Between model and reality, Part II

Or why diagnostics are so crucial for running an accelerator facility

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Abstract
This introductory course gives an overview of why diagnostics equipment is crucial for running accelerator facilities. Even if significant progress has been made over the last two decades in terms of designing and modelling an accelerator, model and reality differ all the time. The commissioning stages of a synchrotron light source and the stability of the beam positions are taken as examples. The main orbit disturbances are driven by alignment errors, drifts with temperature, vibrations, timing system jitters. Reaching a high level of stability and beam availability in facilities is very challenging. This is attained by driving forward the equipment performance. This starts off with the design of the building and the girders supporting the equipment, the optimization of magnets, the stability and precisionof the power supply, the diagnostics electronics, and the careful design of the beamlines. In addition, passive and active corrections have to be devised to maintain the highly demanding beam qualities on a daily basis.

1 Introduction

This lecture aims to give readers an overview of why diagnostics are so crucial for running accelerator facilities and completes the course given by H. Braun [1]. Much material is only briefly presented here. For more details readers are strongly advised to consult the other contributions in these proceedings.

The author's background is mainly in synchrotron light sources. For this reason emphasis will be more on this kind of facility. Topics related to photon beamline diagnostics are treated thoroughly in a dedicated course given by S. Hustache [2]. Nevertheless facilities such as fourth-generation light sources and colliders will also be mentioned (see also Ref. [3]).

Before acting on the beam, one needs to characterize the beam, *to see* it, *to listen* to its pulsations. So one can say that:

Diagnostics can be seen as our eyes and ears.

In an accelerator, the particle beam — which most of the time is ultra-relativistic — circulates inside an ultra-high vacuum environment, namely a vacuum vessel whose transverse dimensions may happen to be very small.

As an example at the Large Hadron Collider [4] (LHC), the vacuum pipe dimensions are 50 mm × 36 mm (see Fig. 1 right). A 7 TeV proton beam circulates at its centre guided by means of superconducting magnets. Figure 1 left shows a transverse cross-section of the vacuum vessel of a SOLEIL [5] straight section (10 mm height, 46 mm width) for a 2.75 GeV electron beam with a 847 kHz revolution frequency. Moreover whenever in-vacuum undulators are closed down to the minimum gap, the full vertical aperture can then be as low as 5 mm.

The reader may argue that these values are still large in comparison with the beam size. But he has to bear in mind that enough room has to be left to enable beam oscillations (a few millimetres) during the injection process, to preserve large enough beam lifetime, or to have a good vacuum conductance.

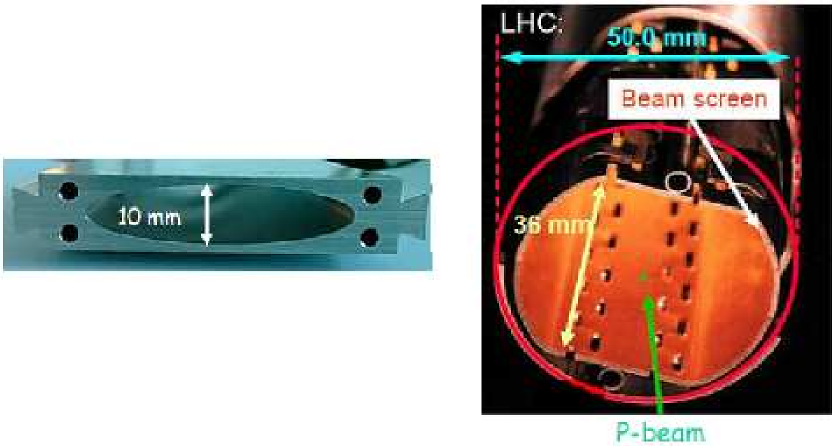

Fig. 1: Left: Vacuum pipe cross-section of an aluminium chamber equipping straight sections of the SOLEIL storage ring: the 2.75 GeV electron beam circulates in a 46 mm $\times$ 10 mm ultra-high vacuum tube. **Right:** Vacuum pipe cross-section of the LHC collider: the 7 TeV proton beam circulates in a 50 mm $\times$ 36 mm ultra-high vacuum vessel and in a 1.9 K environment (courtesy of R. Steinhagen [6]).

Moreover the strongly focused particle beam may have tiny dimensions. Hence requirements from the point of view of orbit stability are pushed down to a few micrometres for colliders and below the micrometre level in third-generation light sources. Reaching such stability is very challenging. It requires active controls relying heavily on the use of diagnostics.

Facility performance is continually pushed higher. Accelerator physicists always dream of making their models in the real world. To be able to produce detailed comparisons between model and reality, ever more demanding and challenging diagnostics equipment has to be devised.

Diagnostics are the only way to monitor the daily operation of facilities in order to ensure that the optimum performance is continuously reached. In this category is included equipment necessary to understand why suddenly the beam is lost, why degradations of the performance are observed, and so on.

Even if the vacuum pipe dimensions are already very small, the situation may be even worse in the real world. Obstacles may be present inside the pipe. Radiofrequency (RF) fingers used to assure RF continuity seen by the beam are often the source of such a limitation: as they pop into the vacuum chamber, they reduce even further the space available for the circulating beam. An example of such a situation is displayed by Fig. 2. *How is the problem solved? What kinds of diagnostics can be used in such a situation?* Hereafter are a number of candidates.

Thanks to *beam-loss monitors*, local activation and higher beam loss count may show up close to the aperture reductions. Use of a local orbit bump is also a way to point to the problem; *Beam Position Monitors* (BPMs) are then very useful to control the bump amplitude at a given location and they can be used as *current monitors*.

Once the diagnostics is done, the vacuum pipe is in a position to be opened and the faulty RF finger can be repaired or replaced during a maintenance shutdown.

This example is used to show the reader that one cannot predict everything in an accelerator facility. *Reality differs all the time from models*. No large accelerator runs the first day with nominal performance. There are suspected and unsuspected sources of perturbations which may be static or dynamic time-wise. Models need time to be tuned and to match the real world. *This is only possible thanks to accurate and outstanding diagnostics equipment*.

After giving an example of the commissioning of a third-generation light source (Section 2), sta-

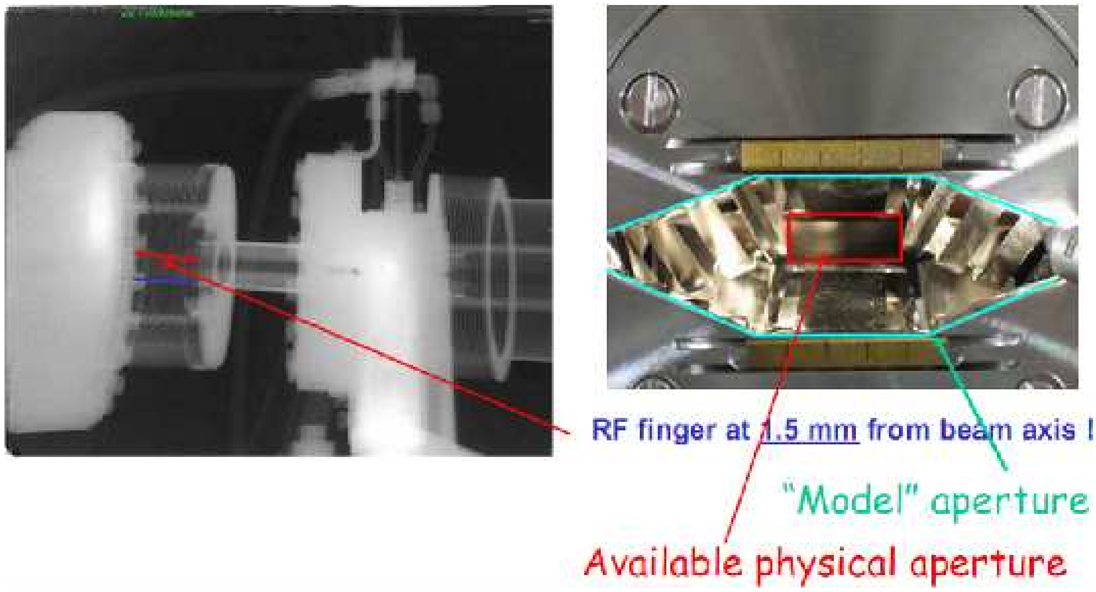

Fig. 2: Left: Gammagraphy of a SOLEIL bellows in the early phase of commissioning. The faulty RF finger bending into the beam path is marked in red. **Right:** Picture of the space available for the beam oscillation seen from the flange upstream to the defective bellow. The circulating beam has an available physical aperture strongly reduced in both transverse directions.

