Accelerator physics trends at the ESRF

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Abstract

The operation of third generation synchrotron light sources at design target goals raises a number of challenging problems in accelerator physics. This paper will review the most recent advances made at the ESRF in some of these areas during the first two years of operation. The lattice performance is dominated by the non-linear effects induced by the requirement for a low emittance; the correction of these effects enables significant increase of the tunability and flexibility of the DBA lattice. Solutions to overcome the instability-related problems linked to the increase of intensity thresholds in multibunch and single bunch modes will be discussed. The achievement of a stability of the beam centre of mass in the micron range is a key issue for all third generation light sources. Present ESRF performances and limitations will be presented.

1. INTRODUCTION

Since the beginning of 1993, the ESRF has been operated in user service mode (USM). At present 25 beamlines are supplied with X-rays produced from insertion devices or bending magnets. In 1995, 5000 hours of operating time for users have been scheduled. In addition a provision of about 1400 hours is being made for machine dedicated time. Table 1 summarises the remarkable increase in performance achieved with respect to the design goals [1].

	design goals	served during USM	present peak performance
Intensity MB (*in mA*)	100	150	185
SB	5	5 15 *(feedback)*	25 20 *(feedback)*
Lifetime MB (*in hours*)	8	60 (100 mA)	70 (100 mA)
SB	8	30 (5 mA)	30 (5 mA)
e^- emittances H (*in nm*)	7	4	4
V	0.7	0.04	0.04
Beam stability	*10 % of size and divergence*	1 % in H 10 % in V	1 % in H 10 % in V

Table 1

This illustrates the main accelerator physics trends currently being tackled: assessing the performance of a low emittance lattice and the lifetime related issues, pushing the current to higher limits, controlling the beam position stability. This paper will review the results achieved so far.

2. LATTICE RELATED ISSUES

The successful running-in of the Double Bend Achromat lattice used for the ESRF storage ring shows that the new lattices for third generation light sources are not over-sensitive, as feared in the past. The DBA lattice has proven to be very forgiving since it was possible to run it for two years with a wrong polarity on a harmonic sextupole (this was discovered by chance at the beginning of 1994). Since target performances of the lattice have by far been achieved, flexibility and tunability issues are now of prime concern in order to satisfy future needs that may arise.

2.1 Lattice flexibility

The lattice is currently run in a mode with alternating zero-dispersion high β and low β straight sections. One attractive way to decrease the horizontal emittance [2] by a factor of 2 and consequently increase the brilliance consists of allowing a finite dispersion all around the machine (Fig. 1).

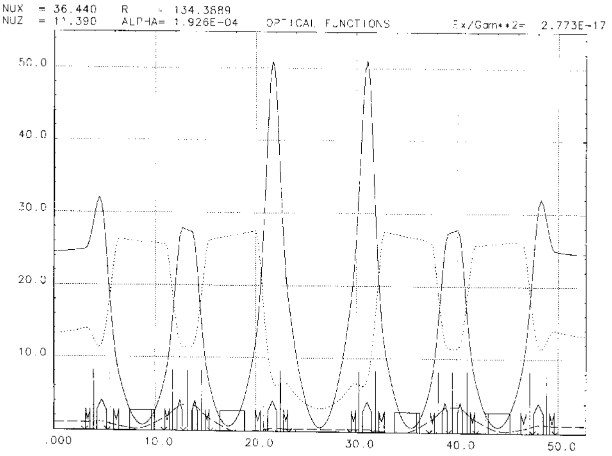

Figure 1

Low emittance settings can easily be derived by detuning the focusing quadrupole of the achromat. This new optics has been successfully tested and an emittance of 4 nm measured, compared to the 7 nm of the regular lattice, whilst keeping the 1 % coupling. The acceptance in momentum and the lifetime are comparable to those of the regular lattice. Ramping to maximum intensity of 185 mA was achieved without any sign of transverse instabilities. This low emittance version of the lattice replaced the standard version in March 1995 in multibunch.

Some of the numerous potentialities of the Double Bend Achromat lattice in terms of flexibility are currently being investigated [3], as illustrated by the examples below:

- The tuning of all straight sections to high βs or of a single straight section from high β to low β has been successfully tested on the machine. The decrease of the vertical β in all high β straight sections sections (from 12 m to 2.5 m) would ease the installation of undulators with smaller gaps than the standard 20 mm currently used. Preliminary tests are very promising.

- Up until now, all efforts to provoke ion trapping, even in the most favourable conditions of low current and uniform filling of the ring, have been in vain. In order to favour the occurrence of ion-related effects, a weak focusing version of the lattice using uniform focusing and smooth β functions (horizontal/vertical tunes of 14.4/12.8) and providing a second generation type emittance (63 nm) has also been run. 50 mA could be stored with a bad lifetime of one hour. No ion-related effects have been observed so far.

- Finally, exciting perspectives could be opened with the ESRF lattice running in a quasi-isochronous mode with even negative momentum compaction. The likely advantages of such an optics in terms of instabilities look very attractive since, among others, it is naturally stable for head tail effects, and strong sextupoles are no longer necessary.

