Challenging Issues during ESRF Storage Ring Commissioning

Annick Ropert for the ESRF Team
European Synchrotron Radiation Facility
BP 220, F - 38043 Grenoble Cedex

Abstract

Third-generation synchrotron light sources raise numerous challenges associated with the low emittance requirement. The 6 GeV ESRF storage ring is among the first of these new sources to successfully meet these challenges. This paper will emphazise some of the most significant outcomes achieved during the ten month commissioning. The experimental approach to obtain the large dynamic aperture needed to allow the injection-accumulation process and a long lifetime will be presented. The upgrading of the predicted current thresholds set by multibunch instabilities and transverse mode coupling will be discussed. We will as well report on photon beam stability which is one of the most stringent requirements for the high brilliance light sources.

1. INTRODUCTION

The ESRF storage ring is a 6 GeV low emittance ring based on a Chasman-Green type lattice. The low emittance is being achieved by low β_x in a large number of dipoles, thus implying a very strong focusing and a large natural chromaticity. The need for strong sextupoles makes the machine highly sensitive to errors. A perfect correction of the orbit is a prerequisite for the obtention of a large dynamic aperture. The first injection trials into the storage ring started on February 17th, 1992. Progress was very successful since all target performances were achieved and even exceeded before the end of the ten months of scheduled commissioning [1], [2]. The issues of adequate dynamic aperture, beam instabilities, X-ray beam stability associated with the running-in of this third genaration light source are discussed.

2. OBTENTION OF A LARGE DYNAMIC APERTURE

The primary challenge in the early stage of commissioning arose directly from the extreme sensitivity of the lattice to imperfections due to the requirement for low emittance. Magnet positioning errors are greatly magnified by the beam in such a high focusing lattice, with amplification factors of 50 (horizontal) and 100 (vertical). Although the tolerance on quadrupole and sextupole alignment had been set to 1/10 mm, the probability of getting the beam transmitted over the entire circumference from the outset was very small.

2.1 First turns

It was decided to immediately test the low emittance optics of the storage ring, and not a detuned version, since we believed that running a detuned version in order to reduce the sensitivity to errors would not bring any valuable information. The strategy used during the turn-on process was to inject the beam on-axis, with no sextupoles and no RF. The achievement of the first turns circulating in the ring as soon as the injection parameters were set proves that this strategy was very effective. The maximum amplitudes of the beam trajectory measured by the Beam Position Monitor (BPM) system operated in the first turn mode was 15 mm horizontally and 5 mm vertically, prior to any correction.

Since we had foreseen these large initial orbit distortions, the first turn correction strategy had been carefully studied. The correction which is based on a step by step transport of the incoming beam makes use of the 96 horizontal steerers and 64 vertical steerers whilst the orbit is sampled at 224 beam position monitors around the circumference. Each corrector strength is computed so as to minimize the orbit deviations on the next position monitors. By means of this step by step correction followed by a careful closing of the first turn trajectory, the maximum excursion of the orbit was significantly reduced in the horizontal plane, thus enabling a circulation of the beam for 15 turns to be obtained.

2.2 First stored beam

After having switched on the RF, we obtained the first stored beam. The lifetime was very short: 100 ms, but long enough to get a fully damped beam (14 transverse and 25 longitudinal damping times). There were good reasons for this short lifetime. Without sextupoles, the uncorrected chromaticity is very large. The beam is widely spread in tune: $\sigma_{\upsilon x} = -115\ \sigma_{\Delta E/E} = -0.12$, $\sigma_{\upsilon z} = -33\ \sigma_{\Delta E/E} = -0.04$, with $\sigma_{\Delta E/E} = 1.06\ 10^{-3}$. Large energy excursions push the tunes to the nearby integer and half integer resonance and thus limit the lifetime. A one hour lifetime was immediately obtained once the chromaticity sextupoles were set to their nominal values. Finally, before accumulating beam, we had to switch to the normal off-axis injection mode and then to power the harmonic sextupoles, the primary role of which is to enlarge the dynamic acceptance spoilt by the chromaticity sextupoles and to accommodate the 8 to 10 mm betatron amplitude which enables the freshly injected beam from the booster to be accumulated.

2.3 Achieved performance

It was essential to correct the closed orbit at best in order to obtain correct performance. Otherwise, puzzling distorted β-functions and non-periodic dispersion could show-up. Measured transverse and longitudinal acceptances are in agreement with estimations. Present lifetime (17 hours at 100 mA, i.e. twice the design value) is vacuum dominated.

Since the first beam was accumulated, the storage ring has been operated on a working point $\upsilon_x = 36.43$, $\upsilon_z = 11.39$ which is understandably close to a coupling resonance. For reasons of injection efficiency, we have always been forced to work near the half-integer horizontally and just below the coupling. We still have to quantify the benefits of this coupling for the dynamic aperture. The resulting vertical emittance (3.2 10^{-9} m.rad) is not as small as the one measured with the fully decoupled optics (6.0 10^{-10} mrad).

