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OPERATION IMPROVEMENTS AND EMITTANCE REDUCTION OF THE ESRF BOOSTER

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Abstract

The ESRF storage ring will be replaced by the Extremely Brilliant Source (EBS) in 2020 and the equilibrium emittance will decrease from the present 4 nmrad to 134 pmrad [1, 2]. The current injector system, composed by a linac and a synchrotron booster, will be used to inject into the new storage ring. To increase the injection efficiency in the new storage ring, three methods to reduce the horizontal emittance of the booster have been considered and tested. This paper presents the studies and achievements in terms of operation improvements and emittance reduction.

OPERATION IMPROVEMENTS

Ramped Injector Power Supply

The Ramped Injector Power Supply (RIPS) is the new power supply for the dipoles and the quadrupoles of the booster, which has been installed in 2016 to improved the shot-to-shot and long term current stability. It is based on insulated-gate bipolar transistor (IGBT) technology.

The time structured filling patterns require the cleaning of parasitic bunches. This has to be performed in the booster in case of top-up operation, to avoid blowing up the beam too frequently in the storage ring, perturbing the user operation. RIPS provides a long term tune stability of ± 0.005 which is required to achieve a good cleaning [3]. The precision of the tune adjustment also allows to couple the beam at a specific time of the accelerating cycle, for example at extraction.

In Fig. 1, two measurements of the vertical tune during the 150 ms accelerating cycle are shown.

Motorized Quadrupoles

The 39 horizontal and 39 vertical orbit correctors of the booster are not ramped in current, so they are used only to correct the orbit at low energy. In order to perform orbit corrections during the full accelerating cycle, 8 focusing quadrupoles and 4 defocusing quadrupoles have been installed on motorized supports allowing a horizontal motion of ±2 mm and a vertical motion of ±1.5 mm, with a 20 µm precision (see Fig. 2).

The movers have a single degree of freedom (horizontal or vertical motion) to decrease the complexity of the system. An independent position measurement is possible. We didn't observe any large drift of the motor positions in four years of operation: only 2 of the 12 motors have been recalibrated because the measured position drifted by more than 50 µm.

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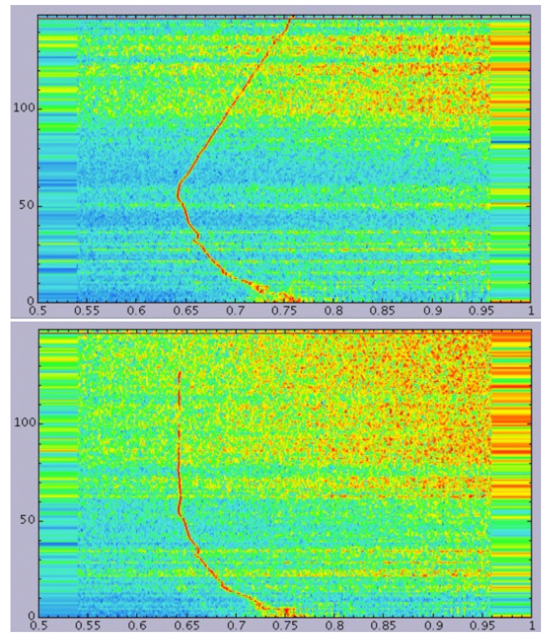

Figure 1: Fractional part of the vertical tune of the booster (x axis) as function of time in ms (y axis) during the accelerating cycle. In the top figure, at extraction time the vertical tune crosses the horizontal at 0.75. In the bottom figure, the vertical tune is kept constant at 0.65 after 60 ms.

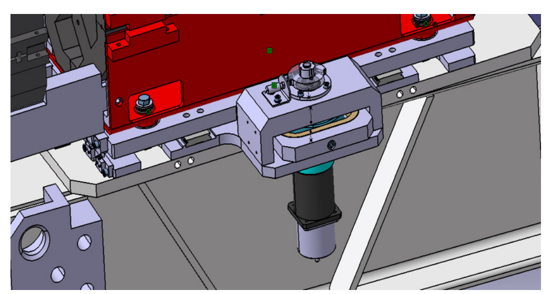

Figure 2: Horizontal mover.

In Fig. 3, an example of orbit correction with the movers is shown. The closed orbit distortion has been corrected to an rms value of 0.87 mm in horizontal and 0.67 mm in vertical from the uncorrected values of 1.2 mm and 1.1 mm.

Orbit Correction in Transfer Line 2

The transfer line 2 (TL2) connects the booster to the storage ring. It is 55 m long, it has 5 dipoles and 14 quadrupoles. An automatic orbit correction application has been installed, based on 7 striplines and 2 BPM for orbit measurement and

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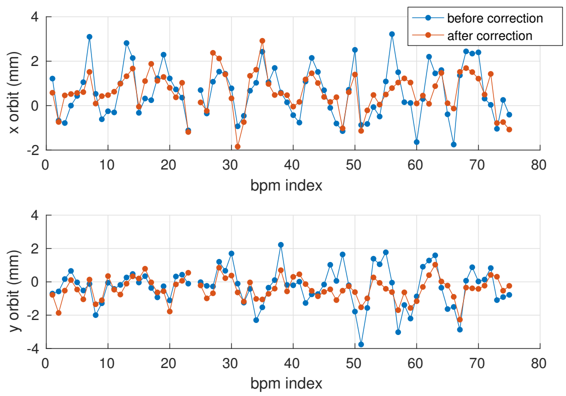

Figure 3: Horizontal and vertical orbit distortion before and after correction with the quadrupole movers.