bility requirements for a few types of particle accelerators and ways to reach these challenging goals will be discussed in Sections 3 and 4. Collective effects and the need for diagnostics in order to get a better understanding of the limitations they introduce will be briefly discussed in Section 5.

2 SOLEIL: an example of recent synchrotron light source needs for commissioning

For illustration we now present a small number of key diagnostics that greatly eased the commissioning of the SOLEIL 354 m long storage ring in 2006. This facility is an example of a strong-focusing, intermediate-energy (2.75 GeV) electron storage ring producing high-brilliance synchrotron light over an extended spectrum ranging from infrared to hard X-rays [5].

2.1 First beam

When commissioning a new facility, the first step is to be able to get the electron beam circulating into the storage ring. Most of the time, there is no beam accumulation: the beam survives only one or a few turns.

The commissioning team then asks: Where is the beam in terms of position? What are its oscillation amplitudes? Is it centred in the vacuum vessel? Where, after how many turns, and why is the beam lost? How much beam (charge or current) is injected into the storage ring? Are the losses distributed or well localized?

Diagnostics equipment provides answers:

- Beam charge is measured using for instance a *Fast Current Transformer (FCT)* [7].
- Position of the beam is given by *insertable screens* [8] or mostly by turn-by-turn *Beam Position Monitors* [9] which have to be synchronized precisely with the injection process [10]. *BPM data are nowadays extensively used in all accelerators.*
  A total of 120 of these devices are distributed around the SOLEIL storage ring. Great care has to be taken when designing them, from the BPM blocs with their electrodes up to the electronics

processing the data. Last but not least, they have to be precisely fixed and aligned.

- For the first injection, the beam oscillates with *large amplitudes* (a few millimetres). Because of this, readouts of the position may be strongly distorted due to the flattened shape of the vacuum chamber and the position of the electrodes collecting the signal. Resolution of a few hundreds of micrometres is nonetheless enough at this stage.
- The *sum signal of the BPMs* provides the commissioning team with a measurement of the beam current around the ring. This feature is very helpful to locate where beam losses occur — as *beam loss monitors* [11] would do. They give clues for understanding the reason for these losses. As soon as four subsequent turns are achieved, algorithms make available a *first estimate of the fractional part of betatron tunes*, which is crucial to proceeding further.
- This stage enables one also *to check polarities* of all (hundreds to thousands) multipole magnets such as dipole magnets (32 in number in the SOLEIL storage ring), quadrupole magnets (160), sextupole magnets (120), orbit corrector magnets (56 for each of the two transverse planes), and skew quadrupoles (32).
- This phase also allows one to *tune finely the injection scheme* and leads to the proper conditions to get the beam stored and accumulated in the storage ring.

2.2 Beyond beam accumulation

Once the accumulation is done, the commissioning team wants to know *how far away* the real machine is from the modelled one. To answer this key question a large number of experiments need to be performed.

- *What is the electron beam energy*? Modern light sources require usually a good relative energy setting in order not to jeopardize the photon spectrum delivered to the experimental stations. A very precise measurement is based on the spin depolarization method (see Ref. [12] for details).
- *Stored beam current* and *electron beam lifetime* are measured using for instance a Direct Current Current Transformer (*DCCT*). The reader is referred to J-C. Denard's course for details [7].
- The *closed orbit* followed by the beam has to be measured with high precision and down to the micrometre level (see Ref. [13] for details). BPMs are then used in slow acquisition mode (10 Hz), using averaged turn-by-turn data to improve resolution. At SOLEIL, the BPM RMS resolution is below 0.2 μm.
- *Betatron tunes* need to be measured and corrected. In general they are off by half to a few units the first day. Wrong tunes are good candidates to prevent good injection efficiency, to jeopardize the orbit correction, etc. They can be measured by means of transverse coherent excitation of the beam using a *shaker magnet* or a *strip-line*: either a white noise or signal obtained by sweeping the excited frequency is injected onto the beam [14, 15]. *Turn-by-turn data collected on the BPMs* are then processed using a FFT-like algorithm to identify the betatron tunes.
- It is crucial to *ensure that the beam is going through the centre of quadrupole and sextupole magnets*. Without any correction the closed orbit is not centred at all as a consequence of residual magnetic centre errors (determined during magnetic measurements) and alignment errors of both magnets and BPM blocs in the tunnel. A standard technique used in most facilities is known as *beam based alignment* [16]. Basically, the BPMs are used to measure the closed orbit distortions for various steerer settings. The beam is well centred in a quadrupole if its position does not depend on the quadrupole strength. At this stage *low noise BPM electronics is mandatory to reach values below the micrometre level* (see Ref. [9]).
- *Physical aperture limitations* need to be determined to identify possible obstacles in the vacuum vessel. Equipment such as *beam loss monitors* [11], *BPMs* (for local orbit motions) are very useful.
- A way to *scrape the beam current down to zero* in a safe manner, i.e., without damaging the accelerator or depositing beam dose in inappropriate locations has to be validated. Depending on

the type of accelerator, equipment such as scrapers, beam dumps, fast kickers may be used for this purpose [17].

– Then the *linear optics* has to be fully characterized [18] and well corrected. Indeed, injection efficiency, emittance, brilliance, lifetime are strongly impacted by any optical (betatron, dispersion) function mismatch or asymmetry. Before any correction, a relative deviation of a few tens of per cent is commonly observed in both horizontal and vertical planes (see Fig. 3 upper left). The correction is performed by measuring the so-called *orbit response matrices* (see Fig. 3 right), the horizontal dispersion function, and the beam noise at the locations of the BPMs. A standard code for the optics restoration is named *LOCO* (*Linear Optics from Closed Orbit* [19]). Basically the modelled orbit response matrix is fitted to the experimental one using a least-squares method. The fitting parameters are quadrupole strengths, BPM gains and cross-talks, steerer magnet strengths and rolls, and skew quadrupole strengths. The optics symmetry restoration is obtained by applying back to the machine the reverse of the fitted model.

