Beam position stability at SOLEIL

The first external users have been welcomed on the beamlines since the beginning of 2008. The position stability of the photon beams delivered to the beamlines is one of the synchrotrons criteria of quality expected by the users. On which factors does the position stability of those beams depend?

The elements that intervene on the beam position stability are of different kinds and occur at different frequencies. A suited solution has been sought to reduce the effects of each instability source.

The position instabilities sources and their minimization

We can mention the slab settlement as a long term effect (weeks), the thermal effects as a medium term effect (hours) and the vibrations as short term effect (fractions of second).

The strategy chosen by SOLEIL was to suppress as far as possible the instability sources by implementing specific solutions to the building, the magnet supports, the vacuum chamber, the regulation of water temperature, the air conditioning inside the experimental hall and tunnels. These resulted in rather stringent specifications.

Long term slab stability

Annual distortion less than 100 µm over 10 meters. Such criterion was reached by choosing a thick monolithic slab resting on piles anchored in the Fontainebleau sands to a depth of 15 m. The Hydrostatic Leveling System (HLS) implemented on the storage ring girders allows following this evolution.

Medium term position stability

i) Temperature stability in the tunnel at ± 0.1 °C

Water cooling circuit of the magnets and vacuum chambers regulated at 21 ± 0.1 °C. The BPM blocks (position monitors) are thus all kept at 21 ± 0.1 °C constant temperature.

Air conditioning inside the tunnel regulated at 21 ± 0.1 °C.

ii) Isothermy maintained between the storage ring tunnel and the Experimental hall, which is regulated at 21 ± 1 °C.

iii) No contact between the vacuum chambers and the dipole, quadrupole and sextupole magnets in order to enable the chamber expansion (due to the heat deposited by the beam) without inducing any motion on the ring magnets.

iv) The BPM blocks are fixed on rigid supports and decoupled from the vacuum chamber movements thank to bellows.

v) Permanent correction of the beam trajectory (Slow Orbit FeedBack, SOFB) in order to maintain it as close as possible to a reference trajectory

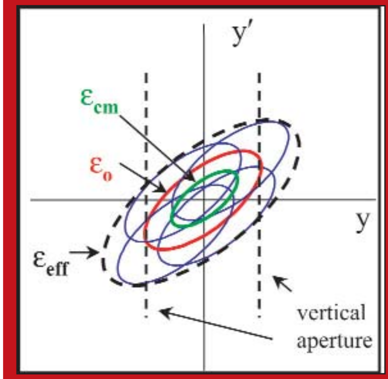
vi) As a result the stability that can be achieved depends essentially on the stability of the BPM blocks and of their electronics (Digital LIBERA modules with a resolution of 0.2 µm).

vii) It is planned to implement by the end of 2008 the Top-up injection mode which, by maintaining the beam intensity almost constant, will allow to get rid of any drifts

Stability criteria

The position but also the angular fluctuations have some impact on the effective emittance seen by the beamline optical components. So, they need both to be minimized at the same time.

The impact of a beam position instability transmitted through an aperture depends on the time scale of the fluctuation itself in relation to the sampling frequency or the integration time of the detector located on the beamline.



For frequencies higher than the detector integration time, the beam spot is diluted in the phase space (angle (y') – position (y) see the figure above), enlarging its surface but without introducing noise. The most penalizing case happens when the fluctuation frequency is commensurable with or inferior to the detector sampling frequency. The beam spot moves through the aperture and the movement of its centre of mass introduces detection noise.

Hence, the effective emittance becomes:

$$\varepsilon_{eff} \cong \varepsilon_0 + 2\,(\varepsilon_0\varepsilon_{cm})^{1/2} + \varepsilon_{cm} \qquad \Delta\varepsilon/\varepsilon = 2\,(\varepsilon_{cm}/\varepsilon_0)^{1/2}$$

ε_o: electron beam emittance

ε_{cm}: emittance corresponding to the movement amplitude of the beam centre of mass.

