Review of alignment and stability tolerances for advanced light sources

A Khan, S Sharma and V Smaluk

BNL, NSLS-II, Upton, NY, 11973-5000, USA

E-mail: akhan1@bnl.gov

Abstract. Alignment and mechanical-stability specifications are essential to the performance of low-emittance storage rings. Beam dynamics simulations are usually performed to establish these specifications. However, the simulation procedures and the input parameters related to magnet positions are not well established which leads to differences in the final specifications. In this paper we discuss important parameters of the mechanical/structural systems of the storage ring that impact on the alignment and stability specification. We reviewed the alignment and stability specifications used at modern light sources across the world that will help to propose an efficient model for a low-emittance upgrade of NSLS-II.

1. Introduction

Achieving a good level of performance in the low-emittance light sources places demanding requirements on the field quality and alignment precision of the magnets. Identifying and rectifying the major sources of machine errors is a major task during the commissioning of a new accelerator, and efforts to reduce errors and improve machine performance are frequently continued throughout the facility's lifetime. Modeling the sensitivity to various errors is also an important part of the design process, which includes studies of diagnostics to identify the sources of errors and the correction systems to compensate for them. Thus, to ensure any facility will perform as expected by reducing uncertainty, advancing design in a cost-effective way requires finding the proper alignment and stability tolerances. This is achieved by considering the work of others, and developing the suitable models for accommodating results.

There are two types of errors, static and dynamic, concerning lattice magnets. Static errors, such as misalignment and field errors, are time independent or change slowly over time. These affect dynamic aperture, dispersion, beta beating, lifetime and chromaticity. We can reduce the impact of such errors by deploying a diagnostic and corrective system. Dynamic errors, such as jitter in the power supply, floor motion, girder vibrations, and temperature variations, are ones that change with time on a scale of milliseconds to hours, as discussed in the section on noise sources. These errors affect a variety of beam properties, including orbit stability, and if we can monitor them in real time, the correction can be implemented in real time as well. Detailed beam dynamics simulations give the specification of upper limits on these errors in a machine.

It is also necessary to think through the specification of tolerances in order to avoid unnecessary costs. In this report, we discuss the alignment and stability tolerances of different light sources.

2. Overview of alignment tolerances

The misalignment can be caused by the occurrence of some mounting errors and other errors in the manufacturing and assembly process of the magnets. Considering the parameters change (for convenience from the computational viewpoint) and the physical meaning of the parameter deviations, the random nature of errors is assumed [1].

There are three most important factors from beam dynamics point of view to decide the alignment tolerances for a light source: *beta beating, beam orbit and dynamic aperture*. The general steps for such simulations are as outlined in Refs. [2, 3]:

- Apply misalignment errors and beam-offset to the lattice model
- Perform trajectory correction until the beam reaches one turn
- Perform global trajectory correction until sufficient multi-turn transmission is achieved
- Perform global trajectory correction including RF cavities until closed orbit is found

Table 1. Specifications for magnets and girders alignment in modern light sources around the world. Each element is misaligned randomly in a Gaussian distribution with given RMS amplitude σ. Where NA^+ corresponds to Not Applicable and NA^* corresponds to Not Available.

Machine	**E** (GeV)	**C** (m)	**Magnet-to-magnet** (μm)	**Cut-off** ($\pm\sigma$)	**Girder-to-girder** (μm)	**Cut-off** ($\pm\sigma$)
ALS-U	2	196.5	10	2	50	2
APS-U	6	1103.608	30	2	100	1
Diamond-II	3.5	560.574	25	2	150	2
ESRF-EBS	6	843.97	60	2.5	NA^+	NA^+
NSLS-II	3	792	30	1	100	1
SIRIUS	3	518.4	40	1	80	1
MAX-IV	3	528	20	1	NA^*	NA^*
SOLEIL-II	2.75	353.74	30	2	50	2

Table 1 summarizes the magnet-to-magnet and girder-to-girder alignment specifications in advanced light sources around the world, including ALS-U [4], APS-U [5], Diamond-II [6], ESRF-EBS [7], NSLS-II [8], SIRIUS [9], MAX-IV [10] and SOLEIL-II [11].