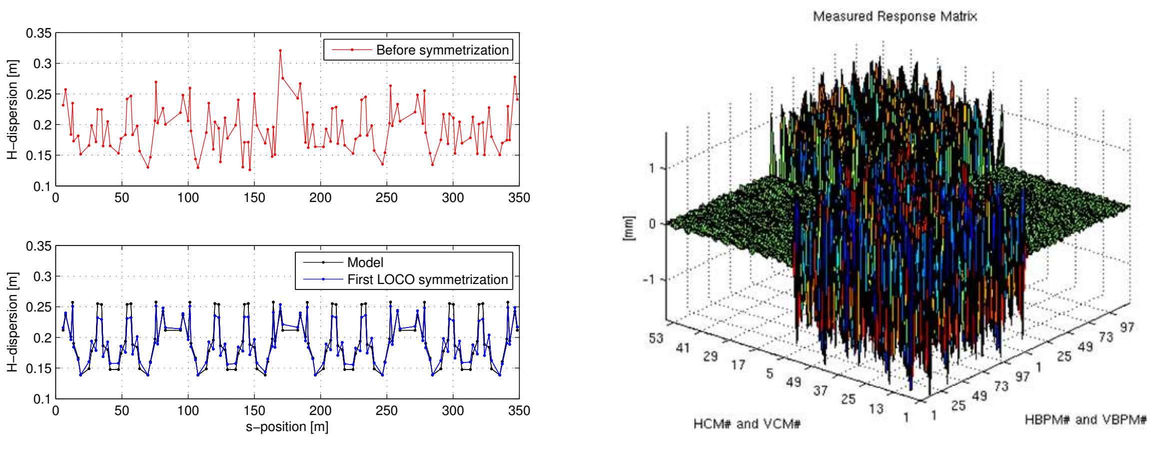

Fig. 3: Left: SOLEIL horizontal dispersion function along the storage ring prior to any symmetry restoration on the first day (top) and after restoration (bottom). **Right:** Orbit response matrix given the orbit distortion at each BPM location when changing the current in each steerer magnet individually.

– *Correction of the betatron coupling* is also decisive to control vertical beam size and to reduce sensitivity to errors. It can also be used to control beam lifetime. Natural coupling is a direct consequence of alignment and magnetic centre errors. Emittance measurement is usually performed using pinhole-like techniques [20].

– After a careful tuning of the linear model, *the non-linear model of the accelerator has to be probed*. The global idea consists in exploring large amplitude dynamic behaviour of the beam for on- and off-momentum particles. Investigating the non-linear dynamics helps in understanding the limitations of the facility performance (injection efficiency, lifetime, etc.). A standard technique is to kick the beam synchronously to large amplitudes in the horizontal and vertical planes and in energy. Getting the foot-print of the beam (Fig. 4) using analysis techniques such as *frequency map analysis* [21] is incredibly rich dynamics-wise. These techniques are based on turn-by-turn data collected on BPMs for large off-axis positions. This is a way to explore and to validate the non-linear model of the machine, including the effects of inherent multipole errors. It also helps one to understand non-linear effects introduced by equipment such as wavelength shifters or insertion devices.

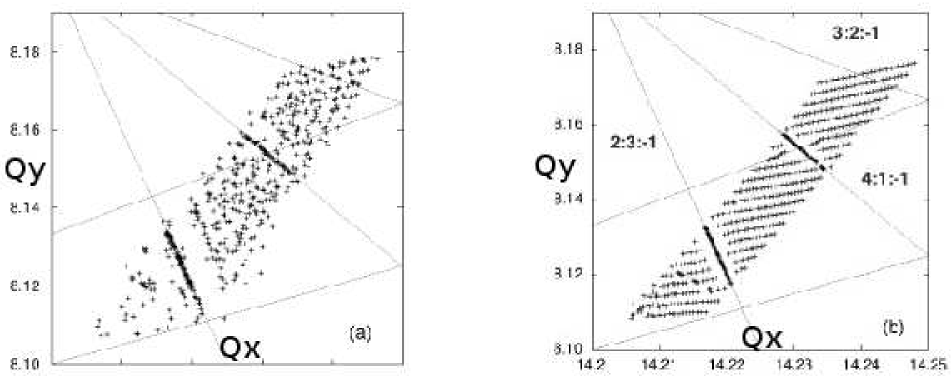

Fig. 4: First experimental frequency map (right) measured at the Advanced Light Source (Berkeley, USA) compared to the modelled one (left) in 1999 [22]. Horizontal and vertical betatron tunes are denoted respectively by Qx and Qy. Resonance lines are shown as solid lines. The excellent agreement between model and reality has only been possible thanks to many years of improving diagnostics and techniques to explore non-linear dynamics of particles in accelerators.

2.3 Improvements and new modes of operation

Finally the same kinds of diagnostics are used for improving the accelerator performance, for finding new working points, for tuning the optics to reach ultra-low coupling values, or for different filling patterns. Accelerator physicists always devise new machine settings for measuring new parameters, setting the machine in an exotic mode such as low-alpha lattice (leading to a reduction of the electron bunch length and a strong production of infrared coherent radiation), femtosecond lattices (enabling one to select a short part of the longitudinal bunch radiation — a few tens or hundreds — of femtoseconds [23]), and so on.

3 Stability requirements

Throughout the previous section the beam position monitor has been presented as a crucial diagnostic tool used at every step of the commissioning of an accelerator facility. This is a nice example of a multipurpose diagnostics tool. Table 1 reviews the BPM electronics requirements for a third-generation synchrotron light source facility. Four modes of operation are described, namely, *first-turn mode* used for first beam injection into the ring, *turn-by-turn mode* used for turn-by-turn measurements, *slow FB mode*, used for slow orbit feedback correction (10 Hz, see Section 4.3), and *fast FB mode*, used for fast orbit feedback (10 kHz) — see the courses of M. Boege [24] and P. Forck [9].

Throughout this section, stability criteria will be presented for different types of facilities.

3.1 Synchrotron light source stability requirements

About 50 synchrotron light sources are in service around the world. Of these about 20 are called third-generation light sources. They are characterized by strong focusing, low emittance, high brilliance, micrometre-level or sub-micrometre level orbit stability, and many undulator-based beamlines.

Brilliance (B) — defined as the number of photons emitted by unit of time, unit of surface, unit of solid angle for 1% bandwidth — is the figure of merit to be preserved. Its expression is simply given by

$$B \propto \frac{1}{\epsilon_x \epsilon_y} \equiv \frac{1}{\sigma_x \sigma_y \sigma'_x \sigma'_y}\ , \tag{1}$$

where $\epsilon_{x(y)}$ is the horizontal (vertical) emittance, $\sigma_{x(y)}$ and $\sigma'_{x(y)}$ the horizontal (vertical) beam size and beam divergence.

Table 1: BPM electronics requirements for SOLEIL. Four modes of operation are listed together with their characteristics. BPMs are a crucial diagnostics tool used in all stages of accelerator operation: commissioning, user operation, accelerator physics dedicated shifts.

	First turns	Turn-by-turn	Slow FB	Fast FB
Absolute accuracy	$\leq$ 500 µm	$\leq$ 200 µm	$\leq$ 20 µm	$\leq$ 20 µm
RMS resolution	$\leq$ 500 µm	$\leq$ 20 µm	$\leq$ 0.2 µm	$\leq$ 0.2 µm
@ rep. rate	@ 847 kHz	@ 847 kHz	@ 10 Hz	100 Hz BW
Measurement rate	847 kHz	847 kHz	10 Hz	$\geq$ 4 kHz
Dynamic range	0.4–4 mA	4–600 mA	20–600 mA	20–600 mA
Current dependence	NA	$\leq$ 500 µm	$\leq$ 1 µm	$\leq$ 1 µm
8 hour drift	NA	$\leq$ 500 µm	$\leq$ 1 µm	$\leq$ 1 µm
1 month drift	NA	$\leq$ 500 µm	$\leq$ 3 µm	$\leq$ 3 µm
Bunch pattern dependence	$\leq$ 500 µm	$\leq$ 50 µm	$\leq$ 1 µm	$\leq$ 1 µm

High brilliance is obtained by pushing the parameters of the lattice to reach a *very low emittance value* and to maintain a constant *large beam lifetime*. As the reader can directly see by using Eq. (1), the brilliance is inversely proportional to transverse beam sizes; a typical stability criterion is *one tenth of the beam sizes and divergences*.

