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OPERATION OF THE ESRF BOOSTER FOR THE EBS STORAGE RING

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Abstract

The Extremely Brilliant Source (EBS) has replaced the old ESRF Storage Ring (SR) during the 2019 one-year shutdown. The injector chain, composed of a Linac, a booster synchrotron, and two transfer lines, was not replaced. Nevertheless, some major hardware upgrades were anticipated prior to the long shutdown to ensure its long-term reliability. The shutdown interventions focused on reducing the machine circumference to cope with the new RF frequency of the SR. The status of the upgraded booster will be presented with a focus on the strategy used to lower horizontal emittance especially via emittance exchange.

INTRODUCTION

The ESRF booster has three FODO arcs and three straight sections with zero dispersion: one for injection, one for extraction and one for RF cavities. Its design emittance is 120 nm [1]. Some hardware upgrades were done during the last years of operation [2] to increase its reliability and flexibility.

The EBS storage ring [3, 4] has been installed in the 2019 long shutdown and fully commissioned in 2020 [5].

The new storage ring is 40 cm shorter than the old machine, so the booster length also had to be reduced to use the same RF frequency. All the booster girders were displaced by 17.3 mm towards the center of the ring, to reduce the booster length by 10.8 mm. In order to reduce the booster equilibrium emittance from 120 nm to 85 nm, we decided to operate the booster with a 40 kHz higher RF frequency, which corresponds to an off-energy operation of about δ=−1.4 %. It was planned to also change the horizontal tune working point from $\nu_x = 11.75$ to $\nu_x = 12.75$ to further reduce the horizontal emittance from 85 nm to 63 nm, but this is still under study and not yet used in operation.

This paper will describe how we operate the booster off-energy, with different features used to optimise the charge captured, and the horizontal emittance at extraction, that has a large impact on injection efficiency in the storage ring. The implementation of an emittance exchange scheme, and the corresponding results will be described in details.

Booster main parameters are summarised in Table 1.

OFF ENERGY OPERATION

The RF frequency mismatch of 40 kHz allows to reduce efficiently the horizontal emittance to the cost of a larger longitudinal emittance and a more complex beam dynamics and beam tuning. Once off-energy, the beam follows a dispersive orbit, with a peak of 12 mm where the dispersion is the highest.

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Table 1: ESRF Booster Parameters

Parameter	Value
Length	298 m
Energy	0.2 GeV to 6 GeV
Tunes (h/v)	11.75/9.65
RF	4 LEP cavities
RF voltage	0.25 MV to 9 MV
RF frequency	352.2 MHz
Frequency mismatch	40 kHz
Repetition rate	4 Hz
Emittance @6 GeV (h/v)	85/5 nm rad
Energy mismatch	dp/p=-0.014
Momentum compaction	9.1E-3
Harmonic Number	352
Charge in few bunch	1 to 5 bunches of 0.1 nC
Charge in multibunch	300 bunches of 5 pC

Going off axis in the setupoles has an impact on the closed orbit but the largest effect is on the betatron tunes. Therefore tune and chromaticity control during the acceleration cycle cannot be considered independently. Beta functions modulation up to 20% is also induced by going off axis in sextupoles.

Betatron tunes are monitored along the cycle and can be adjusted by tuning the ramping waveform of the power supplies feeding the quadrupoles, allowing tune control along the whole cycle. Sextupoles ramping parameters are a compromise between keeping chromaticity close to zero in both planes, to mitigate collective effects, and optimisation of the transverse dynamic aperture, to ease capture of the beam coming from the linac.

Orbit steering had to be adapted to take into account a non zero reference orbit to be corrected to. The orbit control in the booster is handled by a set of 38 DC steerers in both planes and 12 motorised quadrupole supports used to translate them [2]. Offset quadrupoles act as ramped correctors and provide orbit correction all along the cycle, especially at high energy where the steerers are inefficient. Operation experience with the motorised supports show a great reliability of the mechanics and a precision for the positioning in the order of 20 µm. Installing more of these devices is under discussion.

The closed orbit correction software has been adapted in order to provide visualisation of the reference closed orbit, the measured one as well as the difference between the two, that is what needs to be corrected. Figure 1 shows the high level application for closed orbit correction, able to trigger correction at injection and extraction energy using both steerers and motorised quadrupoles independently or combined.

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Figure 1: Orbit correction application layout.

CAPTURE OPTIMISATION

Careful optimisation of the capture of the beam coming from the linac has been performed. Once closed orbit is corrected, the trajectory of the injected beam is tuned via the steerers of the transfer line and the injection septa. The observable to minimize is the size of the beam image as seen from a visible light monitor that integrates betatron oscillations of the injected beam [6].