17 correctors (8 horizontal and 9 vertical). The residual orbit after correction is about 200 µm, which allows to change the TL2 optics at constant orbit.

EMITTANCE REDUCTION

In order to have a good injection efficiency in the EBS, the horizontal emittance of the booster has to be reduced. Three solutions were found to reduce the horizontal emittance:

- optimized tune working point
- off-energy operation
- fully coupled beam at extraction

Tune Working Point

The ESRF booster has a simple FODO lattice, with three zero-dispersion straight sections, which are used for the injection, the extraction and for the RF cavities.

The lattice has two families of quadrupoles and two families of sextupoles, so there are only two degrees of freedom to change the linear optics.

From a tune scan performed with AT [4] [5], we can see that with a one unit higher horizontal tune the equilibrium horizontal emittance decreases from the 120 nm of the nominal working point (where $\nu_x = 11.75$ and $\nu_y = 9.65$) to about 100 nm (see Fig. 4). Tune values with smaller emittance have been rejected because they had too weak defocusing quadrupoles, which are used to deflect the extracted beam, or because the dynamic aperture was too small.

Off-Energy Operation

The length of the new storage ring will be 41 cm shorter than the present, so the RF frequency will be 172 kHz higher. The booster and the storage ring have to share the same RF source, so a full realignment of the booster will be needed.

To reduce the equilibrium emittance, the booster will operate off-energy by realigning it with a circumference longer than the one matched with the storage ring RF frequency. In this configuration, the beam will follow a dispersive orbit and the quadrupoles will produce some anti-bending effect, contributing to reduce the equilibrium horizontal emittance. The off-energy operation has the same effect of a Robinson

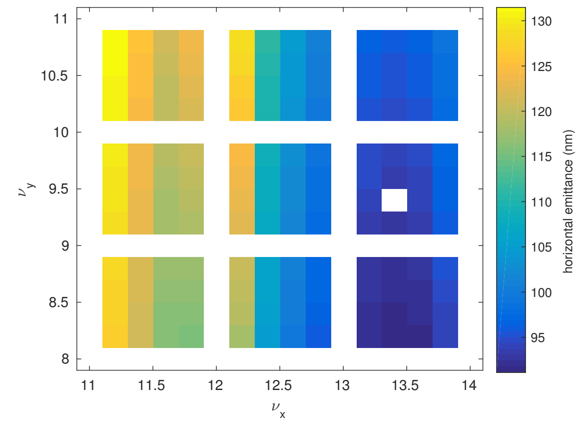

Figure 4: Equilibrium horizontal emittance for different tune working points of the ESRF booster.

Wiggler in the machine: the horizontal damping partition number increases and the longitudinal decreases. Therefore, the longitudinal emittance is increased with the off-energy operation.

It has been chosen to operate the booster with 40 kHz larger RF frequency, to decrease the horizontal emittance by 38 % increasing the bunch length by 12 % and having an rms horizontal orbit distortion of 13 mm. By increasing the RF voltage from 8 MV to 11 MV, the bunch length at 40 kHz with the higher tune will reduce from 22.5 mm to 17.9 mm.

In Fig. 5, the equilibrium emittance and bunch length as a function of frequency deviation are shown for the two working points. In Fig. 6, the value of the horizontal partition number (J_x) as a function of the RF frequency variation is shown for the two working points.

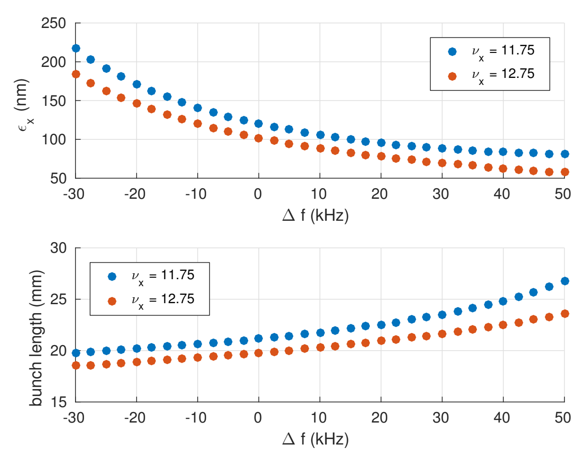

Figure 5: Equilibrium horizontal emittance (top figure) and equilibrium bunch length (bottom figure) as a function of change in RF frequency for the two tune working points.