If any ground vibration is transmitted to the girders supporting the magnets, these latter will move leading to a time dependence of the orbit position and a growth of the emittance, whence to a reduction of brilliance. Figure 5 summarizes this process.

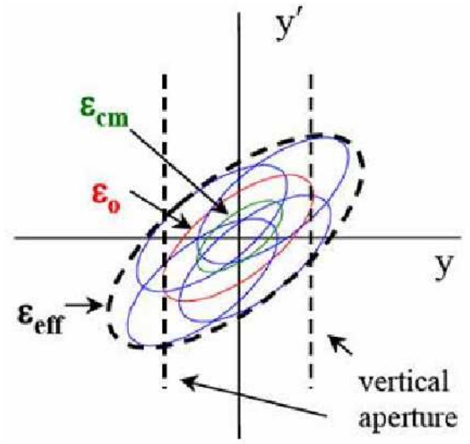

Fig. 5: Emittance growth (courtesy of L. Farvacque): here ϵ_0 is the emittance given by the optics in an ideal case. The effective emittance $\epsilon_{\rm eff}$ seen by the user is the convolution of the beam motion $\epsilon_{\rm cm}$ and the ideal one ϵ_0. The two vertical dashed lines show the vertical aperture at the experimental station. All photons outside those lines are considered as lost for the users.

In addition to orbit stability other key parameters have to be preserved: betatron tune, chromaticity, coupling, and beam energy values.

- Relative beam *energy* has to be better than 10^{-4} to 10^{-5} in order to preserve spectral resolution (see Ref. [12] for details).
- The *betatron tune variations* have to be typically maintained within 10^{-3}.
- Light sources operate at *low coupling values* (from 1 down to 0.1%). As a consequence, this parameter is very sensitive to insertion device errors and settings.

– Finally, chromaticity constraints are usually much looser.

A difficult task in this kind of facility results from the fact that *many insertion devices* are installed all around the storage ring and are fully controlled by the users. Inherently, insertion devices impact globally on the beam parameters in terms of closed orbit, focusing, and coupling values. Consequently source points, lifetime, and brilliance happen to be modified. The operation of one single undulator device may be seen on all the beam lines: this is precisely what has to be avoided. This is another challenging aspect of light sources.

3.2 XFEL stability requirements

The European X-Ray Free-Electron Laser [25] (XFEL) is a 3.4 km long linac-based accelerator optimized to produce spatially coherent light with a very high peak brilliance (10^{33}photons/s/mm^2/mrad^2 for 0.1% bandwidth) in ultra-short (around 100 fs) bunches with wavelengths down to 0.1 nm. For this kind of facility any *orbit distortion* leads to beam shape variations and consequently to a drastic reduction of the Self Amplified Spontaneous Emission (SASE) power and gain length.

One difficult aspect of such facilities is the *undulator alignment*. At XFEL there are 700 m of undulators divided into 5 m long segments embedded in 12.2 m long FODO cells. A non-exhaustive list of constraints on undulators is:

- keeping the tunnel temperature within 0.08°C (as a reminder, the temperature expansion of stainless steel is 13 µm/m/°C);
- gap control to be as low as 1 µm;
- undulator alignment errors to be kept below 100 µm;
- gun charge, energy spread, and emittance fluctuation to be controlled;
- beam shape variation and bunch density to be maintained to preserve the SASE power;
- finally, orbit stability is required to be better than *one tenth of the beam size*.

3.3 Collider stability requirements

For lepton accelerators (LEP, PEPII, KEK-B, etc.), the main figures of merit are *collider luminosity* and *collision stability*. Moreover systems have been developed to preserve the effective emittance of the beams, to minimize the coupling (orbit leakage in sextupole magnets) and spurious dispersion (orbit leakage in quadrupole magnets). Tune and orbit feedback systems are mostly used during energy ramping from injection energy to collision energy [6].

For hadron colliders (HERA, LHC, RHIC, Tevatron, etc.), the first requirement is to *keep the beam safe in the pipe*. Indeed, a significant amount of energy is stored in the beam (360 MJ is stored in the LHC 7 TeV proton beam). Any partial or total beam loss may lead to superconducting magnet quenches or to serious damage to the accelerator. Control of the beam losses is of the uppermost importance in such facilities. Collimators, beam dumps, and machine interlock systems are very complex, critical, but mandatory for safe operation [26].

Another fundamental parameter to control is the *orbit stability* which impacts directly on the luminosity inside the experimental insertions: 25 µm is the constraint at the collimators for the LHC [17].

Relative *energy preservation* has to be as good as 10^{-4} at the LHC [6].

Ramping the two proton beams from injection energy (450 GeV) to collision energy (7 TeV) without losing the beams also leads to strong constraints (Fig. 6):

- need to *synchronize together thousands of magnets*;

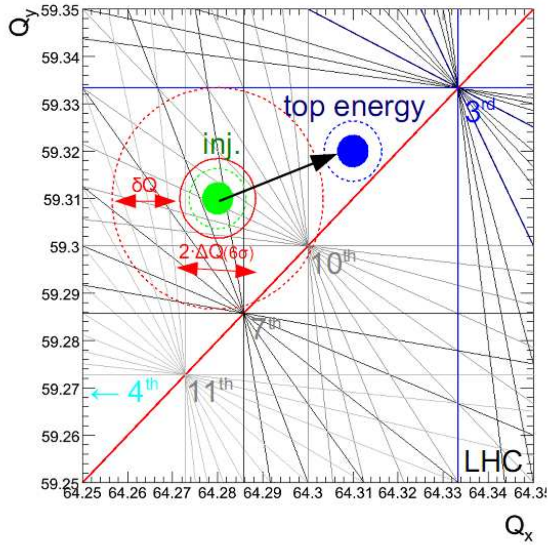

Fig. 6: LHC tune diagram (Qx, Qy) with working point for injection (green dot), working point for best collision performance (blue dot). The difficult part is then to constrain tune variations far away from strong resonance lines (bold solid lines) in order not to lose the beam partially or totally (courtesy of R. Steinhagen [6]).

- need for *different working points*, in the tune diagram, optimized either for injection or for luminosity performance;
- need to *avoid any strong resonance crossing* during energy ramping up;
- all these constraints lead to *very strict tune and chromaticity controls*. For example at the LHC, tunes have to be kept better than 10^{-3} and chromaticities 2 ± 1 (knowing that chromaticities change by more than 100 units during the course of the ramping up process!);
- all these performance are only reached with the use of feedforward and feedback systems for the closed orbit, the tunes, the chromaticities, and the coupling value.

4 Orbit stability for accelerator facilities

4.1 Sources of ground vibrations

Sources of beam orbit instability may be classified in categories depending on the time scale upon which they act on the orbit: long term (weeks to years), medium term (minutes to days), short term (milliseconds to seconds), and very short term (higher frequency or shorter periods).