For the longitudinal plane, optimal RF voltage at injection is a compromise between lowering the RF voltage to get as close as possible from an adiabatic capture and keeping the RF voltage high enough to mitigate beam loading effects in the cavities.

Two additional cavities have been installed in 2017, in addition to the two initial ones, to enhance the redundancy and maximum voltage provided by the RF system. The voltage in each cavity has consequently been reduced making them more sensitive to the transient beam loading induced by the injected beam. The RF system working point at injection is tailored to the booster operation mode, with different settings depending on whether the booster has to accelerate a few high charge bunches, with low average current, or a uniform train of low intensity bunches but with high average current as described in Table 1. For this last mode of operation, beam loading is higher and RF voltage has to be enhanced at injection.

Thanks to the BPM system upgrade done in 2015 [7], turn-by-turn (TBT) data is available. By measuring horizontal TBT position on a BPM located in a dispersive section, it is possible to visualise synchrotron oscillations induced by longitudinal mismatch of the injected beam. Matching is performed by tuning the injection energy and RF phase of the injected beam to reduce these synchrotron oscillations as presented in Fig. 2.

Capture efficiency of the beam coming from the transfer line is between 50 and 60 %. Improvements are still foreseen in the near future, especially on orbit control. The present orbit reading does not correct the BPM non linearity at large amplitudes, while the beam is strongly off axis. The induced error is of 10 % at 10 mm. Also it is planned to seek for a better tuning of the RF system to make it less sensitive to beam loading transients. It is also foreseen to

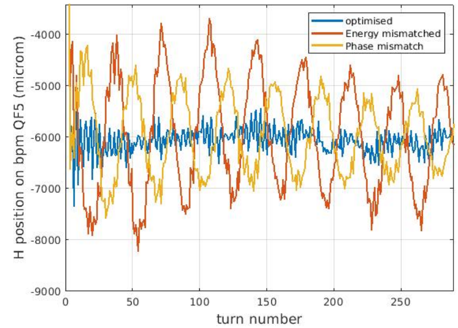

Figure 2: Synchrotron oscillations of the beam entering the booster for three different cases. Blue: optimised, yellow: phase mismatch, brown: energy mismatch.

optimise the linac to booster transfer line optics. A better matching of linear parameters can most probably be found especially for dispersion. Since a position measurement is now available at the end of the line, the dispersion can be measured and minimised at the line exit. Properly matching the zero dispersion of the injection section will minimise orbit variation linked to linac energy fluctuations.

EMITTANCE EXCHANGE

Emittance exchange in the booster synchrotrons to reduce horizontal emittance and improve injection efficiency was proposed by Kuske in 2016 [8] and successfully tested at SLS using the fast tune crossing technique [9].

Simulations for the ESRF EBS case showed that a smaller horizontal emittance, even with a higher vertical emittance, would improve injection efficiency, as shown in Fig. 3.

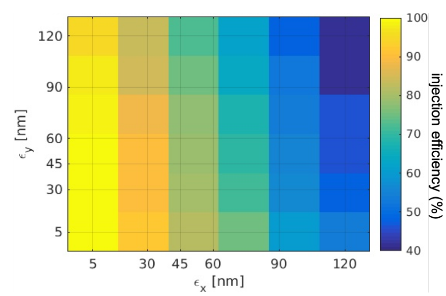

Figure 3: Injection efficiency in the EBS SR as a function of horizontal and vertical emittance of the injected beam.

The horizontal/vertical emittance exchange has been studied in simulation, to understand if the specifications of the booster ramped power supply were sufficient to have a full emittance exchange. Three cases have been simulated: a fast vertical tune change, a fast horizontal tune change and both tunes changed simultaneously. The vertical tune change was found to be the most effective. The multiparticle simulations have been performed with matlab Accelerator Toolbox [10], using 5000 particles for 12000 turns, including radiation damping and quantum diffusion.

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The duration of the tune crossing has been scanned, from a minimum of about 10 turns to 4000 turns. The booster transverse damping time is about 1500 turns. The optimum tune crossing duration is between 500 and 1000 turns (Fig. 4). Figure 5 shows the horizontal and vertical emittance when the tune crossing is too fast, optimal or too slow.

