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A FLEXIBLE INJECTION SCHEME FOR THE ESRF-EBS

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Abstract

The ESRF-EBS storage ring light source started commissioning in 2019 and successfully resumed users operation in 2020. Due to the smaller emittance and consequently reduced Touschek lifetime frequent injections are required that can potentially disturb beam lines experiments. In addition, operating the machine with low β straight sections and reduced insertion devices (ID) gaps are considered as future upgrades, therefore reducing the vertical aperture of the machine. Alternatives to the standard off-axis injection scheme allowing for efficient injection in reduced apertures with minimized perturbations are explored. A flexible layout for potential integration in the ESRF-EBS lattice is proposed.

INTRODUCTION

The ESRF-EBS injection systems are very similar to the original storage ring design [1,2]. It is a standard off-axis injection scheme consisting of two in-air septa S1 and S2, one electro-magnet and one permanent magnet, one in-vacuum septum S3 and four kicker magnets K1 to K4 to generate the injection bump. The horizontal β-function is increased at the septum S3 to increase the transverse acceptance and injection efficiency. The injection perturbations compensation methods and systems presented in Ref. [3] were successfully applied to the ESRF-EBS storage ring. Nevertheless, the normalized residual injection perturbations are approximately an order of magnitude larger than for the previous machine due to the beam size reduction. The injection efficiency in User Service Mode (USM) with gaps closed is of the order of 80 % for a fully optimized machine [4]. While the choice of the standard off-axis injection scheme was considered a low risk option, and allowed for an efficient commissioning of the injectors, it is now showing its limits to achieve the ultimate goal of transparent injection with 100 % efficiency. This paper explores potential upgrades of the present ESRF-EBS injection scheme and systems to improve its performance and allow for future upgrades of the straight sections.

UPGRADE OF THE KICKERS POWER SUPPLIES

The ESRF-EBS injection perturbations compensation systems are based mostly on feed-forward techniques [3]. A major difficulty for these systems is to achieve large deflections with sufficient bandwidth to affect the bunches individually. This is particularly true for the injection kickers perturbation with a rise time of the order of 1 μs. In order to mitigate this issue and the detrimental effect from eddy currents flowing in the Titanium coating of the ceramic chambers, we have developed new kicker power supplies with slower rise and fall times. Their characteristics are shown in Table 1. The proposed solution, based on IGBT (Insulated Gate Bipolar Transistor) technology significantly increases the ramping time of the kicker pulses and improves by a factor 4 the pulse-to-pulse jitter, thereby reducing the random fluctuations that cannot be corrected with a feed-forward system. The fall time is presently set to approximately 2 μs corresponding to one storage ring turn but could be increased further depending on the horizontal tune working point.

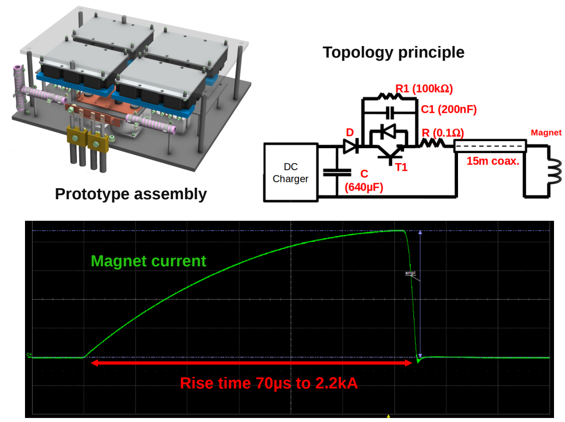

Figure 1: New kicker power supply assembly, topology and pulse shape.

Table 1: Comparison Between the Present Thyratron and the New Design

	Thyratron	New design
Voltage rating	30 kV to 40 kV	600 V
Max. current	2200 A	2200 A
Flat-top	1 μs	No flat-top
Rise/fall time	450 ns / 800 ns	70 μs / <2 μs
Pulse-to-pulse jitter	±0.2 %	±0.05 %

Figure 1 shows the new kicker power supplies assembly, topology and pulse shape. The design and assembly are done in-house. 2 prototypes were built and tested demonstrating the parameters shown in Table 1 and showing excellent identity between the 2 systems, which is essential to minimize bump non-closure. Installation and commissioning was initially planned for the end of 2020, however it was postponed by 6 months due to unexpected delays in the procurement of electronic components.