- **Long term**
  - ground settlement (millimetre scale);
  - seasonal ground motion (millimetre scale);
  - Sun and Moon tides (circumference variation of a few micrometres). See as an example Fig. 7.
- **Medium term**
  - diurnal temperature (1 to 100 micrometres);
  - crane motion;
  - filling pattern (heat load, BPM process);
  - river, dam activity, heavy rains, etc. (1 to 100 micrometres);
  - stored beam intensity decay (thermal drifts, electronics drifts of BPMs etc.);

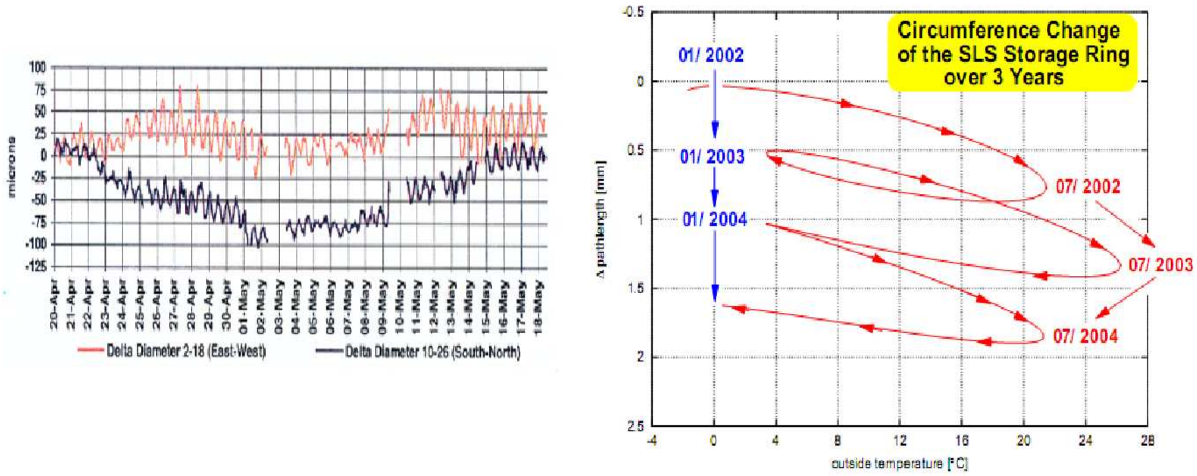

Fig. 7: Left: ESRF circumference variation due to gravitational Earth tides of the Sun and the Moon (courtesy of L. Farvacque). **Right:** Circumference change of the SLS storage ring over three years following seasonal temperature [24].

  - circumference variation (1 to 100 micrometres);
  - startup following a shutdown period (thermal drifts);
  - drift of vacuum vessels due to temperature, etc.;
  - ramping in energy or modification of the working point.
- **Short term**
  - ground vibration, road traffic, train traffic, construction work, etc. Owing to the amplification factor of the girders, *nanometre amplitudes may change to micrometre amplitudes*;
  - cooling water, liquid helium, nitrogen, system vibrations (micrometre level);
  - rotating machinery (air conditioners, pumps, chillers, etc.);
  - booster operation (micrometre level);
  - insertion devices (1 to 100 micrometres);
  - orbit transients creating by switching of devices (eddy current, etc.);
  - power supplies;
  - injection (1 to 500 micrometres).
- **Very short term**
  - $50/60$ Hz of the mains;
  - D/A converter digitization noise;
  - pulsed power sources;
  - switching frequencies of power supplies;
  - radio-frequency cavity micro-phonic noise;
  - synchrotron oscillation (1 to 100 micrometres);
  - single or multi-bunch instabilities (1 to 100 micrometres);
  - electromagnetic interference (appliances in the laboratories, radio broadcast masts, etc.).

The following subsection will briefly present commonly used solutions for reaching the orbit stability for a small number of noise sources.

Applied to the SOLEIL storage ring, the stability criterion of one tenth of the beam size gives 18 µm RMS and 0.8 µm RMS respectively in the horizontal and vertical planes for a 1% coupling value in the straight sections. *Reaching sub-micrometre level stability is a very challenging task* but not impossible if passive and active solutions are combined.

4.2 Technical solutions to fulfil orbit stability criteria

4.2.1 Long term stability

A stability criterion of 100 µm/10 m a year is the goal for the SOLEIL synchrotron. This implies slab settlement below 50 µm a year and a maximum vibration amplitude smaller in size than ±0.5 µm. To meet this goal, a careful design of the building was made including the foundation and piles supporting the accelerator and experimental slabs which are connected together as a monolithic set (see Fig. 8).

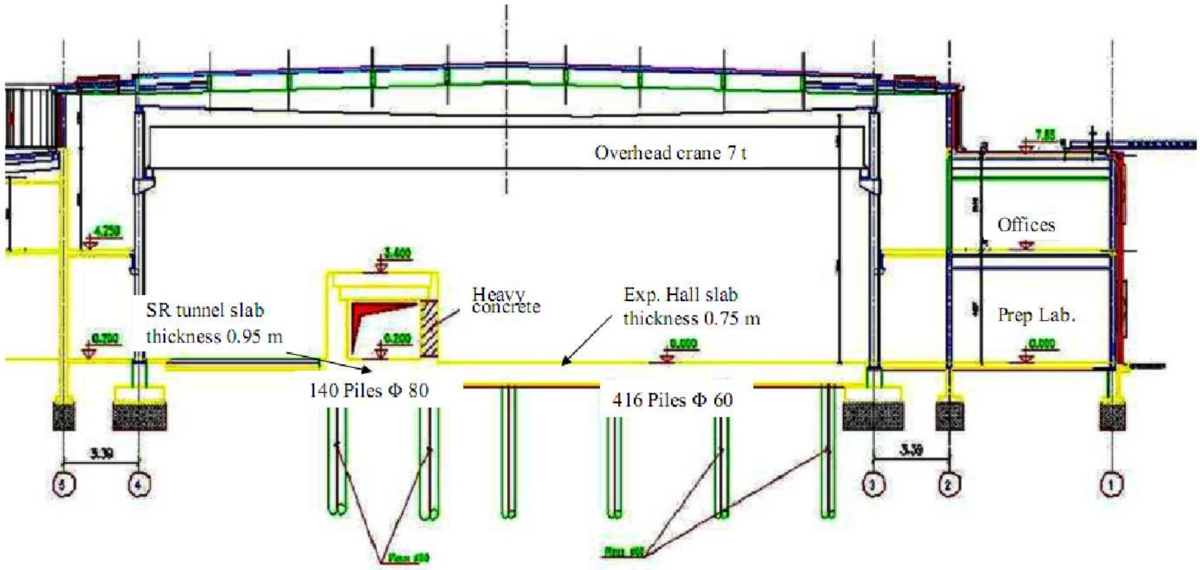

Fig. 8: Cross-section of the building hosting the accelerators and the experimental hall of SOLEIL. Stability is assured using an almost 1 m thick slab lying on 20 m long piles. The ground composition is made of a clay layer on the top of *Fontainebleau* sand.

4.2.2 Medium term stability

In order to reach the stability criterion over time-spans of hours, standard passive solutions used are stabilization of the air temperature in the tunnels and the water cooling systems within ±0.1°C. Readers have to keep in mind that the expansion of stainless steel is 13 µm/m/°C whereas beam has to be kept below 0.1–1 µm stability levels. The experimental hall is also equipped with air conditioning systems to keep temperature within ±1°C. The same kind of solution has to be applied to keep, for instance, a stability of the energy delivered by the injection systems (linac system, accelerating cavities, etc.).

Even if such solutions are applied, orbit will not be stabilized enough. Figure 9 depicts orbit drifts over an 8 hour time-span with a stored beam current of 210 mA. At SOLEIL, orbit drifts in the horizontal plane reached values as large as 50 µm when orbit feedback systems were turned off.