2.2 Enlargement of the acceptance in $\Delta p/p$ and correction of resonances

Lifetime is a key issue for third generation sources, due to the much smaller emittances and insertion device gaps than machines of the previous generation. During lattice design, the achievement of a large dynamic acceptance and a low emittance took priority over longitudinal acceptance despite this being the key solution to a long lifetime, especially in the few bunch mode where Touschek related effects play a major role. Since the start of operation, the efforts to upgrade the design figure of 8 hours have been very successful thanks to the optimisation of machine tuning (careful choice of working point, optimisation of the sextupole distribution to enlarge the $\Delta p/p$ acceptance, correction of all resonance lines in the vicinity of the working point [4]). The benefits from this strategy are demonstrated in Figure 2. Despite the large vertical chromaticity, large excursion possibilities are found in the tune diagram. When compared to the initial acceptance in momentum ($-8\sigma/9\sigma$), the enlargement ($-18\sigma/22\sigma$) is spectacular.

Although the correction of resonances is not usually practised in electron storage rings, the beneficial effects are evident. For each resonance line, the correction is performed by 2 pairs of correctors arranged so as to correct the driving term in amplitude and phase and to cancel the harmonic 0. The recent implementation of a global correction algorithm based on the use of the response matrix of each type of resonance minimises the cross-talk between corrections.

The correction of the 2 coupling resonances $\upsilon_x - \upsilon_z = 25$ and $\upsilon_x + \upsilon_z = 48$ enables the coupling to be decreased by a factor of 10 down to the 1 % range. The half integer stop-bands $2\upsilon_x = 73$ and $2\upsilon_z = 23$ are perfectly mastered since these resonances can be crossed without any beam loss. Their correction almost cancels the modulation of β functions induced by focusing errors and also the blow-up of the horizontal emittance which could reach values of 8.5 to 11 nm without corrections. At present, the correction of the integer quadrupolar stop-bands is less efficient since it is impossible to go below $\upsilon_x = 36.03$ or $\upsilon_z = 11.065$.

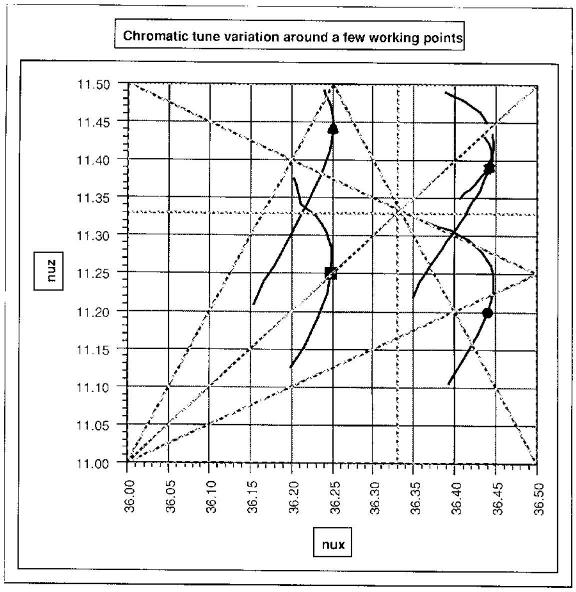

Figure 2

3. ULTIMATE CURRENT LIMITS

3.1 Multibunch case

Low instability thresholds resulting from the excitation of coupled bunch instabilities driven by the Higher Order Modes in the RF cavities effectively limit the maximum current to about 60 mA when the machine is filled in the uniform filling mode. A simple solution has been applied to nevertheless overcome the predicted threshold and go significantly beyond the 100 mA design current. It consists of adopting a non-uniform filling leaving an empty gap corresponding to two-thirds of the circumference. In addition to being less sensitive to transverse resistive wall instabilities, this filling pattern provides a stabilising effect thanks to the beam loading of the cavity at every passage of the bunch train. The induced amplitude modulation of the voltage increases with current and provides enough Landau damping via the spread of the synchrotron frequencies in the bunch train to damp coherent oscillations. Peak intensity could be pushed to 185 mA without any sign of instability thanks to this trick and the large over-compensation of the vertical chromaticity ($\xi_z = \Delta\upsilon/\upsilon)/(\Delta p/p) = 0.6$) applied to overcome resistive wall-related instabilities.

It must be emphasised that such a large positive chromaticity has obviously some impact on the optimisation of the dynamic aperture and the necessary sextupole strengths. The possibility of running the machine with natural chromaticity has been questioned. Initial tests have been carried out in that direction (20 mA stored with a negative chromaticity close to the $\xi_z = -2$ natural figure).

Another solution [5] to avoid the excitation of HOM-related instabilities consists of detuning the responsible HOMs away from the beam eigen frequencies by regulating the cavity temperatures to ±0.1 °C. This method enabled the intensity threshold to be doubled in the uniform filling mode and is currently applied when the machine is operated with 16 equally spaced bunches and cannot benefit from the beam loading damping effect.