3. BEAM STABILITY

3.1 Target specifications

The quality of the closed orbit correction is essential for obtaining intrinsic performances (small spurious dispersion to avoid spoiling the low emittance, large dynamic aperture for injection and lifetime,..) and ensuring the reproducibility of the X-ray beam alignment. Beam position stability requirements have been expressed in terms of a maximum value of 10 % of the beam size in each plane. Assuming that the beam is stabilized at high frequency, these values should be satisfied in a very large frequency range: higher frequency of the order of 100 Hz, longest periods in terms of days. A feedback system using special fast steerers is implemented in each straight section to compensate for the high frequency fluctuations whilst slow fluctuations are corrected with the standard orbit steerers.

3.2 Influence of the environment

Environmental stability is of prime importance to achieve stabilities of a few microns. In the long-term this performance can be affected by movements of the tunnel resulting from ground settlements. Permanent monitoring of the relative girder vertical position is performed by means of a Hydrostatic Levelling System. A peak to peak evolution of 3 mm over the circumference following the removal of a large amount of earth was recorded during commissioning. This global movement did not affect storage ring performance since the wavelengths were long compared to the betatron wavelengths. However, the zero of the HLS system was moved outside its operational range, thus imposing a realignment of the ring. Thanks to the use of remote-controlled jacks that equip the girders, this operation took only a couple of hours in January 1993. Following the realignment, the machine performance in terms of residual closed orbit was easily re-established.

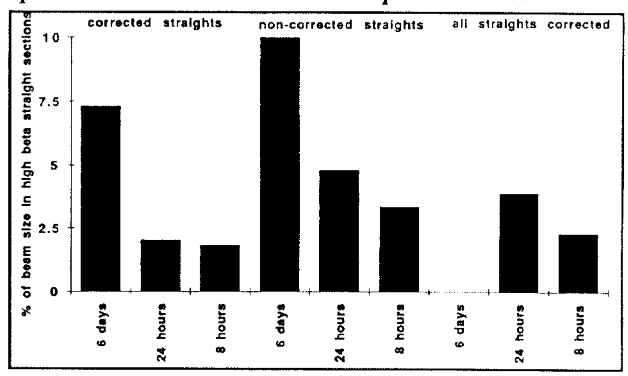
Medium-term stability of the closed orbit can be deteriorated by temperature variations along the tunnel. A variation of 0.2° C over one week is currently recorded at a given location around the circumference. Low frequency vibrations induced by cultural noise could also affect the closed orbit. Components at 7 Hz induced by the eigenmodes of the girders and at 10 Hz from the pulsed magnets of the booster have been identified. Their contribution is below the 10 % target.

From the outset of commissioning, we had a strong concern about any misalignment of the photon beam impacting the vacuum vessel, since power densities from insertion devices are equivalent to that of a welding machine and a fault on a single steerer can generate an intolerable orbit distortion. The protection of the vacuum chamber is therefore ensured by a low frequency interlock relying on a set of dedicated beam monitor positions triggering a fast beam abort system (<2 ms) based on RF switch-off. In the early stage of commissioning, we ran by accident and for several hours a 20 mA beam which was coherently unstable in the vertical plane and thereby damaged a few vacuum vessels. This instability, occuring at betatron frequencies (140 kHz), was not detectable on the interlock system. We have now installed a dedicated interlock.

3.3 Present closed orbit correction strategy and results

The closed orbit procedures consist in a combination of local bumps and harmonic compensation. They routinely bring the orbit distortions within 120 µm rms horizontally and 140 µm rms vertically. These figures are as expected. This does not ensure the reproducibility of the beam position within the specifications because the orbit drifts with time, more specially in the horizontal plane, so that a new orbit correction is necessary after a few hours.

Therefore a permanent closed orbit correction had to be implemented. This periodic correction must ensure that the drift between two corrections does not exceed the stability specification and that the beam displacement induced during the correction itself is acceptable. This is presently achieved with a correction automatically triggerred every 15 minutes. A global correction is first applied by means of an harmonic compensation of a few harmonics around the tune. It has the advantage that all the existing BPMs are not necessary to compute the correction; we therefore exclude the straight sections which might be influenced by the local feedback. Also this method provides a correction at all source points. The ultimate stability in straight sections is achieved by two local bumps (to provide both position and angle) which are powered as a function of the readings on 2 BPMs. Each straight section can be corrected independently of its neighbours. The resulting long-term stability presented in the graph hereunder is below the 10 % specifications.



3.4 Local feedback

This already excellent performance can be improved by means of a feedback. For that purpose, each insertion device front-end is equipped with two photon beam position monitors. The signals from these sensors are used to feed four fast steerers located at both ends of the straight section which act on the position and angle of the electron beam in both planes. The first feedback was installed and commissioned on the machine diagnostics beamline. The typical performance is the following: a factor of 10 gained at 7 Hz and a factor of 2 at 50 Hz. Since then, three more feedbacks are operational and enable to obtain peak to peak displacements of a few microns when the loop is closed.