Active systems such as feedback loops (see Section 4.3) on the BPM readouts are then used to keep the beam down to a position stability of a few micrometres.

Reaching sub-micrometre stability is only possible when the light sources run in the so-called *top-up* (or *top-off*) mode of operation. This mode allows the stored beam current to be kept at constant value. Figure 10 shows the normal mode of operation of a light source where the beam current decays over a

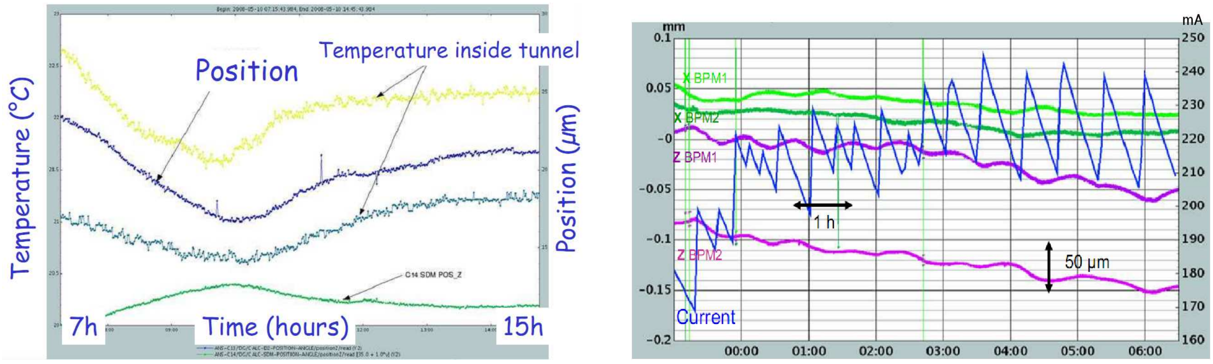

Fig. 9: Left: Correlation between orbit and temperature drift over an 8 hour time-span at SOLEIL during the course of a failure of the air conditioning system. **Right:** Natural drift of the orbit in the absence of orbit feedback systems. The horizontal orbit drifts by more than 50 µm over 8 hours.

few hours leading to a current refilling several times per day. During the decay, the thermal load on the beamline optics (mirrors, monochromators etc.) leads to optical bumps, optic deformations resulting in drifts of the photon positions on the samples. Similarly the non-constant thermal load on the accelerator equipment gives rise to thermal drift on BPM electronics, for instance, which jeopardizes any attempt to correct for sub-micrometre level variations. On the other hand the top-up operation mode allows one to maintain the thermal load thanks to recurrent injections every few seconds or minutes keeping the stored current the same at a percentage or fraction of a percentage level.

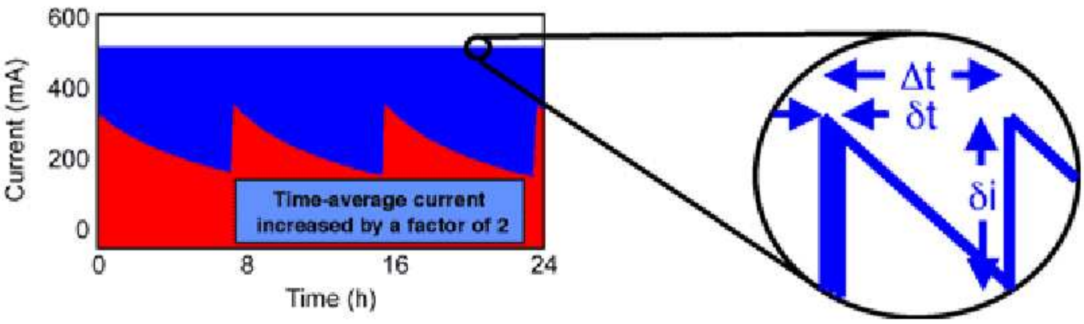

Fig. 10: Normal current decay operation mode: the beam intensity decays over hours. Here after 8 hours the beam intensity decreased from 350 mA down to 200 mA leading to a significant variation in thermal load. In the so-called top-up mode of operation, the current is maintained at a constant value (here 500 mA) by injection every few seconds (Δt) of small amounts of current (δi). The key point is to get a beam injection without perturbing the position stability of the stored beam (courtesy of D. Robin).

Operating in such a mode requires a very careful design of the top-up system. At SLS users asked for an additional bunch-by-bunch current feedback allowing the charge to be kept uniform in all bunches (less than 1% level [27]). Briefly, the system consists of a photo-diode looking at the synchrotron light emitted by each bunch circulating in the storage ring. The signal is digitized and all bunches are sorted by current values. At the next injection time, only the less charged bunches get a top-off of current. The grid of the linac gun can be modulated in order to adjust finely the current needed in the specific bunches. This kind of system requires very robust architecture in terms of diagnostics and control system to ensure that the full injection chain is always working as expected, that only the marked bunches are filled in. A strong effort monitoring the quality of the beam all along the injection chain (linac, booster, and transfer lines) is a highly desirable feature.

4.2.3 Short term stability

A key passive component for reaching a short term orbit stability is the girder (see Fig. 11 left), supporting all equipment in the storage ring tunnel (alignment tolerance values for SOLEIL are given in Table 2). The girders were designed in order to damp down vibration amplitudes and to have a first eigen-frequency as large as possible (46 Hz for SOLEIL long girders). Figure 11 right displays the power spectral density measured on a long girder of the storage ring. Indeed orbit distortions are less amplified by the optics when magnets sit on girders. The amplification factors of the optic function reduce significantly from 30 (10) in the horizontal (vertical) plane down to 16 (3).

Table 2: Alignment tolerance of magnets and BPMs at SOLEIL

Error type	RMS amplitude
Girder transverse displacement	0.10 mm
Girder roll error	0.10 mrad
Quadrupole transverse displacement	0.03 mm
Bending magnet transverse displacement	0.50 mm
Bending magnet roll error	0.50 mrad
BPM transverse displacement	0.10 mm

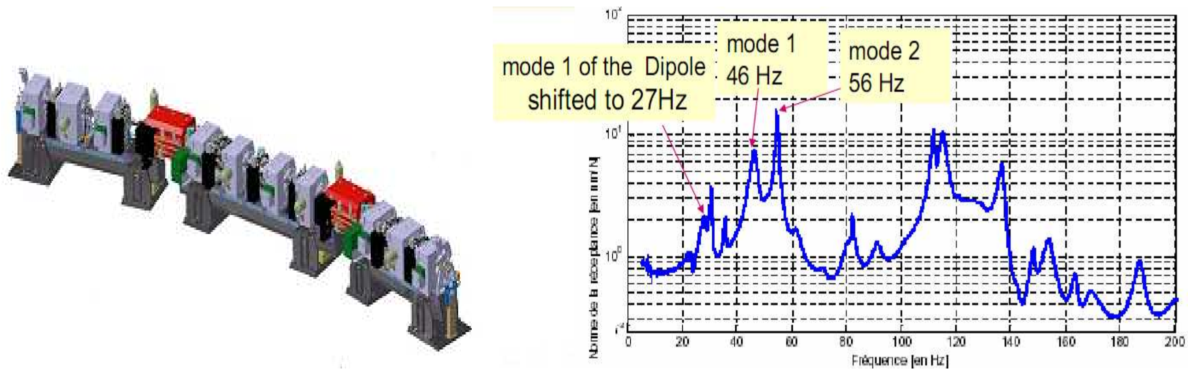

Fig. 11: Left: SOLEIL girders equipped with quadrupole and sextupole magnets. Dipole magnets sit in between girders. **Right:** Power spectral density measured using a vibration sensor. The first girder oscillation frequency is at 46 Hz, well above a large number of typical noise frequencies in accelerators.

