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# TRANSPARENT INJECTION FOR ESRF-EBS

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*Abstract*

The commissioning of the ESRF-EBS storage ring will start in December 2019 ultimately providing a horizontal emittance of 130 pm, 30 times lower than the previous one. Due to the reduced beam lifetime top-up operation will be required for all operating modes. Transparent injection, i.e. with negligible perturbations on the stored beam, is necessary to allow continuous data acquisition for beam lines experiments. Several options have been considered at ESRF to reduce these perturbations down to a fraction of the rms beam size. First, new kickers power supplies with slow ramping time to facilitate active compensation are under development and will be implemented in the coming years. In parallel, long term solutions using non-linear kickers and longitudinal on-axis injection have been investigated.

## INTRODUCTION

Since the introduction of top-up operation at ESRF in 2016 significant efforts were made to minimize the perturbations for the beam line users during injections [1]. The main limitation was found to be the presence of strong sextupoles inside the injection bump. These sextupoles are not present at large bump amplitude in the ESRF-EBS lattice design [2] and a significant reduction of injection perturbation amplitude is expected. However, due to the reduction of horizontal emittance perturbations normalized to the beam size are expected to increase by a factor 10. The absence of sextupoles at large amplitude inside the injection bump will not compensate for this increase and mitigation measures will be required to maintain the present performance.

This paper will first describe the ESRF-EBS injection scheme and report on the techniques developed in Ref. [1] that will be applied to the ESRF-EBS storage ring. The development of new injection kickers power supplies and the feasibility of non-linear kicker and longitudinal injection to further minimize the perturbations will finally be discussed.

## ESRF-EBS INJECTION

The ESRF-EBS injection systems are very similar to the original design presented in Ref. [3]. It is a standard off-axis injection scheme consisting of two in-air septa S1/2, one in-vacuum septum S3 and four kicker magnets K1 to K4 to generate the injection bump.

Figure 1 shows the optics functions, layout and injection orbit bump in the injection cells of the ESRF-EBS storage ring [4]. The horizontal $\beta$-function is increased at the septum S3 location to increase the transverse acceptance and injection efficiency. Sextupoles are located inside the injection bump but their impact on perturbation is significantly reduced as they sample only minor orbit variation during

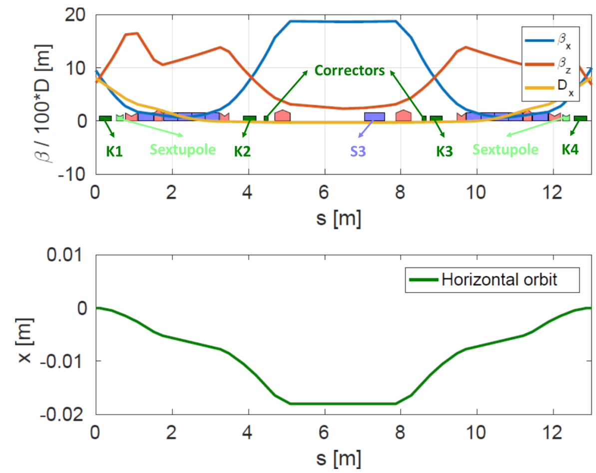


Figure 1: ESRF-EBS injection cells

injections. As will be discussed in the following section residual non-closure introduced by these sextupoles can be compensated by the two correctors located in the central part of the injection bump. For ESRF-EBS, the S1/2 magnets consist of one electro-magnet (S2) and one permanent magnet (S1) as opposed to two electro-magnets in the former design in order to reduce the perturbation. Power supplies with tighter specifications will equip the S3 (in-house development) and S2 [5] magnets in order to reduce random fluctuations that are difficult to correct and improve injection efficiency.

## MITIGATIONS DEVELOPED FOR ESRF

With the introduction of top-up injection several methods were developed to reduce the injection perturbation. This section will summarize the developments that can be used for ESRF-EBS. Details can be found in Ref. [1].

Sextupoles within the injection bump introduce residual bump non-closure due to their non-linear fields. This effect can be the source of large perturbations on the stored beam when the injection bump is pulsing. It was first suppressed at Spring8 using dedicated sextupole settings as shown in Ref. [6]. Unfortunately this method could not be used at ESRF as it reduced the lifetime to unacceptable levels. Alternatively, compensation can be achieved using higher order multipoles or compensation sextupoles at larger bump amplitude. In the case of ESRF-EBS, the correctors located within the injection bump shown in Fig. 1 are used.

