HORIZONTAL FOCUSING OPTICS AT THE ESRF

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Abstract

Third generation light sources like the ESRF are almost diffraction-limited in the vertical plane. But the horizontal photon beam size is dominated by the electron beam emittance contribution. The virtual focusing of the electron beam downstream a beamline provides the possibility of reducing the photon beam horizontal spot on the user sample. This in turn leads to a significant increase in spectral flux per unit surface. This horizontal focusing has been implemented at the ESRF by operating the lattice with modified optical functions in the middle of the corresponding straight section. The challenging issues arising from the breaking of the periodicity of the optics, as well as the results achieved so far with this new optics, are discussed in this paper.

1 BEAM SIZE MINIMISATION

The photon horizontal beam size σ_x and divergence σ'_x result from the convolution of the electron beam and single electron emission contributions. They are expressed as:

$$\sigma_x = \sqrt{\varepsilon_x(\beta_x + 2\alpha_x D + \frac{1+\alpha_x^2}{\beta_x} D^2) + D^2 \frac{\lambda}{2L}}$$

$$\sigma'_x = \sqrt{\frac{1+\alpha_x^2}{\beta_x}\varepsilon_x + \frac{\lambda}{2L}}$$

with D being the distance between the source and the sample, λ the wavelength of the radiation and L the length of the undulator

In a hard X-ray ring like the ESRF, the electron beam horizontal emittance ε_x dominates the diffraction emittance. The electron beam optical functions β_x and α_x in the middle of the straight section mainly dictate the photon beam size and divergence on the user's sample.

The spot size is usually minimised by using a beta function equal to the distance source-sample. A significant reduction in the beam size can be achieved by operating the lattice with a non-zero α_x and a large β_x in the middle of the straight section [1]. This corresponds to a virtual focusing of the electron beam somewhere downstream the beamline. For a given β_x, the minimum size is obtained for $\alpha_x = -\frac{\beta_x}{D}$

Figure 1 shows the expected reduction in beam size with the ESRF parameters (ε_x = 3.8 nm, β_x = 35 m, D = 30 m, L = 5 m, photon energy 20 keV). Besides the anticipated beam dynamics problems (chromaticity correction, dynamic aperture, sensitivity to field errors,…), achieving very large βs ($\beta_x \geq$ 100 m) would impose prohibitive gradients on the quadrupoles. More realistic β_x values ranging in the 50 m zone could provide a gain by a factor of 2 on the beam size and on the photon spectral flux.

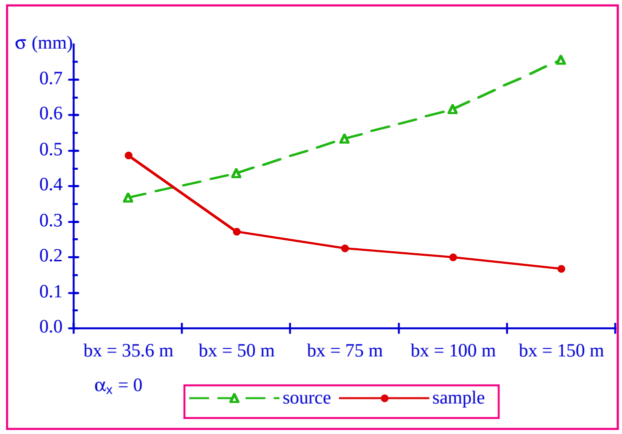

Figure 1: Horizontal rms beam sizes at the source and at the sample for various choices of β_x and α_x

2 DESIGN OF THE HFO

In order to demonstrate the effectiveness of such a scheme providing a converging beam in an undulator straight section (Horizontal Focusing Optics) [2], a new optics had to be designed, taking into account operational performance aspects as well as hardware limitations.

2.1 Tuning challenges

Maintaining the characteristics and performances of the regular optics are the primary requirements involved in the optimisation of the new optics providing horizontal focusing in one straight section. In particular the electron beam emittances and the β values at the other source points should be kept unchanged. As far as performances are concerned, breaking the 16-fold periodicity of the regular optics should favour the excitation of numerous resonances. This in turn leads to a reduction in the dynamic aperture and in the energy acceptance resulting in a lifetime reduction.

2.2 Optics optimisation

The following strategy was applied for the first-order design of the HFO:

i) Treat the straight section as a transfer line, starting at the exit of the dipole preceding the insertion with the optical functions of the regular lattice. The horizontal optical functions are fitted to desired values in the middle of the straight section and restored to regular values at the entrance of the dipole following the insertion by means of the 6 quadrupoles of the straight section.

ii) Insert the straight section in the description of the circular machine. The β-modulation introduced by the mismatch induced by the small changes in phase advances is corrected by a second fit with all family quadrupoles in straight sections.

The resulting optical functions are shown in Figure 2. The lattice functions in the middle of the modified straight section are β_x = 55 m, α_x = -1.18.

