DYNAMIC APERTURE STUDIES AT THE ESRF

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Abstract

Machine performances in third generation light sources could be significantly affected by an insufficient dynamic aperture. At the ESRF, the dynamic aperture is mainly dominated by the strong chromaticity correcting sextupoles and by lattice imperfections. Despite the more demanding requirements induced by the evolution of the optics (reduction of the initial 7 nm emittance down to the present 3.7 nm figure, decrease of the vertical beta function in the straight sections from 13 to 2.5 m), a significant enlargement of the theoretical dynamic aperture has been achieved. In this paper, the results of dynamic aperture measurements are presented and compared with simulations. A troubleshooting method to identify unexpected transverse aperture limitations is also discussed.

1 LATTICE EVOLUTION

In 1992, the ESRF was the first third generation light source to be commissioned with the design low horizontal emittance lattice (ε_x = 7 nm). The original optics was based on a double bend achromat with alternating high and low β straight sections and zero-dispersion. Since then, major changes in the optics have been implemented:

i) with a view to providing an increased brilliance with respect to the original target, the Chasman-Green optics was modified in 1995: by detuning the quadrupoles in the achromat, a new dispersion pattern is generated with, in particular, non-zero dispersion in the straight sections. The dispersion is better balanced in dipoles, thus enabling the horizontal emittance to be reduced to 4 nm.

ii) in 1996, the vertical β in the undulator straight sections was reduced from 13 to 2.5 m to allow operation with narrow gap vessels (±4 mm vertical beam stay-clear). Figure 1 shows the optical functions of this new version of the optics which is characterized by a jump of the vertical tune by 3 integers and a 3.7 nm emittance.

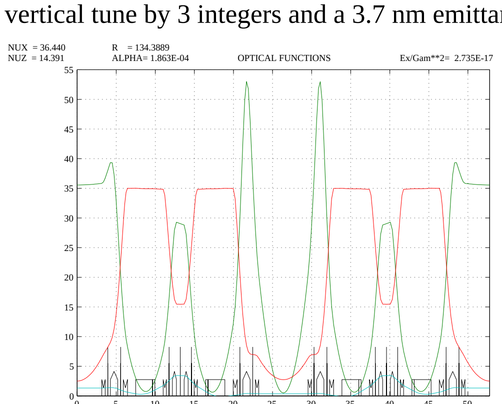

Figure 1: Optical functions of the low β_z optics

In parallel to the reduction of the horizontal emittance, the design 10 % coupling has also been significantly reduced [1]. The machine is now routinely operated with less than 1 % coupling.

2 CHROMATICITY CORRECTION AND DYNAMIC APERTURE

Due to the strong sextupoles required for chromaticity correction, this type of lattice was reputed to provide a very small dynamic aperture. Thanks to additional harmonic sextupoles and to a careful minimization of the driving terms of sextupolar resonances close to the working point and of the linear tune shifts with betatron amplitudes [2], a large dynamic aperture could be obtained.

The increased focusing implied by the evolution of the optics causes an increase in natural chromaticities (Figure 2) which leads to more demanding requirements on chromaticity correcting sextupoles. In order to cope with the resistive wall instabilities induced by the increasing number of narrow gap, stainless steel, insertion device vacuum vessels, the following chromaticity over-compensation is required: $\frac{\Delta\upsilon_x}{\Delta p / p} = 4$, $\frac{\Delta\upsilon_z}{\Delta p / p} = 7$

