ 200	~ 45	~ 5

– see their parameters and tolerances in Table 3. There are two major effects which limits the performance of HCs. The first is the transverse emittance growth due to fast (turn-to-turn) dipole angular kicks $\delta\theta$ produced by bending field fluctuations in dipole magnets $\Delta B/B$ or by fast motion of quadrupoles σ_q which has a rate of [4] $d\epsilon_N/dt = (1/2)\gamma N_q f_0^2 \bar{\beta} S_{\delta\theta} (\Delta\nu f_0) \simeq (1/2)f_0 \gamma \bar{\beta} N_q (\sigma_f/F)^2$, where f_0 is the revolution frequency, $\Delta\nu$ is fractal part of tune, $S_{\delta\theta}$ is the PSD of $\delta\theta = \sigma_q/F$, F is the focusing length, $\bar{\beta}$ is mean beta-function. The requirement of $d\epsilon_N/dt < \epsilon_N/\tau_L$, where τ_L is the luminosity lifetime, sets a limit on the turn-by-turn jitter amplitude which looks extremely tough – of the order of the atomic size! Comparison with results of measurements (see next section) shows that for all three HCs the effect may have severe consequences.

Another values in Table 3 are for quad-to-quad alignment tolerances in order to keep the COD within 5 mm, and the estimated time after which cumulative drifts due to ground diffusion (see discussion on “the ATL law” in next section) will cause the distortions [5]. One can see that the SSC and the Megatron have to be realigned very often – or, another solution, to have strong and numerous correctors.

3 MEASUREMENTS

Vast spectrum of stability related problems was under study: natural and cultural ground vibrations, tunnel drifts, resonant amplification due to supports, thermal deformations, influence of Earth tides, impact of nearby trains and overpassing planes, barometric pressure effects, floor drifts due to floods, ground water and precipitation, vibrations due to turbulence of cooling water and liquid Helium flow, earthquakes, sources of magnetic and electric fields ripple, seasonal effects, mechanical stabilization, etc., and of course beam orbit motion and its stabilization. We discuss here some of the results.

As most of disturbances are *noises*, then statistical spectral analysis defines the *power spectral density* $S_x(f)$ (PSD) of noise process $x(t)$ at frequency $f \geq 0$ as:

$$S_x(f) = \lim_{T \rightarrow \infty} \frac{2}{T} \left| \int_0^T x(t) e^{-i2\pi ft} dt \right|^2. \quad (1)$$

The dimension of the PSD is *power in unit frequency band*, e.g. m^2/Hz for the PSD of displacement. PSD relates to the *rms value of signal* $\sigma_{rms}(f_1, f_2)$ in the frequency band from f_1 to f_2 as $\sigma_{rms}^2(f_1, f_2) = \int_{f_1}^{f_2} S_x(f)df$, e.g. below we note integrated rms amplitude that corresponds to $f_2 = \infty$. The *spectrum of coherence* $C(f)$ of two signals $x(t), y(t)$ is defined as:

$$C(f) = \left| \frac{\langle X(f)Y^*(f) \rangle}{\sqrt{\langle X(f)X^*(f) \rangle \langle Y(f)Y^*(f) \rangle}} \right|, \quad (2)$$

here $\langle \dots \rangle$ means averaging over different measurements and $X(f), Y(f)$ are Fourier transformations of x, y . The coherence does not exceed 1.0 and is equal to 0 for completely uncorrelated signals.

3.1 High frequencies

A lot of ground motion measurements at accelerators have been made during the last decade. Fig.1 compares the value of $S_x(f)(2\pi f)^2$ for the so-called ‘‘New Low Noise Model’’ [6] – a minimum of geophysical observations worldwide – and data from accelerator facilities of HERA [7], UNK [8], VEPP-3 [9], KEK [10], SSC [11], CERN [12], APS [13], and SLAC[14]. These PSDs of velocity say us that: 1) accelerators are essentially ‘‘noisy’’ places; 2) ground vibrations above 1 Hz are strongly determined by cultural noises (see numerous peaks in Fig.1); 3) even among accelerator sites the difference is very large, that gives a hint for future accelerator builders. As the value of the amplitude above the given frequency is important for accelerators, then Fig.2 presents the integrated RMS vibrations amplitude for tunnels of HERA(DESY) [15], TT2A(CERN) [12] and SLAC Linac [14], which differ from each other within an order of magnitude above 1 Hz. Dotted line represents a ‘‘rule of thumb’’ of $RMS[nm] = 20/f[Hz]$ which corresponds to $S_x(f)[m^2/Hz] = 2 \cdot 10^{-16}/f^3$. Below 1 Hz the amplitudes are about 0.3-1 μm due to remarkable phenomena of ‘‘7-second hum’’ waves produced by oceans – see a broad peak around 0.14 Hz in Fig.1 – with wavelength of about $\lambda \simeq 30$ km. The ‘‘hum’’ produces negligible effect on accelerators, because λ is much bigger then typical betatron wavelength.