Full Coupling

The third method to decrease the horizontal emittance for the EBS injector is to extract a fully coupled beam (round beam), by crossing the tunes at the extraction time. In this

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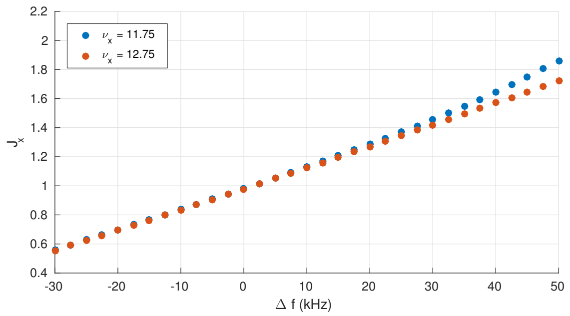

Figure 6: Horizontal damping partition number as a function of change in RF frequency for the two tune working points.

case, the vertical emittance increases. Simulations have shown that the injection efficiency in the EBS improves by decreasing horizontal beam size, even increasing the vertical, so a round beam or a full emittance exchange , as proposed in [6], would be beneficial.

The horizontal and vertical emittance of the round beam (ε_{round}) depends on the values of the horizontal and vertical damping partition numbers (J_x and J_y) with the following formula:

$$\varepsilon_{round} = \frac{J_x}{J_x + J_y} \varepsilon_x \tag{1}$$

where ε_x is the equilibrium horizontal emittance without coupling. J_y is 1 also with the off-energy operation.

When the RF frequency is increased by 40 kHz, the emittance reduction due to the coupling is not a factor 2, but approximately a factor 1.6.

EMITTANCE MEASUREMENTS

Emittance measurements in the booster have been performed in four different settings:

- nominal linear optics, without coupling (setting 1);
- nominal linear optics, with full coupling (setting 2);
- horizontal tune increased by one unit, RF frequency increased by 40 kHz, without coupling (setting 3);
- horizontal tune increased by one unit, RF frequency increased by 40 kHz, with full coupling (setting 4).

The emittance is measured by measuring the beam size from the synchrotron radiation and using the beta functions and dispersion of the perfect model. Examples of beam images are shown in Fig. 7 (setting 1) and Fig. 8 (setting 4).

The results of the emittance measurements of the four settings and their theoretical values are reported in Tab. 1. The measurement errors come from the uncertainty of the gaussian fit and from a horizontal β-beating of 4 % rms. The β-beating value is obtained simulating the magnet misalignments and confirmed by fitting the orbit response matrix.

The reason of the disagreement between the theoretical value of the emittance for the nominal case and the measured value is not clear, however the measured emittance reduction

Table 1: Theoretical values of horizontal emittance and bunch length and measurements of horizontal emittance.

Setting	ε_{x-theo} (nm)	σ_z (mm)	ε_{x-meas} (nm)
1	120	21.1	147 ± 7
2	60	21.1	97 ± 5
3	63	22.5	75 ± 4
4	39	22.5	54 ± 3

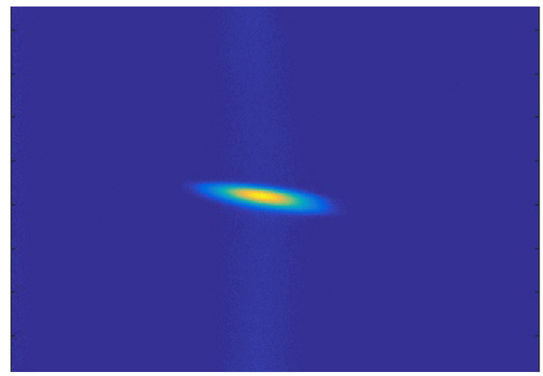

Figure 7: Beam size image with nominal booster setting (setting 1).

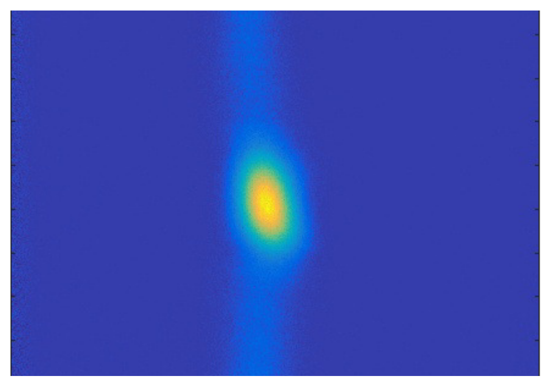

Figure 8: Beam size image with maximum emittance reduction (setting 4).

factor from setting 1 to setting 4 is compatible with the factor 3 expected.

Emittance measurements in the transfer line with the method of the quadrupole scan [7] have been also attempted, but without successful results.

CONCLUSION

The new Ramped Injector Power Supply and the installation of the quadrupole movers improved the performances of the ESRF booster in term of tune stability and orbit control.

The horizontal emittance of the booster will be decreased to improve the injection efficiency in the EBS. Three different methods to do it have been successfully tested. The emittance reduction measured in the booster is compatible with the factor 3 expected from simulations.

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