In this case, a position movement with amplitude of 10% of the beam size σ combined to an angular movement with amplitude of 10% of the beam divergence σ' induces an increase of 20% of the effective emittance. As such value appears acceptable for the beamlines, this stability criterion is often targeted for the position and the angle of the beam centre of mass:

$$\sigma_{cm} < 0{,}10\,\sigma \quad \text{and} \quad \sigma'_{cm} < 0{,}10\,\sigma'$$

Considering the actual rms beam sizes, and with due respect to the very low vertical coupling measured on the SOLEIL storage ring, challenging stability values lower than 1 micron (position) or 1 microradian (angular) shall be achieved in the vertical plane

Electron beam size in the middle of a medium straight section	σ_{e^-} (µm)	σ'_{e^-} (µrad)	σ_{cm} (µm)	σ'_{cm} (µrad)
Horizontal	182	30.4	18	3
Vertical (0.4% coupling)	5.1	2.9	0.5	0.3

The sensitivity to position fluctuations depends on the photon energy

When only one electron circulates in the machine (zero size electron beam) the emittance of the photons produced by this single electron depends on the energy at which the radiation is observed and on the way it is generated.

Thus the emittance of a photon beam at wave length λ_{photon} is

$$\varepsilon = \sigma\sigma' = \frac{\lambda_{photon}}{4\pi}$$

The photon emittance generated by this single electron will be all the higher since its wavelength is large, i.e. for low energy photon beam.

In a bending magnet, the photon beam vertical divergence is:

$$\sigma'_{photon} = (0.58/\gamma)\,.\,(\lambda_{photon}/\lambda_{critic})^{1/2}$$

(for $\lambda >> \lambda critic$ = 1.45 Angström)

In an udulator of length L_{und} the horizontal or vertical divergence of the photon beam is:

$$\sigma'_{photon} = (\lambda_{photon}/2L_{und})^{1/2}$$

Considering now the photon emitted by all the electrons, the photon beam emittance ε_{phtot} received on a beamline results from the convolution of the single electron photon emittance ε_{ph} with the electron beam emittance ε_{eH} or ε_{eV} (we suppose that we have Gaussian distributions).

Example of the different emittance contributions in the case of the TEMPO beamline, with 1.6 keV photon energy

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	Electron beam		Photon beam	
	σ_e (µm)	σ'_e (µrad)	σ_{tot} (µm)	σ'_{tot} (µrad)
Plan H	182	30,4	183	34
Plan V	5,1	2,9	6,5	16

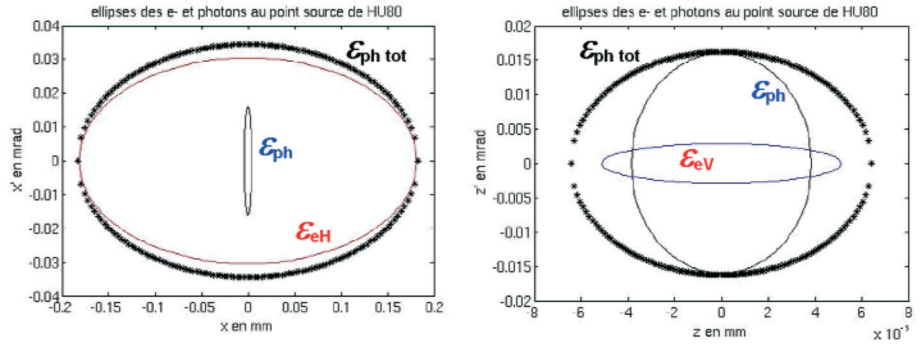
At SOLEIL, the horizontal electron emittance is roughly 5.5 nm.rad in the straight sections (taking into account the contribution of the energy spread) whereas the vertical electron emittance is as low as 0.015 nm.rad.

The table below shows the values of the single electron photon emittances, as well as the H and V total photon emittances resulting from the convolution in the case of 4 SOLEIL typical beamlines.

Beamline	E_{photon} (eV)	ε_{photon} (nm.rad)	ε_{phtotH} (nm.rad)	ε_{phtotV} (nm.rad)
DESIRS	40	2,5	14.7	2.5
TEMPO	1600	0.062	6.15	0.099
PROXIMA1	18000	0.0055	5.8	0.027
DIFFABS (dipole)	35000	0.0028	-	0.821

A beamline will be all the more sensitive to position fluctuation if the total photon emittance reaches low value or a value close to the electron emittance. Thus the DESIRS VUV beamline will not be very sensitive to a position or angular fluctuation of the electron beam and more particularly in the vertical plane. Soft X-ray beamlines such as TEMPO (undulators on medium straight sections) will be somehow slightly sensitive to fluctuations in the vertical plane. Concerning the hard-X ray beamlines, the beamlines on bending magnets will not be that sensitive to vertical fluctuations. On the other hand hard-X ray beamlines on in-vacuum undulators located in short straight sections, such as PROXIMA1, will be the most sensitive ones with a quite high sensitivity in the vertical plane.

Such general statements can obviously be inflected according to the beamline optical layout.