Thorough investigations of spatial characteristics of the fast ground motion have shown that above 1-4 Hz the correlation significantly drops at dozens of meters of distance between points. Fig.3 shows the spectrum of coherence between vibrations of two quadrupoles distanced by 60m at the APS(ANL) [13]. The coherence falls with increasing distance L between observation points, and sometimes a 2-D random waves model of $C(f) = |J_0(2\pi fL/v)|$ with $v = 200 - 500$ m/s fits well to the experimental data [14].

There are very few measurements at frequencies of several hundreds of Hz up to several kHz – a region of concern for the emittance growth in HCs. Measurements of the LEP beam motion [16] were found to be in satisfactory agreement with the estimates made from measured ground motion spectra [12]. Turbulent flow of liquid Helium – cooling

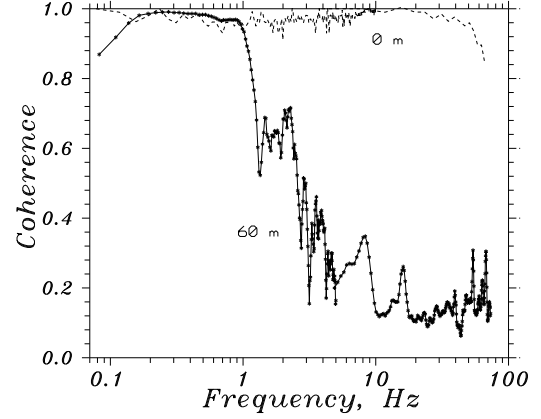


Figure 3: Coherence spectra at APS.

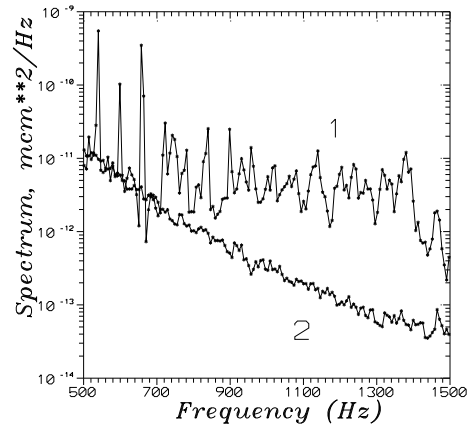


Figure 4: Spectrum of LHe-induced vibrations .

media in superconducting magnets – can produce vibrations of the magnets as a whole or their vacuum chambers with ‘‘frozen’’ magnetic field. Fig.4 demonstrates the PSD of the SSC dipole cold mass vibrations with (line 1) and without (curve 2) LHe flow of 45 g/s [11]. The induced noise takes place at 700-1500 Hz and its rms amplitude is about 0.2 nm – twice the SSC tolerance.

3.2 Low frequencies

Long term drifts (e.g. thermal, due to quads motion, etc.) influence beam trajectory in accelerators only if they are uncorrelated from magnet to magnet.

Some, though numerous data on uncorrelated slow ground motion support an idea of ‘‘space-time ground diffusion’’. An empirical rule that describes the diffusion – so called ‘‘the ATL law’’ [8] – states the rms of relative displacement dX (in any direction) of two points located at a distance L grows with time interval T :

$$\langle dX^2 \rangle = ATL, \quad (3)$$

where A is site dependent coefficient of the order of $10^{-5 \pm 1} \mu m^2/(s \cdot m)$. As long as the diffusion coefficient A is very small, the wandering presents only a tiny, but im-

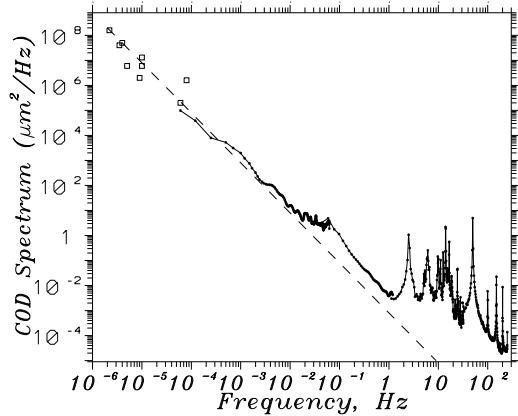


Figure 5: Spectrum of vertical COD at HERA-p.

portant contribution to the total ground motion. The PSD of ATL diffusion is equal to $S_{ATL}(f) = AL/(2\pi^2 f^2)$. The ground diffusion should cause corresponding COD diffusion in accelerators with rms value equal to [5]:

$$\langle \Delta x_{COD}^2 \rangle = \frac{\beta ATC(\beta_F + \beta_D)}{8F_0^2 \sin^2(\pi\nu)}, \quad (4)$$

here C is the accelerator circumference, F_0 is the focal length of each quadrupole in $FODO$ lattice, ν is the tune of the machine, β is the beta-function at the point of observation.