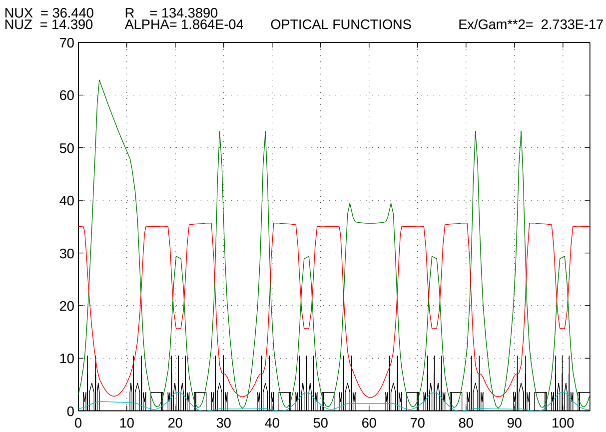

Figure 2: Optical functions for 1 / 8 of the ring

A reasonably large dynamic aperture (Figure 3) is obtained after retuning the harmonic sextupole families. The usual optimisation (enlargement of dynamic aperture and minimisation of tune shifts with amplitude) is applied to the family sextupoles. In the modified straight section, the 2 pairs of sextupoles are mainly used to cancel the driving term of the $3\upsilon_x$ = 109 resonance close to the working tune (υ_x = 36.44).

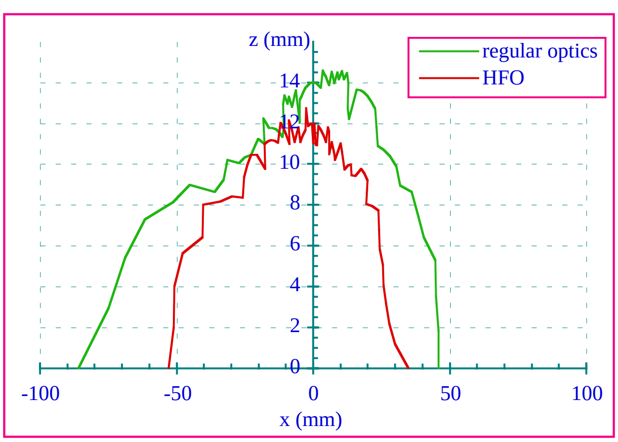

Figure 3: Comparison of the dynamic apertures of the HFO and of the regular optics

2.3 *Implications for hardware*

The new tuning implies an unsymmetrical powering of the downstream and upstream quadrupoles of the straight section concerned, as well as inverted polarities on some of them. Since ESRF quadrupoles are powered in families, tests were initially performed with in-house modified power supplies and "active" shunts allowing different currents in the downstream and upstream homologous quadrupoles [3]. Although this system provided the required characteristics, the tuning of the active shunts proved to be somewhat tricky and limited in the available intensity range. Therefore, the procurement of individual power supplies for the magnets of two straight sections had been decided.

3 EXPERIMENTAL RESULTS

Tests of a provisional scheme on the ID6 machine beamline (β_x = 50 m, α_x = -1.1, D = 30 m and "active" shunts) started mid-1998 [4]. Moving to the final configuration for the ID20 beamline (β_x = 55 m, α_x = -1.18, D = 47 m, individual power supplies) took place from May 1999 onwards [5] and since then the performances of the HFO have been fully assessed. The first use in User Service Mode is scheduled in September 2000.

3.1 *Lattice functions*

Measurements of the β-functions around the ring and in the HFO straight section have been performed using the classical method of changing the current in a quadrupole and recording the change in tune. In the ESRF case, this was realised with passive shunts installed on all quadrupoles. More recently, the operation of the turn by turn BPM system allowed faster results to be obtained. The results of both measuring techniques in the HFO straight section are presented in Figure 4. The agreement with the expected values is excellent. The β-beat along the machine is measured after correction of the half-integer resonances. As illustrated in Figure 5, there is a ±10 % modulation. This figure is comparable to the results of the regular optics and shows that the HFO insertion does not introduce any mismatch.

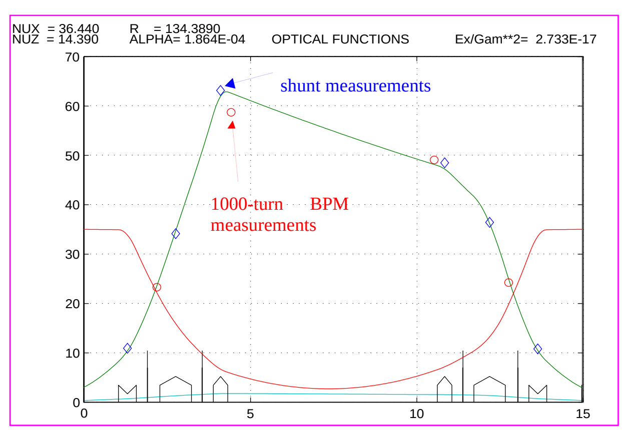

Figure 4: Comparison of measured and predicted β-functions in the HFO straight section