Alignment specifications at APS-U are specified for two different stages: (1) the alignment requirements that have to be achieved as a zeroth-order machine alignment prior to the beam commissioning, and (2) the requirements that have to be ensured during standard machine operation [12].

The ESRF-EBS facility described that girder-to-girder tolerances are not of particular significance to the facility with loose magnet-to-magnet tolerance. From a beam dynamics perspective, as long as magnet-to-magnet tolerances (single magnet rms position errors) are met at every location in the machine, including between magnets standing on adjacent girders, the desired dynamic aperture and lifetime are achievable. It worked effectively for ESRF-EBS, well beyond expectations/simulations [13].

At SOLEIL-II, magnet tolerances are tight 30 μm and much tighter for neighboring girders (50 μm in H and 30 μm in V). The major issue is that machine lattice is so compact that considerable offset in sextupole magnets would have a significant impact on the lattice performance [14].

3. Overview of stability tolerances

One of the most critical parameters for synchrotron light source users is beam stability. It encompasses beam position, angle, beamsize, emittance, beam energy, and energy spread stability. The general stability requirements for orbit initially of 10% of the beam sizes is changing with the advancement of beamline experiments [15]. Table 2 specifies the typical beam stability requirements for moderately demanding synchrotron radiation experiments, which helps to define the stability tolerances for a particular facility [16].

Table 2. Typical beam stability requirements for moderately demanding synchrotron radiation experiments [16].

Measurement parameter	**Stability Requirement**
Intensity variation $\Delta I/I$	$\ll 1\%$ of normalized I
Beam position and angle	$<$ 2-5% of beam σ and σ'
Energy resolution	$< 10^{-4}$
Timing stability	$<$ 10% bunch length
Data acquisition rate	$10^{-3} - 10^{5}$Hz

A variety of sources can compromise the system's stability once the accelerator support system has been installed and the components aligned over a large range of time scales, ranging from milliseconds to years, with disturbance amplitude decreasing with increasing frequency. These sources are characterised in different time-scale as following [15]:

3.1. Noise sources

- Short term (t $<$ 1 hour): Ground vibration induced by human activities, mechanical devices like compressors and cranes or external sources like road traffic potentially attenuated by concrete slabs, amplified by girder resonances and spatial frequency dependent orbit responses, cooling water circuits, power supply noise, electrical stray fields, booster operation, etc.
- Medium term (t $<$ week): Movement of the vacuum chamber (or even magnets) due to changes of the synchrotron radiation induced heat load especially in decaying beam operation, water cooling, tunnel and hall temperature variations, day/night variations, gravitational sun/moon earth tide cycle.
- Long term (t $>$ 1 week): Ground settlement and seasonal effects (temperature, rainfall) resulting in alignment changes of accelerator components, including girders and magnets. Disturbances on this time scale are not a problem for users, since experiments are regularly realigned.

The frequency content of motion due to vibrations is given by the Power Spectral Density (PSD) which depends on the geology of the site and cultural noise amplified by the girders and supports. The square root of integrated PSD gives the RMS beam motion induced by vibration. We only discuss the magnet-girder assembly specifications and thermal specifications in this report.

3.2. Magnet-girder assembly specifications

For a better mechanical stability, it is required that all structures (stands and mechanics from the floor to optical component) must have high natural frequency for eigenmodes that influence the resolution, spot sizes, etc. A standard vibration diagnostic of mechanical structures starts with an operational response measurement at various sites. The amplification factor, peak frequencies, natural frequencies, and the outline of the structure's mode form are all analyzed initially, followed by the vibration amplitude at a few important spots. If the level of vibration is lower than the tolerance, the structure is stable. The lowest natural frequency of magnet-girder assembly of different light sources is given in table 3.

Table 3. Lowest natural frequency of the magnet-girder assembly of different light sources [9, 11, 17–19].