Ellipses of electrons and photons at the TEMPO beamline HU80 undulator source point.

linked to the intensity or beam power variations (thermal effects on the machine and on the beamline optics).

It is worth noting that, in any case, the beam position is feedback to the reading of the BPM blocks located in the storage ring tunnel. So, the stability of the beamline equipments with respect to these BPM blocks is crucial. This relative stability is partly ensured by the choice of a common unique slab on which both the storage ring tunnel and experimental set-up lie, and by the common temperature that is permanently maintained (machine on or off) inside both tunnel and experiment Hall that suppresses the medium term thermal effects on the concrete structures.

Very short term position stability

It means minimizing the beam vibrations in a range that can perturb the beamline detectors i.e. between 1 and 200 Hz.

i) Most vibration sources have been put away from the synchrotron building (all the whirling machines of the cooling circuits are located in the technical building). The surfacing of the main road along the site has been renewed. The movement zones in the synchrotron building have been disconnected from the slab holding the machine and the beamlines.

ii) The girders supporting the storage ring magnets were designed to minimize the amplification of low frequency vibrations (1-20 Hz) that can be transmitted by the slab. The first eigen mode of vibration appears beyond 45 Hz.

iii) The BPMs have a measurement range spreading beyond 1 kHz.

iv) A global Fast Orbit FeedBack is under development and will allow acting over the whole storage ring in a frequency range from 0.1 to 200 Hz.

Insertion devices effects

When a beamline varies the magnetic field of its undulator, the imperfect compensation of the field integrals may induce position or angle changes that affect the beam trajectory all around the machine. Thus, after intensive and high resolution magnetic shimming achieved on the magnetic measurement benches, a rather long period of tuning on the beam is required to further compensate with dedicated correctors the small residual effects on the beam trajectory.

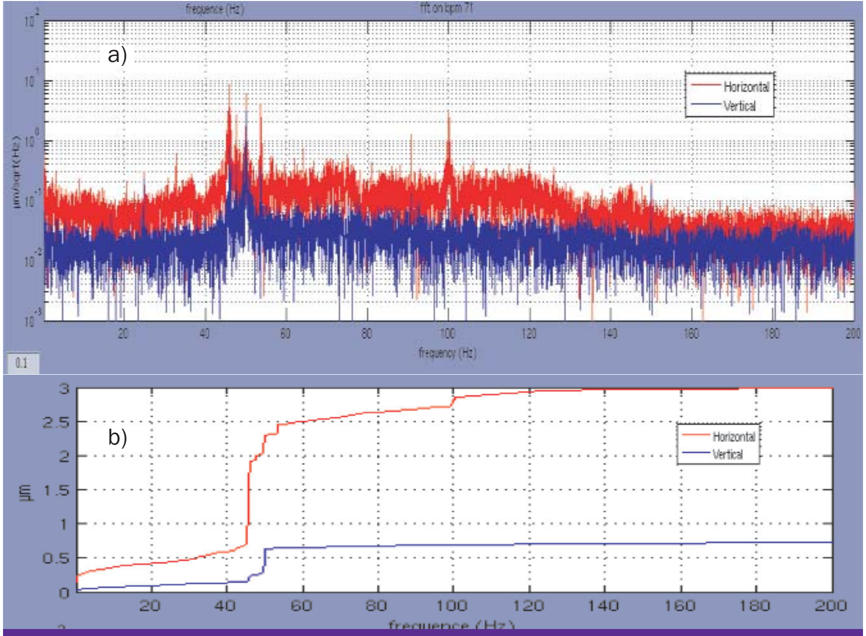


Figure 2: a) Noise spectra measured on the electron beamin a range from 1 to 200 Hz. b) Integrated noise, in horizontal and vertical.

Present performances

Long term stability

The machine long term stability is excellent. The machine has been initially aligned in Spring 2006 (just before the start of the commissioning). A magnet position survey was then performed during the summer 2007. It showed that for almost all magnets, the position changes were less or equal to 1/10 mm. Thus it was not considered necessary to realign the machine. Furthermore, the natural beam closed orbit (trajectory obtained when all the correctors are off) has remained nearly unchanged since the start of the commissioning. This demonstrates the great stability of the slab and of the magnet supports.

Medium term stability

Without any regular action on the correctors, the drift of the beam position over an 8-hour period during which beams intensity is maintained around 200 +/- 30 mA, reaches at the most 60 microns in the horizontal and vertical planes.