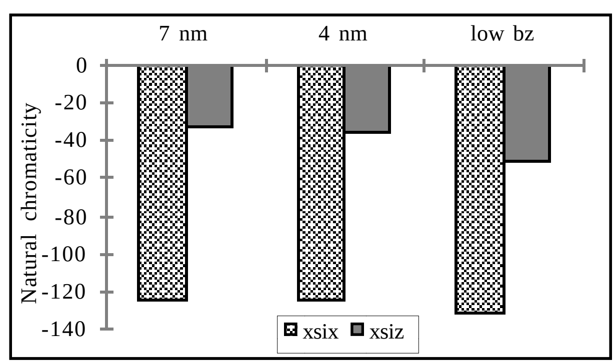

Figure 2: Natural chromaticities of the different optics

Despite the increased detrimental effects induced by these strong sextupoles, the strategy defined to optimize the dynamic aperture for on-momentum particles has proven to be very successful. A significant enlargement of the dynamic aperture of the ideal machine has been achieved, as illustrated in Figure 3. Normalized amplitudes ($x/\sqrt{\beta_x}$ and $z/\sqrt{\beta_z}$) are used to allow for relevant comparisons between the different optics. Although all sextupoles contribute to the chromaticity correction in the optics with distributed dispersion, the 4 sextupole families in the straight sections are still primarily used to enlarge the dynamic aperture, whilst the sextupoles in the arcs ensure the major part of the chromaticity correction.

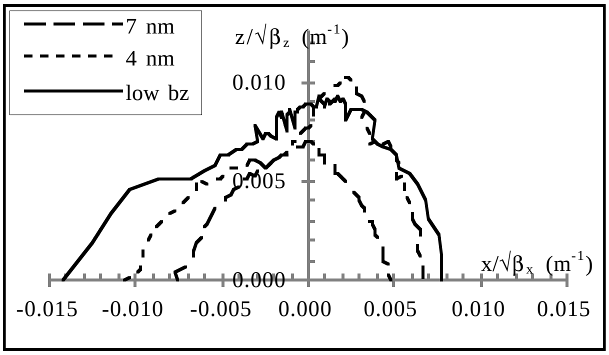

Figure 3: Comparison of the dynamic apertures of the different optics

The sensitivity to magnetic errors and resulting tolerances had been quoted during the design phase for the original DBA optics. The effects on the dynamic aperture have been updated for the low β_z optics by using measured data (harmonic content of the field of dipoles and quadrupoles, gradient errors and sorting of quadrupoles, residual 100 μm rms closed orbit after SVD correction). Results are shown in Figure 4. The more severe dynamic aperture reduction is induced by gradient errors in quadrupoles. It has already been experienced experimentally that the quadrupole sorting strategy which was optimized to minimize the detrimental effects of gradient errors for the 7 nm optics could amplify them for other optics. However the expected dynamic aperture remains larger than the physical aperture which is determined by the injection septum (on the inner side) and the narrow gap insertion device vessels (in the vertical plane).

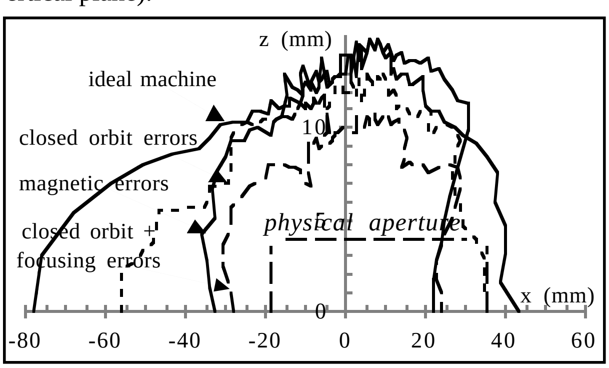

Figure 4: Effects of real errors on the dynamic aperture

3 DYNAMIC APERTURE MEASUREMENTS

3.1 Measuring technique

The horizontal aperture is measured by exciting a horizontal betatron oscillation of increasing amplitude with one injection kicker and recording the lifetime evolution versus time. As long as the amplitude of the oscillation is smaller than the aperture, no lifetime reduction should occur.

In order to allow for reliable comparisons in various intensity conditions, the initial lifetime contribution is removed as follows: $\tau = \dfrac{\tau_{I_{kicker}=0} * \tau_{I_{kicker}}}{\tau_{I_{kicker}=0} - \tau_{I_{kicker}}}$. The threshold for the lifetime characterizing the limit of stable motion is arbitrarily chosen at 10 h (compared to the normal 50 h).