Following the time evolution of the position of the girder is very helpful in order to keep within beam stability specifications. Girders can be equipped with *Hydrostatics Levelling Systems* (HLS) for monitoring their altimetry and torsion along the beam axis, sensors such as *Horizontal Position Systems* (HPS) follow the horizontal motion between girders. Even more ambitious dynamic beam-based alignment of the girder can be envisaged with girder movers that are remotely controlled [28]. *BPM position monitoring systems* (POMs) are another diagnostics tool to sense transverse motions of the blocs with reference to adjacent quadrupole magnets. The dial gauges enable one to monitor motion of the BPMs which are taken as static references in the orbit correction algorithms, especially for the feedback systems. These techniques have been installed, for instance, at the SLS storage ring in Switzerland [29].

Continuous surveillance of the environmental noise can be performed using *vibration monitors* such as *velocimeters* or *accelerometers*. Such equipment may be installed inside the tunnel, on magnets, BPMs, X-Ray BPMs (X-BPMs), but also in the experimental hall or outside the building to follow and understand any noise source. This piece of diagnostics is very helpful to identify the location of noise sources and for taking counter-measures. Power spectral density of noise can also be obtained from the analysis of turn-by-turn data from electron BPMs or photon BPMs.

Correction in order to reach short term stability is assured by active systems such as feedback loops or feedforward systems depending on the kind of perturbation. Disturbances are either predictable or not.

4.3 Feedback and feedforward systems

4.3.1 Introduction

Feedback and feedforward systems are used for correcting for closed orbit, tune, chromaticity, coupling, and energy values.

Sources of perturbations are insertion devices in all light sources, tune shift dependence with the current per bunch (because of impedance issues), injection systems, top-up operation mode, ramping from injection energy to nominal energy (mostly in colliders).

These systems rely heavily on *beam based measurements* of the closed orbit, tunes, and chromaticities.

An example: the *tune measurement* [15] can be made in electron facilities by exciting the beam using a shaker magnet or a strip-line and by signal processing BPM turn-by-turn data. However, these non-passive techniques can alter the beam performance. One single-bunch excitation using fast transverse feedback can be an alternative (used at Elettra [30, 31] or SOLEIL) to lessen beam noises that perturb the photon beam qualities. For hadron machines, the measurement methods have to be passive since the beam damping times are very long. Equipment such as Schottky detectors are used at the LHC and RHIC. Tune phase locked loops allow one to detect excitation levels well below 1 μm. The reader is referred for details to the course by F. Caspers [32].

Beam emittance and coupling measurement are usually performed with one of the following:

- Coupling phase locked systems with an excitation level below 1 μm. This method is used, for instance, at the LHC [6].
- Pinhole systems which consist in imaging the X-ray part of the beam radiation. This kind of system is used in most light sources and is fully passive.
- Other refined techniques to measure very low emittance and coupling values have been developed in all laboratories. A recent technique using off-axis emission of the vertical polarized radiation developed at SLS seems very promising [33].

4.3.2 Feedback systems

Maintaining orbit stability relies heavily on the use of BPMs and X-BPMs distributed all around the ring for monitoring the beam position (see schematic in Fig. 12). The beam is steered back to its reference thanks to dedicated horizontal and vertical dipolar magnets and to the master clock reference (energy feedback in the horizontal plane).

For the orbit correction, different philosophies are to be chosen depending on the storage ring and on the equipment architecture.

- Two feedback systems can coexist: a slow system (DC part to 1 Hz) and a fast system (1–200 Hz).
- Dead zones in the frequency domain can exist or not to avoid destructive interaction between fast and slow systems.
- Feedback systems can interact and exchange data such as residual orbit, information to keep average current in fast steerers close to zero, etc.
- The system can be unique from the DC part to the high frequency domain.

These systems are complex and have to be designed in such a way that they have a large gain in

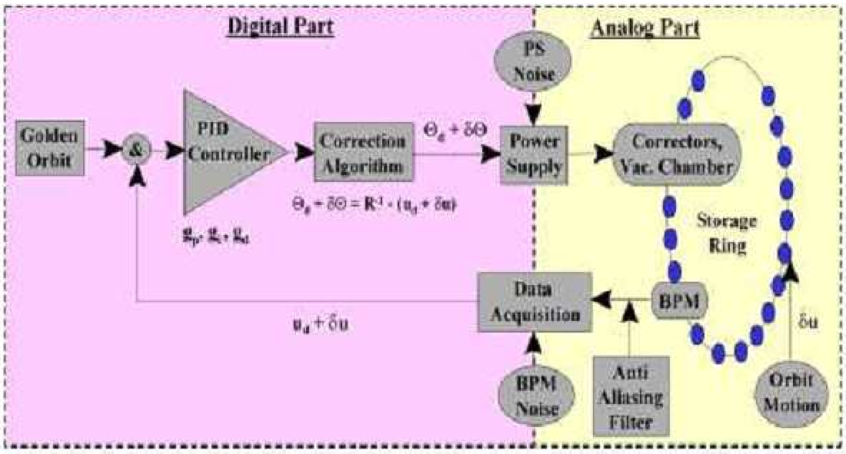

Fig. 12: Block diagram of global orbit feedback. The difference between the orbit read on BPM stations and the golden orbit is computed. Using a Proportional Integral Derivative (PID) controller and the orbit response matrix, the increments of current for steerer magnets are computed and sent to the power supplies. The whole loop can work up to a few kilohertz rate [24].

the frequency range of correction and do not reject noise at higher frequencies (see an introduction to feedback systems in M. Boege's course [24]).

Figure 13 shows a diagram of interleaved feedback loops for the LHC. In this 27 km circumference ring, the main feature is to make use of the accelerator size for exchanging information and to integrate all loops together while keeping the perturbation on the beam not detectable by users.

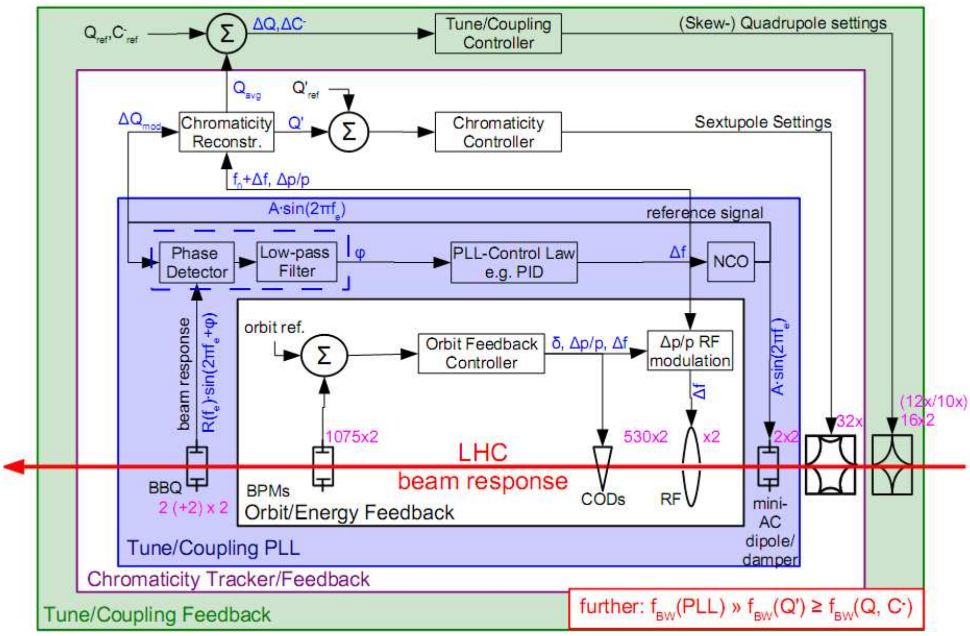

Fig. 13: Example of a cascaded system including orbit, tune, chromaticity, and coupling feedback loops at the LHC (courtesy of R. Steinhagen [34])

4.3.3 *Feedforward systems*

When the perturbation is predictable based either on a model or on beam measurements, *feedforward systems* are employed as *set and forget systems*. Such systems are used on a daily basis for a ramping process to maintain stability in the tune diagram (see Fig. 6), for compensating perturbations which depend on the insertion device configurations leading to likely disturbance in orbit, tunes, chromaticities, coupling, etc.