The Slow Orbit FeedbBack (SOFB) objective consists in reducing this drift. From the reading of the 120 storage ring BPMs, a calculation is performed to define the correction to be applied using the 56 H correctors and the 56 V correctors so as to maintain the trajectory around a reference orbit. A correction is also applied on the storage ring RF frequency that allows maintaining the revolution trajectory length constant. The reference orbit is defined as the best possible trajectory going as close as possible to the quadrupole centres (thus it is not very sensitive to any optical changes such as tune variations).

The SOFB calculates and applies a new correction every 10 seconds.

Presently, the SOFB provides 2 to 4 microns position stability and 2 microradians angle stability at any source point (bending magnets and short, medium and long straight sections) during an 8-hour period as shown on figure 1. Some fluctuations can be observed at the refill times (at 11:00 p.m. and 7:00 a.m). Some BPMs

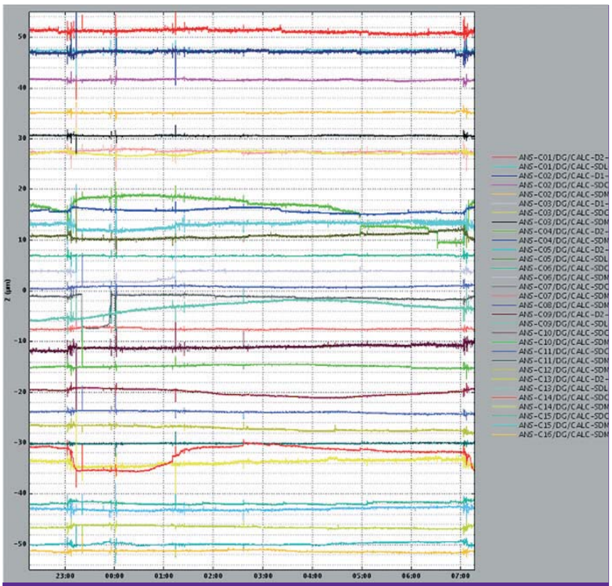


Figure 1: Record of the beam vertical positions at any source point, for an 8-hour period.

induce jumps of about 5 microns at some current thresholds, fortunately on source points on which there is not yet beamlines in operation.

Some effects need still to be improved or better understood in order to be better compensated: this concerns the dependence of the BPM reading on the stored beam current (drifts or jumps at some currents), the effects of the overhead crane motions, the temperature regulation in the tunnels, the Booster power supplies effects, and the insertion devices residual effects.

Short term stability

The BPMs also allow measuring the fast beam position movements. The figure 2 (see on previous page) shows noise spectra measured on the electron beam in a range from 1 to 200 Hz. The first visible frequencies appear around 50 Hz, which corresponds to the first vibration mode of the magnet girders (47 Hz). The integrated noise reaches very low values of the order of 3 µm in horizontal and 0.7 µm in vertical. These values are confirmed by the measurements made with the first X-BPMs (photon beam position monitors) installed on the bending magnet front-ends.

The table 1 summarizes the noise levels integrated in a range from 1 Hz to 1 kHz at different source point levels (short, medium or long straight sections and bending magnets).

	Horizontal plane		Vertical plane	
Source point	Tolerance $\sigma_{ph}/10$ (µm)	Measured noise (µm rms)	Tolerance $\sigma_{ph}/10$ (µm)	Measured noise (µm rms)
LSS (DESIRS)	32	≅ 3.7	6	≅ 1.6
MSS (soft X-rays)	18.3	≅ 3.2	6.5	≅ 1.4
SSS (hard X-rays)	39	≅ 3.4	0.55	≅ 1.1
Bending magnet	4.3	≅ 4.4	1.5	≅ 1.4

Table 1: Noise levels integrated in a range from 1 Hz to 1 kHz at different source point levels (long, medium or short straight sections and bending magnets)

In most cases, the values are below the 10 % tolerance of the photon beam size, except for the hard-X ray beamlines (either dipoles or in vacuum undulators installed on short straight sections).

A global “Fast Orbit FeedBack” system is presently being tested and will allow reducing significantly the noise level all around the machine in a frequency range from 1 to 200 Hz. It will also suppress the transitory effects observed during the changes of the insertion devices magnetic field values.

The requested performances are reached

The specific attention that was brought during the design and construction of all machine equipment and also at the synchrotron building level, enabled the SOLEIL storage ring to reach the requested beam position stability performances.

Some developments in progress will allow improving further this stability in the coming months, in order to guarantee the best beam conditions to the beamlines.

Contact: Jean-Marc Filhol
jean-marc.filhol@synchrotron-soleil.fr