Effects of insertion devices were expected to be very small since the focusing effect scales inversely as the square of the energy. Due to the high field quality achieved after shimming, no significant orbit distortions are observed with the 4 insertion devices presently operated.

4. INTENSITY LIMITATIONS

4.1 Multibunch case

The ESRF has been designed to run mainly in the multibunch mode (992 bunches) at target current of 100 mA. Transverse coupled bunch instabilities appeared at rather low intensities and led to damaging a few vacuum vessels before the problem was clearly identified and cured. The manifestation of the instability corresponds to about 10 betatron lines, each of them associated with a coupled bunch coherent motion with decreasing amplitudes on both sides of every harmonic of the revolution frequency. The source of the instability is the long range wake of the resistive wall instability. To stabilize these modes, we applied the standard over compensation of the chromaticity which enables the spectrum of the mode to be pushed towards the positive frequency region associated with the damping effect of broad-band positive resistance As soon as this remedy was applied, we were immediately able to raise the intensity to 100 mA.

Our present vertical chromaticity stands at 0.4. In the long-term, a large number of flat insertion device vessels will be installed and the resistive wall impedance will increase. Increasing the chromaticity to provide more and more damping cannot be pursued to infinity since it would induce detrimental non-linear pollution of the dynamic aperture and consequently of the injection speed and lifetime. With a view to lowering the strength of the instability, we tried to decrease the vertical tune just above the integer, down to 11.1. In these conditions, the coupled bunch mode with a frequency line at -0.9 f_0 interacts with a lower resistance. However the much lower injection efficiency and the much higher sensitivity of the beam centre of mass to vibrations which spoils the brilliance led us to abandon this solution.

One is more used to coupled bunch modes excited by Higher Order Modes in cavities. Our multicell LEP type cavities with a high shunt impedance at the accelerating 352.2 MHz frequency were predicted to induce longitudinal and transverse coupled bunch instabilities. Threshold currents of the order of 60 mA were anticipated from computations. In the longitudinal plane, we are confronted with strong coupled bunch modes driven by HOMs around 500 MHz and 900 MHz when the machine is filled uniformly. Most of the time, these non-destructive instabilities occur between 90 and 100 mA in a non-systematic way and this leads to a saturation of the filling process or lifetime accidents. Extensive investigations are being made to avoid their excitation; in particular a temperature control of the cavities to keep the HOM frequency away from the beam frequency looks attractive. The present solution consists in adopting a different filling pattern. The beam is clearly very stable (both longitudinally and transversally) with respect to HOMs and the resistive wall, when filling the machine with a gap. Apparently, the 2 μs gap between the passage of the tail and the head renders the coupling impossible. We have already succeeded in storing a 125 mA beam with these conditions. HOM driven transverse instabilities were supposed to severely limit the current. Until now, we did not suffer from them.

4.2 Single bunch

Some experiments of the time of flight type require single short bunch (5 mm) operation. The instabilities are driven by the short term wake resulting from bunch interaction with the vacuum chamber broad-band impedance. On the basis of our model of impedance, no strong bunch lengthening was expected. The transverse instability threshold resulting from the classical fast head-tail scenario of coupling between modes 0 and -1 was expected at a current of about 7.5 mA.

A threshold at 2.5 mA, i.e. 2 times less than the 5 mA target was measured at zero chromaticity. Fortunately, by increasing the chromaticity to a large positive value (ξ_z = 0.7), we have been able to push the theshold up to 10 mA. The follow-up of vertical betatron frequency shift as a function of bunch current indicates that the mechanism of the instability is more complex than mode 0, -1 coupling and that the total frequency shift could be much larger than the nominal synchrotron frequency.

4.3 Few bunch mode

This mode of operation (8 or 16 bunches equally spaced) looks very attractive since it can serve simultaneously a large community of users, those requiring a high current and those running time of flight experiments. In addition coupled bunch instabilities would be much less severe and easier to feedback. For the moment, we have not pushed this mode of filling further because of a surprisingly bad lifetime (only a few hours at 100 mA) associated with a very high pressure. There are however encouraging signs that the bad vacuum conditions are due to the poor electrical contacts from the springs maintaining the RF fingers all around the ring and damaged during bakeout.

4.4 Electrons or positrons

Beam stability and lifetime could be strongly affected by ion trapping. It had been decided at the beginning of the project to start the facility with electrons and to review the need for positrons according to the experience gained worldwide in the mean time. After one year of commissioning and operation, design performance in terms of current, lifetime, emittances have been reached and even exceeded without any evidence of detrimental ion-related effect. Of course, trapping of dust or macro particles cannot be excluded in the future. For the time being however, the positron option will not be implemented.

5. CONCLUSIONS

The innovative solutions developed during the ESRF design phase to face the challenging problems raised by third-generation synchrotron light sources have been successfully applied during commissioning and beginning of routine operation. We are now ready to take up the challenges that will be raised by the next generation of sources.

The author would like to gratefully acknowledge the major contribution of many colleagues to these results.

6. REFERENCES

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