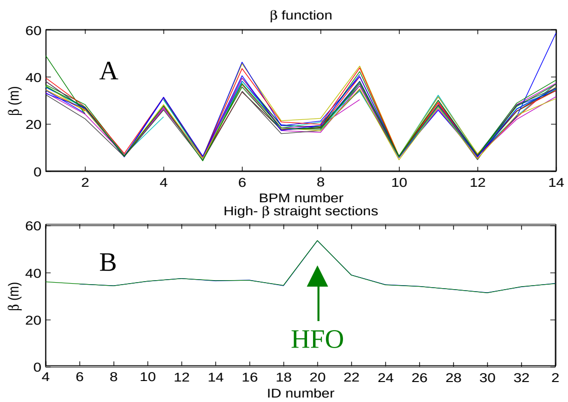

Figure 5: Horizontal β-values along superimposed periods (A) and in the centre of straight sections (B)

3.2 Energy acceptance

It is measured using 2 standard techniques. Both give similar values with respect to the regular optics.

i) Tune path with a RF frequency scan. The energy acceptance deduced from the RF frequencies leading to beam loss is very symmetrical (±3.5 %)

ii) Lifetime evolution in single bunch (3.5 mA) versus RF voltage. As shown in Figure 6, the turning point of the lifetime curve occurs around 8 MV, i.e. 3.2 %.

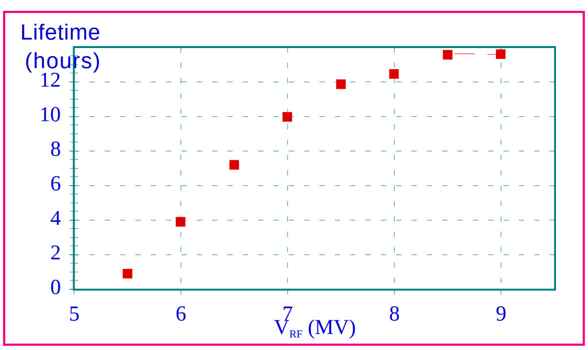

Figure 6: Single bunch lifetime evolution with RF voltage

3.3 Lifetime

The performances of the new optics in terms of emittance and lifetime have been quantified in the different ESRF filling patterns. Emittances measured with X-ray pinhole cameras are conform to expectations: ε_x = 3.8 nm, coupling less than 1 %. Lifetimes in the different filling modes are given in Table 1. The detrimental effects of breaking the lattice periodicity are very moderate, except for the single bunch. Since the single bunch tuning is very tricky, the lifetime is more likely linked to the tuning rather than to the symmetry breaking.

Table 1: Lifetime of the HFO and of the regular optics

	HFO	*Regular optics*
Multibunch (I=200 mA)	60h	65 h
16-bunch (I=90 mA)	10 h	11 h
Single bunch (I=15 mA)	4 h	6 h

3.4 Beam sizes

The gain provided by the HFO was demonstrated by measuring the characteristics of the radiation from one undulator on the ID6 machine diagnostics beamline. Beam sizes were measured at σ_x = 0.31 mm (HFO) and σ_x = 0.62 mm (regular optics). The gain in beam sizes by a factor of 2 is slightly larger than predicted. This gain is also confirmed by the comparison of spectra (Figure 7).

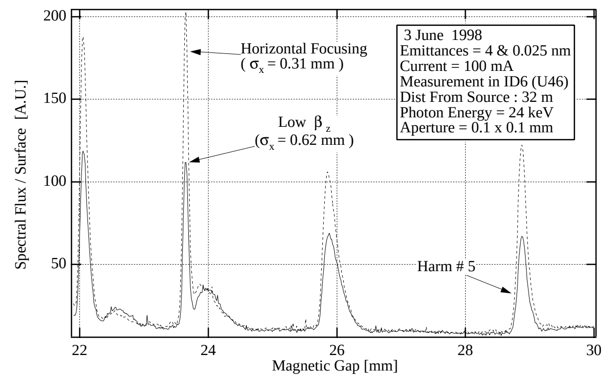

Figure 7: Comparison of spectral flux from one undulator with the HFO and with the regular optics

4 FUTURE PLANS

The successful commissioning of the Horizontal Focusing Optics shows that, by focusing the electron beam downstream a beamline in the horizontal plane, the photon flux can be considerably increased. It looks possible to break the symmetry of the machine without inducing a degradation of machine performance. This opens up a new field of lattice tuning for future machines with matching lattice functions at the undulator source points to individual beamline requirements.

In the case of the ESRF, this flexibility could certainly be added in a few more straight sections. Tests will be started soon with an optics providing converging electron beams in 2 straight sections.

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