ALTERNATIVE INJECTION SCHEMES

Recent fourth generation light source designs feature much smaller transverse beam size, dynamic aperture and

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lifetime. As a result more frequent injections with significantly reduced perturbations are needed to provide stable operating conditions to the beam line users. Advanced injection schemes were proposed in recent years to solve this problem. Four are considered as potential candidates for the ESRF-EBS: (1) single non-linear kicker [5–7], (2) swap-out injection [8–10], (3) longitudinal on-axis injection [11–13] and (4) shared oscillations using a fast kicker [14]. The non-conventional kicker, fast or non-linear, is the main difference between these four schemes. The non-linear kicker$^{(1)}$ resembles a pulsed octupole allowing to kick the injected beam into the transverse acceptance without the stored beam that passes the magnet at the zero-crossing of the field. The swap-out$^{(2)}$ and shared oscillations$^{(4)}$ schemes require a fast kicker with a pulse width smaller than twice the bunch spacing in order to affect only a single bunch. In the first case the injected beam replaces the stored beam, requiring full current injectors and in the second case the injection oscillations are shared between the two beams. Finally, the longitudinal on-axis injection$^{(3)}$ uses a separation in the longitudinal plane and the fast kicker has to ramp from its nominal value down to zero in a fraction of a nanosecond. At ESRF, an in-vacuum septum is present at the injection point, with a large horizontal β-function of 18.6 m. The injected beam initial offset is determined by the thickness of the septum blade and the stored beam stay clear. It can be reduced using an injection bump and canceled by a kicker located at $\pi/2$ from the injection point. In case an injection bump is necessary, slow kickers can be used to reduce the injection perturbations and ease the capabilities to correct imperfections with feed-forward or feedback systems [15]. The non-linear kicker injection scheme requires an offset at the kicker and the optimum phase differs from $\pi/2$.

PROPOSAL FOR THE ESRF HMBA LATTICE

This section evaluates the integration of the 4 options described above for the specific case of the ESRF storage ring. The non-linear kicker is an off-axis injection scheme. It will face the same transfer efficiency limits as the standard 4 kickers bump and the transverse injection oscillations may prevent any reduction of the insertion devices gaps, considered as a potential brilliance upgrade for the ESRF-EBS. It nevertheless represents a good solution for transparent injection as demonstrated in [7] and the injection efficiency may be increased by other means such as a thinner septum blade, low emittance injectors or increased injection β. These represent substantial lattice modifications and potential disruption of the operation schedule of the accelerator complex and this option shall be kept as a backup solution in case on-axis injection would fail. On the other hand, the on-axis injection schemes using a fast kicker all have the potential to fulfil requirements both in terms of injection efficiency and transparency with limited changes with respect to the present lattice layout. The shared injection oscillation scheme is the simplest solution in terms of hardware requirements, integration and potential for evolution but its transparency relies on the injection bump. All these options share similar constraints in terms of layout and lattice requirements and it is therefore possible to design a flexible layout that would eventually allow for the implementation of any of these options. The design constraints are:

- A high-β straight section with an in-vacuum septum to reduce the non-conventional kicker required angle
- A non-conventional kicker located at $\pi/2$ (2 cells) from the injection point. For the case of the non-linear kicker the septum angle and octupoles can be used as phasers
- Standard off-axis injection systems in the high-β straight section to allow for staggered implementation of the non-conventional system
- No beam line experiment or collimation device are present between the two injection straights where the beam oscillates strongly. At ESRF, an RF straight section is present at this location

Figure 2 shows the proposed layout for injection systems. The whole section consists of: the 2 standard injection cells with the horizontal β-function bump, an RF or empty straight section and a standard low-β straight section hosting the non-conventional kickers. The phase advance between the injection point and the non-conventional kickers is $\pi/2$. No adjustments are necessary as the phase advance per cell is approximately $3\pi/4$. The special kicker is placed at the entrance of the straight section such that if it is sufficiently short the second half of the straight section can be used for other purposes: RF cavities or an insertion device for instance. For ESRF-EBS, the ideal straight section (6) for the special kicker is occupied by an insertion device. However, the straight section two cells further (8) is free and can be used for prototyping even though the phase advance is not ideal. In case substantial improvement of the injectors performance is demonstrated, a re-arrangement of the beam-lines might be considered to facilitate the special kicker design and avoid large oscillation in the insertion device in cell 6.

Figure 3 shows the horizontal injection oscillations using the layout proposed in Fig. 2 for the four injection schemes studied in this report. The septum blade is located at 15 mm from the beam axis and the injected beam at 20 mm. In case the injection bump is turned on, the separation between the stored and injected beams is 6 mm. Non-linear kicker injection features large injection oscillations between the injection point and the kicker as shown by the blue curve. These reduce down to the level of the standard off-axis injection after the non-linear kicker. The stored beam is theoretically not affected. The transverse separation between the stored and injected beams at the location of the kicker is approximately 3 mm. The non-linear field generated by the kicker therefore goes from zero to its nominal value of 1.2 mrad in a very short distance. This may represent a significant challenge in the design of the kicker and will require to inject the beam in a strong field gradient which may impact the injection efficiency of such a layout [15]. Swap-out injection features