Figure 2 shows the reduction of the perturbation kick angle along the bunch train and the average beam oscillation in the presence of sextupole correctors. The initial average perturbation amplitude corresponds to approximately $0.5\sigma$ but can be almost perfectly compensated using a pair of sex-

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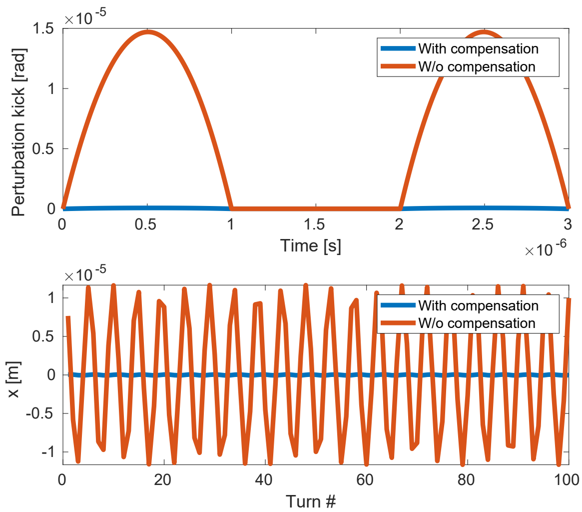


Figure 2: Compensation of the residual bump non-closure using sextupole correctors

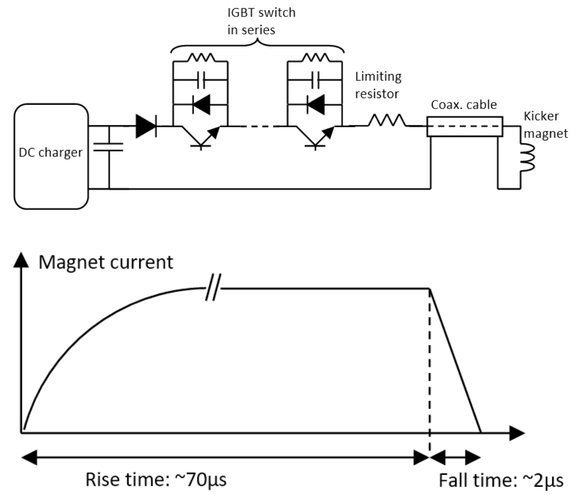


Figure 3: Topology (top) and pulse shape (bottom) of the new kicker power supply

tupole correctors with $K_3L = 0.04\,\mathrm{m}^{-2}$. This corresponds to 0.3 % of the standard sextupole strength and is not expected to affect the beam lifetime or introduce additional perturbations when turned on and off before and after injection sequences. It should be noted that these correctors can also generate a skew quadrupole component which can be used to partially compensate for roll angles of the injection kickers. In addition, active feed-forward systems developed and used in operation at ESRF will be used to compensate for the remaining perturbation coming from the septa and residual bump non-closure after the sextupole compensation. These systems can be activated in both horizontal and vertical planes.

## NEW KICKER POWER SUPPLIES

Although it proved to be very efficient the feed-forward system to compensate for the perturbations introduced by the kicker magnets was limited by its bandwidth preventing it to correct individual bunches. In addition, the present system features random fluctuations accounting for approximately 6 % of the total perturbation that cannot be corrected for. Random fluctuations considered as negligible with respect to other sources in the previous machine will become relevant for ESRF-EBS due to the reduction in horizontal beam size.

In order to facilitate the correction and minimize random fluctuations, new kicker power supplies with slow ramping time and tighter specifications on timing and amplitude jitter are under development at ESRF. The proposed power supply topology is based on the use of power semiconductors IGBT (Insulated Gate Bipolar Transistor) in series (4.5kV voltage rating per IGBT) to switch-on and switch-off the current in the magnet. The use of a high precision low voltage DC charger allows to control accurately the magnet current amplitude. During the ON sequence, the current is ramped up to 2.2 kA in the magnet. The opening phase occurs when the current has reached its maximum value: the energy in the kicker magnet is quickly transferred from the magnet to the capacitors connected in parallel of the IGBTs switches, allowing for a fast OFF sequence within 2µs.

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 3 shows the topology and the theoretical new current waveform. Table 1 summarizes the new power supply main parameters. The proposed solution improves the pulse-to-pulse jitter by a factor 4 and will significantly improve the related injection perturbations. A prototype was built composed of four IGBTs in series and a kicker magnet. A current in the magnet of 2.2 kA with a rise time of 70µs and a 2.2µs fall time was achieved, validating the design.

## NEW INJECTION SCHEMES FOR ESRF-EBS

Despite the mitigation measures presented above imperfections will remain and a fully transparent injection is not achievable with a standard four kickers off-axis injection. Alternative injection schemes have to be considered to achieve this goal. Two schemes have been studied for ESRF-EBS: off-axis injection using a non-linear kicker as developed in Refs. [7–9] and longitudinal injection as described in Ref. [10].