Machine	**Frequency (Hz)**
APS-U	50
ESRF-EBS	55
MAX-IV	50
NSLS-II	30
Diamond-II	50
HEPS	40
SPring-8-II	110
SIRIUS	120
SOLEIL-II	97

There are two main groups with different beam height facilities throughout the world: one with 1.2 m beam height, such as NSLS-II, ESRF, SOLEIL, SPring-8, and the other with 1.4 m beam height, such as APS-U, ALS-U, DIAMOND, and so on. From the standpoint of vibration and stability, as well as tunnel cost, a short beam height is preferable. However, the availability of insertion devices, their manufacturability, and the worker's working environment are frequently factors in determining this height.

Table 4. Uncorrelated Vibration Tolerances [6, 8, 10, 20]. Where H and V stands for horizontal and vertical.

Machine	f (Hz)	**Magnet (nm)**	**Girder (nm)**
APS-U	1-100	10 (H/V)	20 (H/V)
MAX-IV	> 5	20-30 (V)	
NSLS-II	> 4	25 (H), 150 (V)	70 (H), 600 (V)
Diamond-II	1-100	14.7 (H), 21.7 (V)	

Table 4 shows the differences in the vibration tolerances across different facilities. One explanation for this difference could be that, while vibration tolerances are important for providing engineers with simple design constraints, they are based on broad generalizations about the character of mechanical system motion, which could be inaccurate. For example, physicists model magnet-to-magnet vibration within a girder as uncorrelated motion, but in reality, this motion is mostly coupled, and so the amplification factor will differ. It is difficult to compare the beam dynamics of different magnet grouping arrangements because the specifications are based on a specific arrangement.

3.3. Thermal specifications

Thermal excursions are typically caused by day–night temperature variations or by heat loads from thermal system. The thermal system of an accelerator facility consists of heat sources (cables, RF, absorbers, electromagnets etc), the air ventilation and the water cooling system, high thermal inertia components (girders, slabs, concrete walls), and external disturbances including experimental hall and groundwater temperature. Long term stability affected by thermal drift is a crucial task, especially in the first phase of a facility. It might take a long time before the site gets into equilibrium. There is even a risk of periodic drift with seasons.

The thermal specifications for different facilities are given as following:

- **APS-U:** APS-U standards to keep tunnel air temperature stable within ±0.1 °C. This specification has been demonstrated at multiple locations on a one-week time scale and is meant to be maintained throughout the storage-ring tunnel and over weeks/months, rather than only in a few areas over a week.
- **ALS-U:** During steady-state operation, the temperature specification is ±0.05 °C. A study was conducted to examine historical building performance based on data collected from thermal sensors over time. The average temperatures in the storage-ring tunnel ranged from 22.4 − 25.2 °C across the various zones. The majority of the variances are due to differing operational modes.
- **SOLEIL-II:** The extension of the air-conditioning systems to the injector complex, the new booster ring, and special care for the electronics of the storage ring component, whose electronics boards are housed in thermo-regulated cabinets, all necessitate temperature regulation of better than ±0.05 °C.
- **ESRF-EBS:** The ESRF machine had two major thermal issues: first, air-conditioning requires a temperature ramp up to 2 °C along the sector, and second, the storage ring required a four-day warm-up period to attain stable orbit. The ESRF-EBS specifications are outlined to ±0.1 °C by adding the tunnel-sector supplementary cooling systems [21].
- **NSLS-II:** To ensure acceptable thermal stability of the storage ring magnets, process water and tunnel air temperature fluctuations are maintained within ±0.1 °C with 1 hour time scale. The viscoelastic damping pads are used to reduce the thermal bending of the girder by more than one order of magnitude [22].

4. Concluding remarks

For a low-emittance synchrotron, design optimization is a trade-off between performance, environmental conditions, and manufacturing capabilities. Alignment and mechanical-stability specifications of the storage rings of several light sources were reviewed in detail. The differences in the specifications are related to optimization parameters in beam dynamics simulations as well as to input parameters representing mechanical and structural systems of the storage ring. Simulation procedures for the alignment specifications are relatively mature and yield similar results. Stability specifications (both vibrational and thermal) have significant differences, in part because they are not yet firmly grounded in beam dynamics simulations. This study will help us to set up an efficient design model for simulations of the low-emittance NSLS-II upgrade using the Accelerator Toolbox [23].

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