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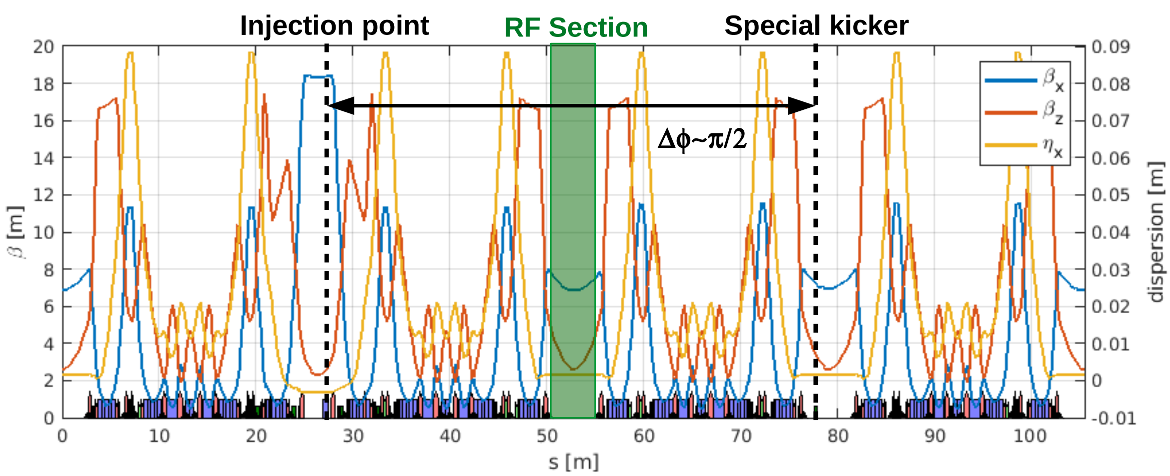

Figure 2: Proposed layout for the ESRF-EBS lattice.

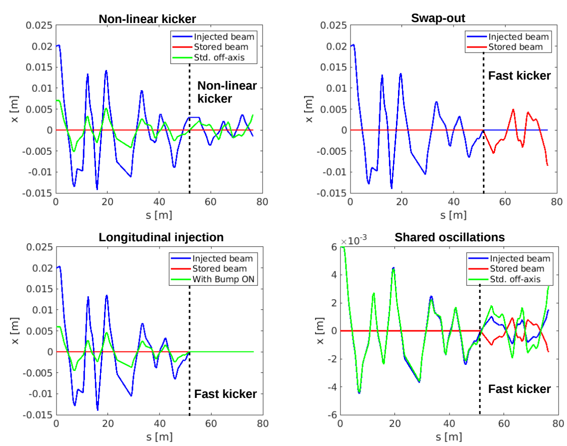

Figure 3: Injection oscillation and perturbations for different injection schemes in the ESRF-EBS.

similarly large injection oscillations between the injection point and the kicker, but they are completely cancelled with a deflection angle of approximately 1.4 mrad. The stored beam is kicked out of the acceptance and could be intercepted on a collimator or on a beam dump at the end of an extraction channel. Longitudinal on-axis injection has similar properties as the swap-out injection in terms of injection oscillation and deflection angle, perturbations are absent in the transverse plane. Designing a sub-nanosecond pulser is a major challenge, using the injection bump the kick angle can be divided by 2, from 1.4 mrad down to 0.7 mrad to reduce the voltage. Finally, the shared oscillations case combines a fast kicker with a closed injection bump. After the kicker, the injection oscillations are shared between the injected and stored beams and therefore reduced by a factor 2. This set-up is certainly the least challenging in terms of pulse width and kicker design as the required kick angle is only 0.25 mrad. It offers the advantage of potential staggered implementation and evolution towards swap-out injection by increasing the kicker strength or longitudinal injection with a faster pulser.

SUMMARY

The ESRF-EBS is presently operating with a standard off-axis injection scheme and already showing some limits in terms of efficiency and transparency in USM conditions. In view of a potential reduction of insertion device gaps to improve the machine performance, a transparent on-axis injection scheme is highly desirable. New kicker power supplies are under construction at ESRF to improve the injection bump fluctuation and ease the feed-forward compensation. In parallel, an upgrade of the injection systems was proposed that provides sufficient flexibility to integrate several advanced injection schemes and at the same time to maintain the present system operational.

Table 2: Pulse Width and Kick Amplitude for Different Injection Schemes, the Values in Parenthesis Correspond to a Special Kicker Installed in Straight Section 8

	Pulse Width	Kick [mrad]
Std on-axis	1 SR turn: 3 µs	2.0 (2.0)
NL kicker	1 SR turn: 3 µs	1.2 (1.0)
Swap-out	2 SR bucket: 6 ns	1.4 (1.4)
Long.	1 ns	1.4 (1.4)
Long. + bump	1 ns	0.7 (0.9)
Shared osc.	2 SR buckets: 6 ns	0.25 0.43)

Table 2 summarizes the preliminary kickers specifications, the shared oscillation scenario is an excellent starting point as it features relaxed characteristics and allows for an easy integration and to gradually evolve towards more involved options. Installing the final systems in straight section 6 should be favored to slightly relax the kicker field and avoid large oscillation amplitudes in the insertion device of cell 6. Further optimizations are possible by retuning the injection cells to increase the injection β.

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