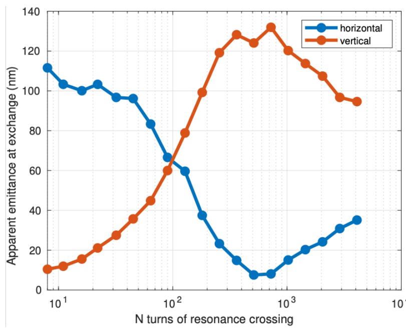

Figure 4: Minimum horizontal emittance and maximum vertical emittance after emittance exchange as a function of duration of the tune crossing.

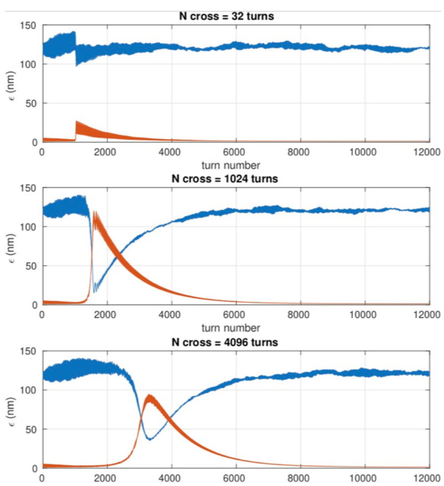

Figure 5: Horizontal and vertical emittance after too fast, optimal and too slow tune crossing.

In order to change the vertical tune by 0.1, the strengths of both the quadrupole families have to change by about 0.5% in about 500-1000 turns, which is 500-1 000 µs for the ESRF booster. The required current change is feasible with the ESRF booster ramped power supply and has been tested. Tune measurements during the acceleration cycle are shown in Fig. 6.

The beam size in the booster during emittance exchange has been measured with a visible light camera taking light from a dipole with low horizontal dispersion. Different quadrupole waveforms have been used, where the tune crossing time was 3 ms, 2 ms, 1 ms and 0.7 ms. A very slow tune crossing done in about 30 ms has also been tested. In Fig. 7, the measured horizontal and vertical beam sizes in arbitrary units are shown as function of time from the injection in the booster. With the best waveform, the horizontal beam size

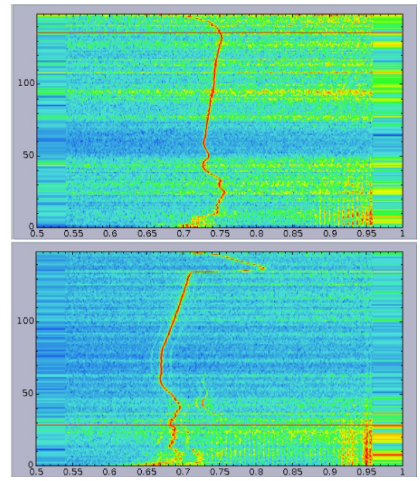

Figure 6: Horizontal (top) and vertical (bottom) tunes for emittance exchange. The vertical tune changes by about +0.1 in 0.7 ms at extraction time (about 140 ms).

is reduced to 60% of the initial one, while with full coupling (obtained with slow tune crossing) the beam size is reduced to 85%. Vertical beam size is increased by about a factor 3.

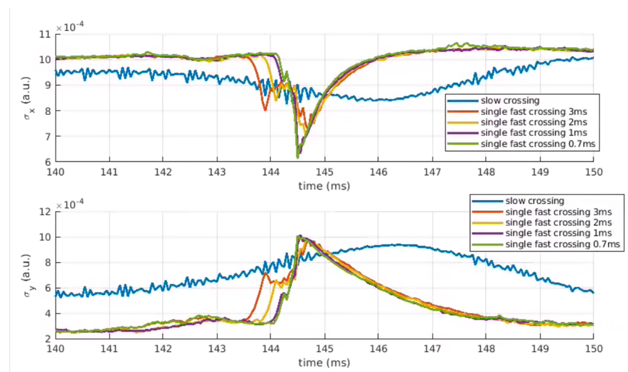

Figure 7: Beam size for different emittance exchange conditions.

In order to maximize the injection efficiency, the emittance exchange has to be synchronised with the booster extraction. We can move the tune crossing by about ±200 µs changing the vertical tune with a very small change of the defocusing sextupoles.

With emittance exchange, the injection efficiency from the booster to the storage ring is about 5-10% higher, reaching 85%. Alternative emittance measurements, with and without exchange, have been performed using the quadrupolar scan technique in the transfer line 2. The results are shown in [11].

CONCLUSION

The ESRF booster has been realigned to be compatible with the new RF frequency of the EBS and with the off-energy operation, that allowed to reduce horizontal emittance. Transverse emittance exchange has been also tested and it is used in user operation, allowing to reach 85 % booster to storage ring injection efficiency.

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