EVALUATION OF THE PERFORMANCES OF A NON-LINEAR KICKER INJECTION SCHEME AT THE EUROPEAN SYNCHROTRON RADIATION FACILITY

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Abstract

In the scope of the upgrade of its injection systems, the ESRF-EBS has decided to replace the classical 4-kicker bumps injection scheme by a Non-Linear Kickers (NLK) injection scheme in order to achieve a fully transparent injection into the storage ring and minimize the perturbations still seen by the beamlines users. This paper presents beam dynamics simulations evaluating the performance of this new scheme including robustness against errors from the transfer line pulsed elements between the booster synchrotron and the storage ring, optics mismatch and compensation of the non-linear kicker field using a sextupole magnet to improve efficiency in realistic operation conditions. Benefits from a booster light upgrade and full energy linac upgrade will also be presented.

INTRODUCTION

In 2020, the European Synchrotron Radiation Facility (ESRF) completed the upgrade of its storage ring with the commissioning of the Extremely Brilliant Source (EBS) [1]. While the lattice was fully redesigned to significantly increase the electron beam brightness, the injection systems were intentionally kept unchanged to simplify the commissioning of the new machine.

Injection into the EBS storage ring currently relies on a conventional four-kickers bump scheme, in which the stored beam orbit is locally displaced. Although robust and simple to operate, this scheme introduces residual orbit distortions due to imperfect bump closure. These perturbations lead to emittance growth and can disturb user operation even with minimization scheme implemented [2]

Such limitations are no longer compatible with the performance requirements of the EBS, motivating an upgrade of the injection scheme. A solution based on NLKs [3] is under consideration, aiming at fully transparent injection with minimal perturbation to the stored beam and also preserving a high injection efficiency. [4]

To meet the EBS injection requirements, three NLKs will be installed in the injection straight section. Each device is 30 cm long and operates at a peak current of 6.9 kA, providing a total kick angle of 12.2 mrad. Each NLK generates an octupole-like magnetic field with a field-free region at its center. The stored beam is aligned within this region and remains unaffected, while the injected beam, horizontally offset by about 8 mm, experiences a strong nonlinear field that drives it into the ring acceptance. This 8 mm horizontal offset is permitted thanks to the increase of the horizontal acceptance at the injection point done by increasing the β_x to 29 m. at this location.

Figure 1 shows a 3D representation of the proposed NLK system based on the SOLEIL design [5–7], while Fig. 2 presents the corresponding pulsed magnetic field profile.

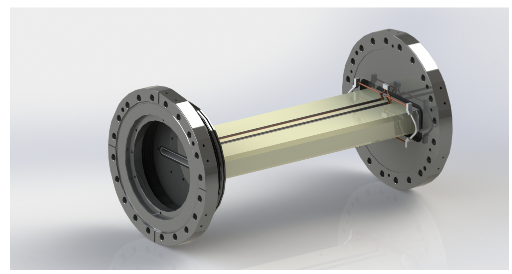

Figure 1: 3D representation of an NLK.

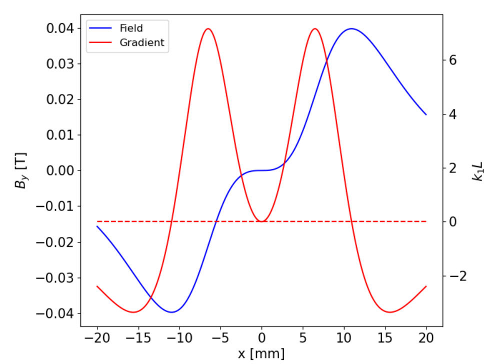

Figure 2: Magnetic field (blue) and gradient (red) generated by an NLK.

ROBUSTNESS TO PULSED ELEMENTS ERRORS

In the ESRF injector chain, the transfer line TL2 transports 6 GeV electrons from the booster synchrotron to the storage ring. Figure 3 shows the corresponding optics functions. Particular care has been taken in the optics matching to minimize the dispersion at the injection point (s = 65 m).

Constraint on the value of the dispersion at the sextupole location (green block on Fig. 3) has also been taken into acccount (details about this method will be given in this paper). In order to enhanced the action of the sextupole in the compensation scheme of the non-linear field, the dispersion at this point must be equal to 0 m. Several round of matching

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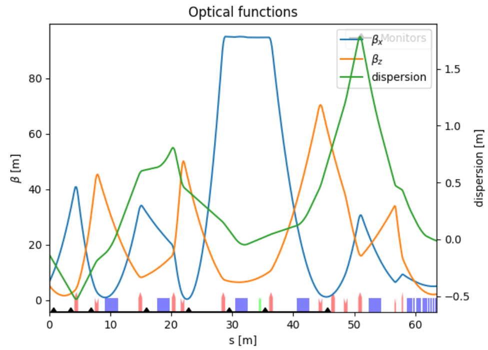


Figure 3: Optics functions of TL2.

of the optics have been done with an acceptable configuration found but a precise study and optimization needs to be done.