The kicker current is calibrated by inserting a scraper to define a known physical aperture limitation. In order to avoid a wrong interpretation of the kicker-lifetime measurements due to a modulation of the horizontal β-function, a systematic retuning of the correction of the $2\upsilon_x = 73$ resonance is performed at each change of experimental conditions. The results of this calibration are shown in Figure 5 and in Figure 6.

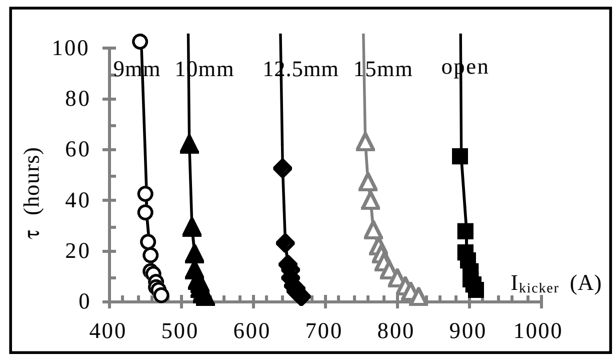

Figure 5: Kicker-scraper lifetime measurements

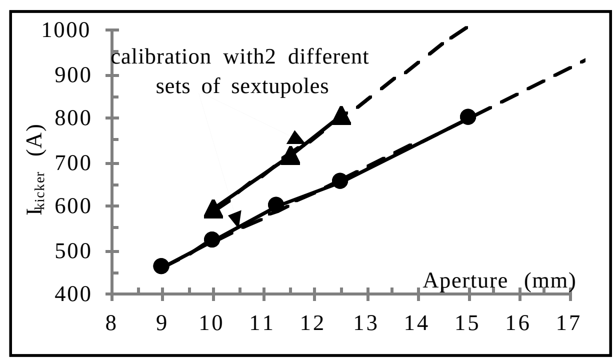

Figure 6: Results of scraper calibration

3.2 Results

The horizontal aperture measured with this technique presently stands at 16.9 mm which is about 89 % of the ideal physical aperture defined by the injection septum. Several reasons could account for the missing millimeters of aperture: resolution of the measurement, unexpected physical aperture limitation or dynamic aperture limitation. Figure 7 shows the results of comparative measurements in various limiting aperture conditions. The limited physical aperture was unfortunately induced by damaged RF fingers creating an obstacle on the beam path. The dynamic aperture limitation was intentionally generated by detuning one harmonic sextupole family. In that case the measured aperture of 9 mm is in excellent agreement with simulations. For the damaged RF fingers, a figure of the same order was found but it was difficult to reconstruct the exact position of the obstacle after venting and inspecting the vacuum vessel.

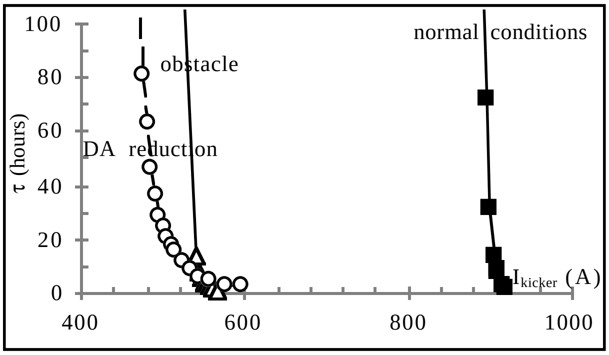

Figure 7: Horizontal aperture limitations

Detuning a harmonic sextupole family is an extreme way of reducing the dynamic aperture. More generally, depending on the sextupole tuning, large tune shifts with amplitude could be induced and bring numerous resonances on the beam path, thus limiting the transverse aperture. This is illustrated in Figure 8 which shows the tune path of particles with increasing horizontal amplitudes (and no vertical amplitude). The set #2 of sextupoles corresponds to the 16.9 mm aperture figure. For the set #1 of sextupoles, the limiting horizontal aperture is measured at 12.5 mm. Particles are lost on the 3rd order resonance $3\upsilon_x = 109$. The limiting aperture can be increased by 2 mm by moving the horizontal tune from $\upsilon_x = 36.44$ to $\upsilon_x = 36.48$, which confirms that $3\upsilon_x = 109$ is one of the sources of dynamic aperture limitation.