3.2 Single bunch case

With regard to single bunch current limitations, the maximum current is limited, as predicted, by the fast head-tail instability, the threshold of which is chromaticity-dependent. As seen in Figure 3, the threshold can be pushed above 20 mA by varying the vertical chromaticity up to $\xi_z = +1$.

At zero chromaticity, the threshold for the transverse instability occurs at very low current (in the mA range) and the instability mechanism is due to the expected coupling between modes 0 and -1. At higher chromaticity, with short bunches like the ESRF ones, the interpretation of the interaction of the bunch with a broad-band impedance looks more questionable. The follow-up of the position of the maximum of the envelope of the synchrotron satellite amplitudes shows that all satellites are defocused by current and move in parallel. In particular, the maximum is not attached to a given satellite. It coincides with the line associated with m = -1 at zero current and $\xi_z = 0$ and with the line associated with m = -3 at $\xi_z = 0.6$ when approaching the threshold of 6 mA. This is far from the conventional mode coupling mechanism. At higher chromaticity, a large number of lines is involved and their follow-up is more difficult. The "damping" mechanism leading to higher thresholds still needs to be understood in detail.

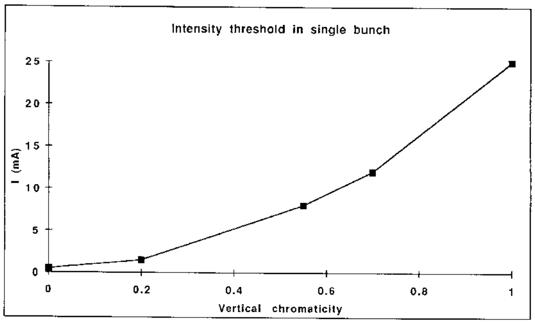

Figure 3

However such large chromaticities lead to large tune excursions associated with $\Delta p/p$ deviations and accordingly to strong Touschek lifetime limitations. The use of a Digital Signal Processing based transverse feedback [6] enables large currents to be stored with still a reasonable chromaticity ($\xi_z = 0.6$). Up to 20 mA have been stored in that mode and 15 mA delivered to users with a lifetime of 15 hours in April 1995.

Following the recent commissioning of our streak camera, a campaign of measurements of single bunch parameters (bunch length, synchrotron frequency and phase evolution as a function of current and RF voltage) is under way. The main goal is to assess the predicted absence of bunch lengthening which was associated with the broadband impedance model used to fit the longitudinal wake field of a bunch passing through the vacuum vessels discontinuities. These measurements are being performed for the regular and the low emittance lattices which (among other contrasts) differ by their momentum compaction ($2.8\ 10^{-4}$ / $1.9\ 10^{-4}$).

Similar results are found for the 2 optics with a bunch lengthening of a factor of 2.75 between 1 mA and 17 mA. This independence of the bunch length on the optics indicates that the beam remains at the turbulent regime when the current is increased and that some lengthening and widening are required to keep it stable. The energy spread is evaluated from the analysis of gap scans of the 7th harmonic of the ID6 machine undulator spectrum. Preliminary estimates confirm that some widening occurs. The objective is now to use in a self consistent analysis the updated data in order to derive a model of impedance and losses.

4. BEAM POSITION STABILITY

In order to avoid spoiling the small achieved emittances, stringent tolerances on the X-ray beam stability and reproducibility in position and angle have to be achieved (the target is set at 10 % in position and angle for both planes). Therefore, in order to stabilise the beam, the requirements on the measurement and correction of the beam position stand in the micron range for the vertical plane and are 10 times less severe in the horizontal plane.

As far as DC closed orbit control is concerned, the adopted strategy consists in correcting the orbit every 5 minutes in 3 steps: a global harmonic correction, a readjustment in position and angle in the straight sections where insertion devices are located and a retuning of the RF frequency. This brings the beam centre of mass stability to a few % of beam sizes over periods of one week. However, the stability of the sensors, i.e. the electron BPMs, is now the limiting factor in the control of beam stability, given the 0.04 nm vertical emittance routinely operated [7]. Among the many effects inducing motions of the sensors in the few micron range, contributions from the machine itself (crane, thermal effects,..) are dominating external influences (tides, water table motion,..) acting with long wavelengths. It appears that thermal effects on the vacuum vessels linked with beam intensity is the major limitation.

In AC mode, fast feedback systems can successfully be operated to minimise the beam displacements induced by vibrations amplified by the magnet girders (naturally of the order of 5 % of the beam sizes at frequencies higher than 1 Hz). However, they suffer the same limitations as the standard orbit correction, namely stability in position of the sensors, mechanical stress on the vacuum vessel, electronics drifts.

Short-term improvements are expected from the installation of new BPMs between bellows at both ends of ID straight sections. The fast feedback system using BPMs will take advantage of their better mechanical stability. Provided similar improvements on the XBPM side could be achieved, angular stability, which is the dominant limiting factor, could be significantly improved by combining BPMs and XBPMs to increase the lever arm. However, the stabilisation of the beam centre of mass to better than 10 % of beam sizes and divergences with third generation light sources vertical emittances still remain a challenging R&D issue.

5. REFERENCES

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