Beam extraction from the booster and injection into the storage ring rely on several pulsed elements. First pulsed magnets are located actually in the booster synchrotron in order to extract the electrons from the booster to the transfer line, three septa magnets are also located at the end of TL2 to give the right orbit to injection beam [8]. These devices are subject to jitter, which can induce orbit distortions along TL2. Simulation studies have been performed to evaluate the robustness of the injection process against such errors and to ensure high injection efficiency over a sufficiently large horizontal phase-space area.

Orbit distortions were modeled through 2D phase-space scans, simultaneously accounting for position and angle offsets induced by the pulsed elements. Simulations were carried out using `pyAT` [9], assuming the nominal beam parameters of the booster, summarized in Table 1. The beam has been tracked during 2000 turns.

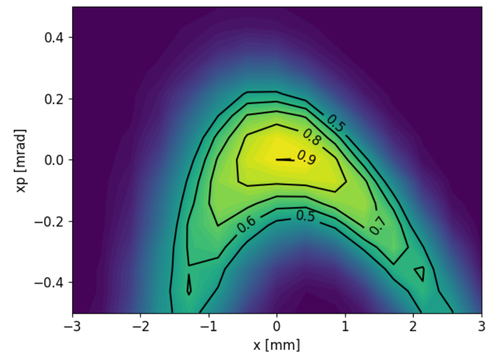
Table 1: Beam Parameters of the Current ESRF Booster Synchrotron

Beam parameters	**Value**
Emittances $\epsilon_{x/y}$	30/60 nm · rad
Bunch length δ_l	20 mm
Energy spread δ_e	1.2×10^{-3}

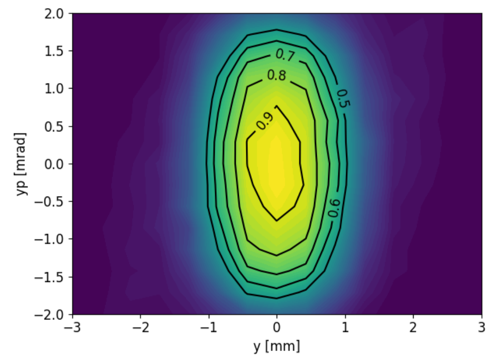
Figure 4a shows the injection efficiency map in horizontal phase space. The efficiency region exhibits a characteristic sextupolar shape, reflecting the nonlinear magnetic field experienced by the injected beam at an offset of 8 mm from the stored beam position. The region with efficiency above 90% remains limited, indicating strong sensitivity to orbit distortions originating from TL2.

Reducing jitter in the TL2 pulsed elements is intrinsically challenging due to their stochastic nature. An alternative approach is to improve the beam parameters to reduce sensitivity to these perturbations. This parallel project to the NLKs one, will be achieved through a modification of the booster lattice aimed at reducing the transverse emittances, as described in [10].

A reduction of approximately 10% in both horizontal and vertical emittances can be obtained as well as a reduction of



(a) Horizontal phase space



(b) Vertical phase space

Figure 4: Injection efficiency maps without sextupole compensation and present booster emittances.

the bunch length, while maintaining the same energy spread. New simulations incorporating these improved parameters have been performed to assess their impact on injection efficiency.

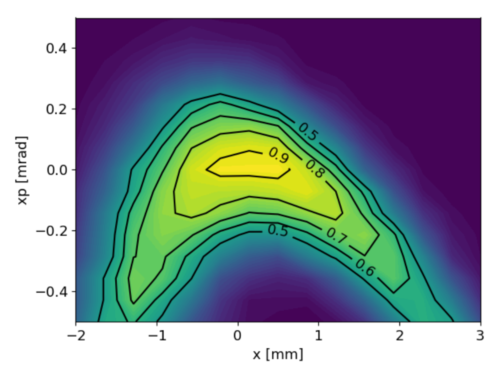


Figure 5: Horizontal phase-space injection efficiency map with improved booster performance.

As shown in Fig. 5, the area with injection efficiency above 90% is significantly increased. This demonstrates that the booster upgrade is an important enabler for efficient operation of the NLK injection scheme.