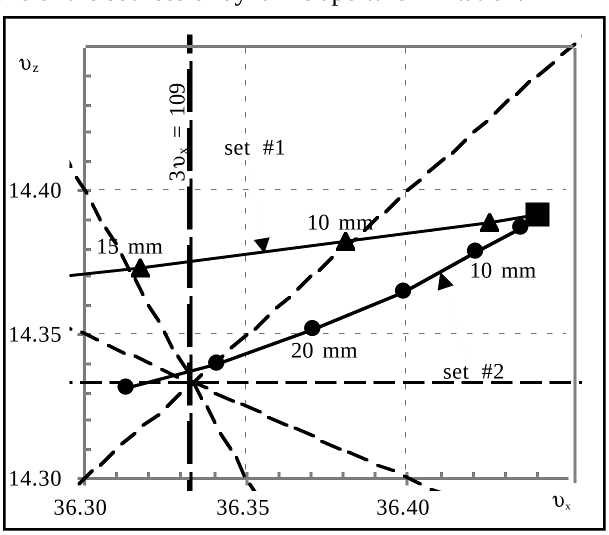

Figure 8: Tune path of particles with increasing horizontal amplitudes

4 IDENTIFYING UNEXPECTED PHYSICAL APERTURE LIMITATIONS

During the past year, we were confronted on several occasions with machine performance limitations (injection efficiency, lifetime) induced by an obstacle on the path of the beam. The problem came from broken RF fingers with fingers being splayed out in all directions.

In order to localize these obstacles, a troubleshooting method has been developed [3]. The procedure consists in mapping the machine with bumps and a kicker-induced betatron oscillation of fixed amplitude. The amplitude of the oscillation is chosen so that the lifetime is at the limit of dropping in a reference cell. Bringing the beam closer to an obstacle shoud be signed by a lifetime accident.

Obviously, setting a bump on a perfect machine induces a lifetime reduction due to detrimental effects induced by symmetry breaking (additional focusing from the off-axis path of particles in the sextupoles enclosed by the bump, detuning of the correction of resonances, dynamic aperture reduction, ...). However, since the machine has a 16-fold symmetry, bumps at homologous locations will produce identical effects. Any abnormal behaviour should indicate the presence of an obstacle. This scanning was successfully applied in straight sections. Figure 9 shows the results of investigations in even cells with a +1 mm bump and a 10 mm kicker-induced amplitude. The presence of damaged RF fingers in the suspected cells was confirmed by in-situ gammagraphies and inspection of the vacuum vessels.

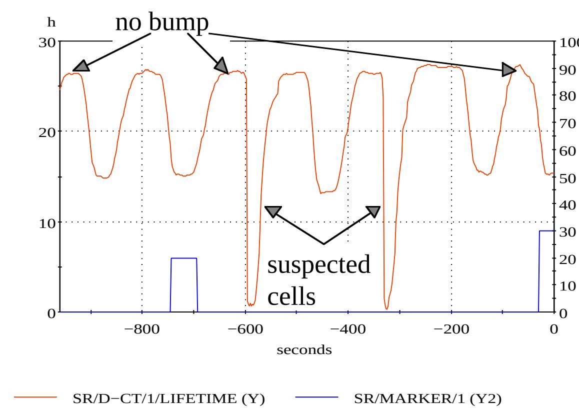

Figure 9: Search for an obstacle

5 CONCLUSIONS

Despite the increased constraints on sextupole strengths brought by the evolution of the ESRF lattice, a large dynamic aperture is obtained in simulations. Measurements yield a horizontal aperture comparable to the physical aperture. The evidence for reduced experimental apertures coming from unexpected obstacles or improper tuning of sextupoles has been demonstrated.

REFERENCES

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[2] A. Ropert, ICFA Beam Dynamics Workshop (Lugano, 1988)

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ACKNOLEDGMENTS

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