These systems are very useful and stable, nevertheless they suffer from a few limitations:

– They may depend on the beam conditions.
– Their corrections are not perfect owing to synchronization mismatch between sub-systems being controlled (magnet power supplies, mechanical jaws of insertion devices, etc.).
– Each system correcting insertion devices, for instance, introduces additional errors or residual closed orbit which have to be taken care of by feedback systems. Moreover, interactions between devices may be very difficult to predict or to measure in all possible configurations: in third-generation light sources, tens of insertion devices are fully controlled by users, giving hundreds of different configurations. In such a situation the main part of the perturbation is usually corrected by the feedforward systems and the residual part by a global feedback system. Interactions between those systems have to be watched carefully.

Figure 14 shows the correction of closed orbit using a feedforward system of the SOLEIL Apple-II type insertion device. It allows one to reduce the beam distortion from a few tens of micrometres (main part) to a few micrometres (residual orbit).

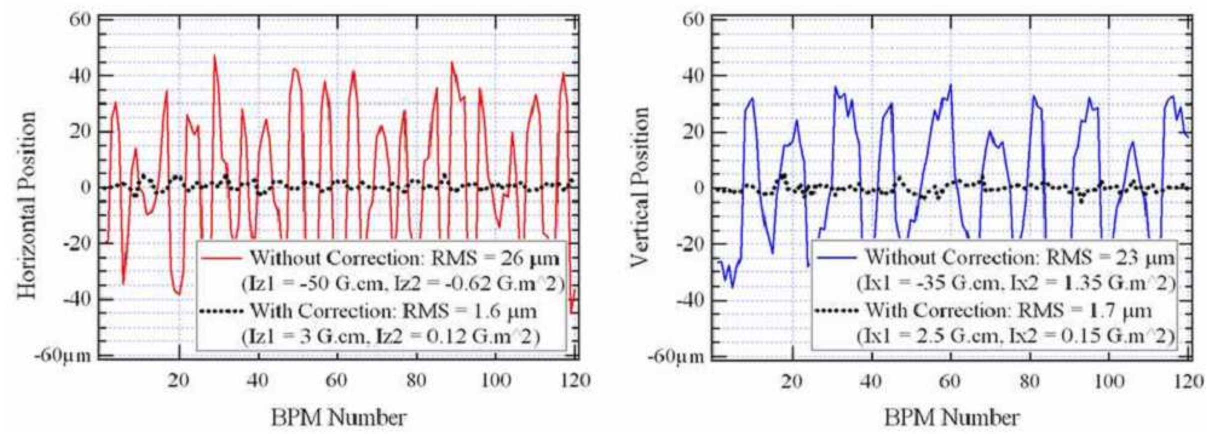

Fig. 14: Closed orbit distortion introduced by one Apple-II type insertion device at SOLEIL observed at the BPM locations. After correction the RMS value reduces from 26 μm and 23 μm (solid line) down to 1.6 μm and 1.7 μm (dashed line) respectively in the horizontal (left-hand side) and the vertical (right-hand side) planes.

5 Collective effects

Collective effects are the main cause limiting the performance of all accelerator facilities in terms of maximum beam current, brilliance, or luminosity. This topic is very rich physics-wise but at the same time very difficult. This field is an excellent example of where model and reality differ more or less greatly most of the time. Diagnostics are very welcome for shedding light on these phenomena.

Collective effects cover all interactions between particles in a single bunch, between subsequent bunches, within a single turn, or many turns, be the nature of the particle leptonic or hadronic. Also, interaction of the circulating beam with its environment (vacuum vessel, bellows, BPMs, flanges, RF cavities, tapers, etc.), with residual gas, or the other beam (for colliders).

Collective effects may trigger instabilities in transverse and longitudinal planes. Instability thresholds depend strongly on the beam intensity, the filling pattern, the bunch length, the pressure, the introduction of new components in the vacuum vessel, and so on.

Fighting instabilities requires a very careful design of the accelerator but also special settings of the accelerator optics. Most of the time, running a facility with the nominal performance is only possible thanks to the use of lots of diagnostics either in dedicated feedback systems or for monitoring the beam behaviour (streak-camera to measure the bunch length, network spectrum analyser to characterize instabilities, etc.).

The topic is rather complex, the reader is referred to the courses given by M. Ferianis [35], by A. Hofmann [14], and by M. Lonza [36] for further details.

6 Conclusion

Throughout this course it was explained to the reader, through examples, why diagnostics are vital for running any accelerator facility. Diagnostics are used at many other different levels.

For daily operation the aim is to provide a high beam availability (more than 96% in light sources), to ensure safe operation, and steady high performance.

One aspect is then to survey the beam parameters (closed orbit, tunes, chromaticities, coupling, current decay, luminosity, injection efficiency, instabilities, etc.).

Another aspect is to control and locate beam losses. As seen previously, this is mandatory in high-energy colliders where a significant amount of energy is stored in the beam and can lead to great damage. This is also important to reduce component activation and to ease maintenance work.

Diagnostics are heavily used in the so-called machine protection systems (see the course by R. Schmidt [17]). This includes the use of thermocouples, instability slots, beam position monitors, pressure gauges, maximum stored current interlock, beam dumps, and so one.

A last aspect is to gain the capacity to understand unexpected beam losses. Log-diaries, post-mortem systems, radiation monitoring systems are then developed and installed to follow the last microseconds to seconds of the *life* of the beam. The aim of diagnostics is also to assure the beam can be injected back subsequently to a given loss event.

As a conclusion we state that during the course of the last 10 to 15 years tremendous improvements have been made to lessen the gap between model and reality. This is mainly due to the development of new types of diagnostics and a change in their use in accelerators, not only as a minimum set to ensure injection of the beam at low cost, but also to maintain and to help improve the accelerator performance.

It is to be hoped that the reader is now aware that it is impossible to foresee all facets of an accelerator. There are static and dynamic error sources which are scattered around the facility. The real set of errors only becomes known when measuring the real beam with diagnostics. Perturbation sources are numerous, known, or unknown.

By pushing accelerator performance ever further over the years, all parameters become very sensitive to any drift: parameter stability zones reduce down to tiny ranges. Guaranteeing high performance is nowadays only possible with the heavy use of lots of feedforward and feedback systems.

A final word would be to say that the better the diagnostics, the better our understanding of the accelerators. This allows one to further reduce the effects of the present limitations in order to answer the ever more demanding accelerator physicist and user requirements.

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