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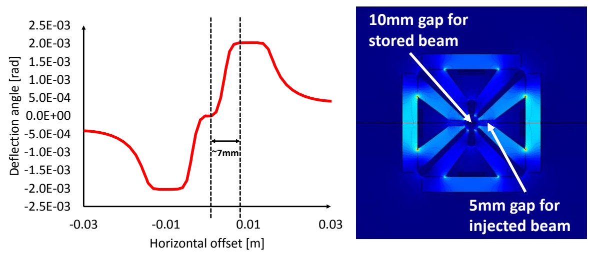


Figure 4: 2D studies of an octupole ferrite core kicker

### *Off-Axis Injection with Non-Linear Kicker*

This scheme uses one or several non-linear kicker magnets with zero field on-axis and non zero field at the location of the injected beam. This allows to steer the injected beam into the acceptance without affecting the stored beam. Sufficiently large offset between the stored and injected beams for the deflecting field to rise from 0 to its nominal value is required in order to obtain realistic kicker design. In the case of ESRF-EBS the optimal location to place the kicker is the injection point where the horizontal $\beta$-function reaches a maximum. The horizontal $\beta$-function can be increased from 18.6 m to 31 m by displacing the 2 central quadrupoles on Fig. 1 towards the injection point. This allows to separate the beams by 7 mm while injecting with approximately 90 % efficiency as obtained with the standard injection. A possible design features 3 non-linear kicker modules with a deflection angle of 2 mrad each to provide the last deflection after S3 and steer the injected beam into the acceptance. All injection magnets are located in the injection straight section. These results assume that all particles receive the nominal deflection. In reality, at ESRF the large horizontal beam size of the injected beam does not allow to achieve such performance unless the derivative of the field is close to zero at the injected beam position, in our case 7 mm off-axis. This sets an additional constraints on the non-linear kicker design. Figure 4 shows preliminary studies of a non-linear kicker fulfilling ESRF-EBS constraints. It consists of 4 C-shape ferrite cores with four conductors arranged to produce an octupole field in the central area and a pure dipole off-axis. The injected beam is sent through a 5 mm gap, of the same order of a closed in-vacuum undulator gap. This allows to run the magnet at a relatively low current of 300 A per coil. The peak magnetic flux density is 0.25 T. Further studies are required to validate the feasibility of this conceptual design.

### *Longitudinal Injection*

The full longitudinal injection as described in Ref. [10] would require a 1-2 mrad stripline kicker with nanosecond range pulse width which is impractical for a 6 GeV machine. The kick amplitude can be significantly reduced by combining this method with the four kickers bump. Assuming on-axis injection, the kickers located in the injection straight section, can be as slow as the septa and their contribution to the perturbation can be corrected by feed-forward systems to maintain transparent injection. In a straight section downstream of the injection point a fast kicker is used to steer

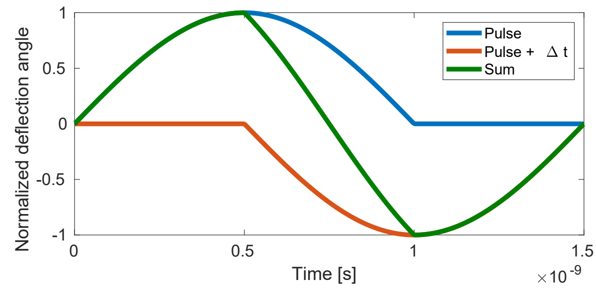


Figure 5: Combining two stripline pulse to reduce the fall time

the injected beam, longitudinally shifted, on-axis without affecting the stored beam. The challenge here is to design a power supply and kicker system that would allow to bring the deflection angle to zero in less than a nanosecond, as defined by the maximum distance between the stored and injected beams, allowing for both beams to remain within the longitudinal acceptance. At ESRF, to achieve 100 % injection efficiency, this distance corresponds to approximately 10 cm or 0.33 ns for a kick angle of 0.5 mrad if the fast kicker is placed in a straight section with the proper phase advance. The kick can be further reduced by increasing the $\beta$-functions at the injection point and the kicker location. Building such short stripline is impractical since a large amount of modules would be needed to produce the required deflection angle. It is however possible to combine two pulses shifted in time either in the two blades of a single stripline (double the voltage) or with two stripline modules as in Ref. [11] (double the length) in order to significantly reduce the fall time. This is shown in Fig. 5 where a stripline of 15 cm is used to generate two pulses of 1 ns shifted by $\Delta$t=0.5 ns. Each pulse is carried by one electrode with the same voltage +V. The combination of these two pulses reduces the fall time to 0.25 ns. This technology does not presently exist and significant developments are required to produce a reliable system compatible with operation.

## SUMMARY

Top-up operation with minimal disturbance to the users was recently established at ESRF and the techniques developed during this effort will re-used for ESRF-EBS. However, the beam size reduction of approximately a factor 10 calls for much tighter constraints concerning injection perturbations. At restart, the absence of sextupoles at high orbit offsets inside the injection bump, permanent septum magnets and new high stability septa power supplies will partially compensate for this reduction. Further improvement will be provided by new kicker power supplies with slow rise-time allowing for better reproducibility and more efficient feed-forward correction. Fully transparent injection can only be achieved with novel injection schemes, the more promising being longitudinal on-axis injection as it potentially offers 100 % efficiency and would allow to run the machine with very low in-vacuum undulator gaps.

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