SEXTUPOLE COMPENSATION OF THE NLK FIELD

Figures 4a and 5 show that the injection efficiency is strongly influenced by the magnetic field shape at the stored beam location. The observed sextupolar component can be mitigated to enlarge the region of high injection efficiency. For this purpose, a sextupole installed in TL2 can be used to compensate the nonlinear field generated by the NLKs. Nevertheless this compensation can work only with strict constraints on the phase advance at the sextupole which must be equal to $k\pi$ in order to cancel the sextupole components of the field where the beam coming from TL2 will be injected. The dispersion at the sextupole location must also be equal to 0 m in order to enhanced the compensation effect.

Preliminary studies have been performed to evaluate the feasibility of this compensation scheme. The simulations assume the improved beam parameters corresponding to the booster light upgrade, in order to reduce sensitivity to other error sources such as jitter in the TL2 pulsed elements.

Although further optimization of the sextupole strength and phase advance at its location is required, first results indicate that this compensation scheme improves the injection process. Simulation results are presented in Fig. 6.

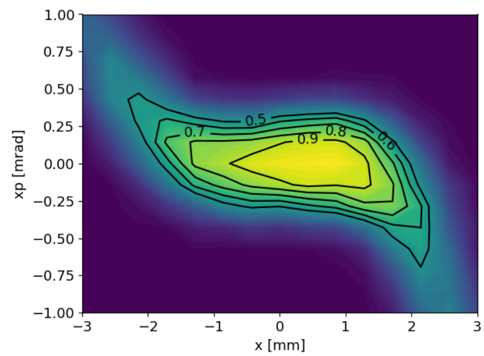


Figure 6: Horizontal phase-space injection efficiency map with booster upgrade and sextupole compensation.

The injection efficiency map exhibits a modified shape due to the sextupole compensation. With the sextupolar component of the NLK field effectively reduced, the dominant contribution becomes octupolar, leading to the observed distribution. In addition, the region with efficiency above 90% is significantly increased compared to Figs. 4a and 5, confirming the potential of this approach.

INJECTION PERFORMANCE WITH A FULL ENERGY LINAC

In the longer term, ESRF is considering replacing the current injectors chain, composed of a linac and a booster synchrotron, with a full-energy linac [11]. Such an upgrade would significantly improve the beam dynamics at injection and increase the accessible injection efficiency area.

The proposed full-energy linac is expected to deliver beam parameters summarized in Table 2.

Table 2: Beam Parameters of the Foreseen 6 GeV Linac

Beam parameters	Value
Emittances $\epsilon_{x/y}$	1/1 nm · rad
Bunch length δ_l	1 mm
Energy spread δ_e	1.2×10^{-3}

The strong reduction in horizontal emittance facilitates matching of the injected beam within the storage ring dynamic aperture. As a result, the sensitivity to orbit distortions induced by TL2 pulsed elements is significantly reduced, leading to improved injection robustness, as illustrated in Fig. 7 where the beam has been tracked during 2000 turns.

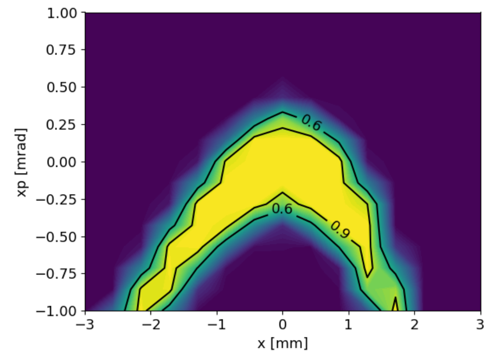


Figure 7: Horizontal phase-space injection efficiency map with a full-energy linac.

Although the overall shape of the injection efficiency map remains influenced by the sextupolar component of the magnetic field, the region with efficiency above 90% is substantially enlarged across the phase space.

CONCLUSION

The performance of the proposed NLK-based injection scheme has been evaluated through simulations including sensitivity to pulsed-element errors and optics mismatches at the storage ring injection point. The results confirm that the scheme meets the expected performance; however, it would significantly benefit from a booster light upgrade and, in particular, from sextupole compensation of the nonlinear NLK field. These improvements increase the region of phase space where the injection efficiency exceeds 90%, thereby easing the injection process.

A careful optimization of the transfer line optics between the booster synchrotron and the storage ring remains necessary to achieve an adequate phase advance between the compensation sextupole and the injection point. These studies are still on going.

Preliminary studies assuming beam parameters from a full-energy linac have also been carried out. As expected, the NLK-based injection performs even more robustly in this scenario, even without sextupole compensation. Overall, these results indicate that a full-energy linac injector chain would provide significant benefits in terms of injection efficiency and beam dynamics performance at ESRF.

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