Fig.5 presents the PSD of the HERA- p vertical orbit (scaled for $\beta = 1$ m) which clearly demonstrates “diffuson-like” behavior of the COD at frequencies below 0.1 Hz – the dashed line is for $S_{COD}(f) = 8 \cdot 10^{-4}/f^2$ [$\mu m^2/Hz$] which is in agreement with the ATL law with $A = 1.5 \cdot 10^{-5} \mu m^2/(s \cdot m)$. Peaks above 2 Hz are due to technological equipment. The squares at lower frequencies represent the Fourier spectra of proton orbit in 131 BPMs from different fills of the storage ring [17]. Solid line is for data from a low noise BPM [15]. The motion of quads was checked to be the only candidate that can explain these drifts. It was stressed in [17], that having completely different magnet lattice, the HERA electron ring orbit also performs diffusion with the constant of $A_e \simeq (0.4 \pm 0.1) \cdot 10^{-5} \mu m^2/(s \cdot m)$, which is applicable up to 1-month-long time intervals.

Review of ground diffusion data (see V.Shiltsev in [19]) points that the diffusion coefficient A depends on tunnel depth and type of rock. The question of the limits of applicability of the ATL law is still open – available data cover T from minutes to dozen years, L from meters to dozens km.

4 CORRECTION

Depending on time scale of beam distortions, several ways of correction can be implemented at future accelerators. The first and the most known is mechanical alignment of elements. At large machines like LEP, which in recent years is

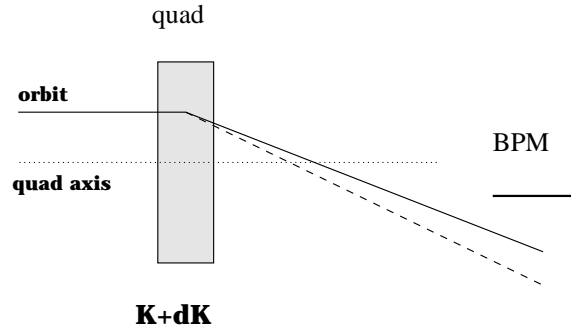


Figure 6: Beam-based alignment.

realigned about once a year with about $150 \mu m$ rms dispersion with respect to a smooth goal curve (see M.Hublin,*et.al*, in [19]), it could take a significant time (about a month). The ESRF(Grenoble) is perhaps the most advanced aligning storage ring – a system of 288 hydrostatic levels (on each girder around 844-m circumference) together with sub-micron-step magnet movers automatically aligns the whole ring during 2 hours within $10 \mu m$ error of vertical neighbor quads positioning (see D.Roux in [19]).

Another modern tool is a “beam-based alignment” that supposes an extensive use of BPM readings. In circular accelerators this method (also referred as “K-modulation”) is based on a fact that if the strength of a single quadrupole $K = Gl/Pc$ in the ring is changed on dK , the resulted difference in closed orbit is proportional to the original offset of the beam in the quadrupole – see Fig.6. From the measured difference orbit the offset can be determined, yielding either the quad offset to eliminate or the offset between quadrupole axis and BPM adjacent to the quad for global correction. The method is widely used now at many accelerators, e.g. in HERA-e all of 148 quads were equipped with switches in order to vary the strength of magnets individually, that allows to align the ring within 0.05 mm error in less than 24 hours and, therefore, to increase maximum polarization (see M.Boge and R.Brinkmann in [19]).

In linear colliders three methods could be implemented depending on tolerances (detailed description can be found in [18]). In the simplest “1-to-1” correction, the correction kicks try to steer the beam to the centers of the BPM at the location of next focusing quadrupole. Thus, the BPMs alignment determines the trajectory. This method fits with the TESLA requirements. For LCs where emittance dilution due to dispersion or/and wakefields is severe, more sophisticated algorithms named “Dispersion-Free(DF)” and “Wake-Free(WF)” corrections have been devised which look similar to K-modulation. They mimic change of the energy (or the charge) of the bunch by varying strengths of quads and attached correctors (all together in the DF, differentially for focusing and defocusing magnets in the WF) and use the BPM readings along the linac for extracting information about what dipole correction is necessary in each quad. Limitation of these methods is the BPM precision which could be in a micron range.

At the end, if no one of the beam-based methods works due to high frequency of vibrations, then mechanical stabilization with local feedback can be used. Experiments [20] show that 4-10 times reduction of 1-20 Hz vibrations is possible.

5 CONCLUSIONS

Certainly, sources of beam distortions other than considered above can be important and researchers worldwide thoroughly investigate them, as well as ways to eliminate their dangerous impacts. We see, that a lot of efforts to keep beam stability should be taken in Linear Colliders and in hadron supercolliders. Vast experimental and analytical studies have been done to the moment, resulting in reasonably optimistic look into the future.

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