# DESIGN OF A NON-LINEAR KICKER INJECTION SCHEME FOR THE EUROPEAN SYNCHROTRON RADIATION FACILITY EXTREMELY BRILLIANT SOURCE

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## *Abstract*

The European Synchrotron Radiation Facility Extremely Brilliant Source (ESRF-EBS) injection scheme consists in a classical four kickers off-axis injection. During injections, beam lines are perturbed and have to stop data acquisition. A new injection scheme using non-linear kickers was designed. The storage ring and transfer line optics and layout had to be modified to integrate the non-linear kickers in the injection cells and preserve injection efficiency in the presence of strong non-linear fields. This paper reports on the status and advancement of the project.

## INTRODUCTION

The standard four kicker bump injection scheme used on the previous machine [1, 2] was adopted for the ESRF-EBS as a low risk solution for the commissioning of the new machine. This option also allowed to recuperate existing hardware from the previous machine such as the septum magnets or the kickers power supplies. 80 % injection efficiency could be achieved in user service mode (USM) with this scheme [3]. Nevertheless, the normalized residual injection perturbations are approximately an order of magnitude larger than for the previous machine due to the beam size reduction. Even though new slow kicker power supplies combined with feed-forward corrections [4] allowed for a major reduction, experiments with beam lines indicated that significant reduction would still be required to achieve transparency [5]. The present systems are now showing their limits to achieve the ultimate goal of transparent injection and alternative schemes have to be considered. Preliminary studies [6] have shown that the non-linear kicker (NLK) injection scheme [7] would provide full transparency while maintaining injection efficiency. The project is now fully integrated in the ESRF long term scientific plan (LTSP).

## STORAGE RING LATTICE

In order to facilitate the design of the NLK it is desirable to increase as much as possible the horizontal acceptance at the injection point. The acceptance theoretically scales with $\sqrt{\beta}$, increasing the $\beta$-function at the injection point is therefore a natural way of increasing the horizontal acceptance. For the ESRF-EBS storage ring this is easily achieved by reducing the distance between the last 2 focusing quadrupoles on either side of the injection point. While leaving sufficient space between those 2 quadrupoles to insert the NLKs in the injection straight it was possible to increase the horizontal $\beta$-function from 18.6 m to 29.0 m. In order to preserve non-linear dynamics, additional constraints on the cell phase advance and twiss parameters at the sextupoles were included in the optics matching. Figure 1 shows the optics function for the 2 injection cells of the NLK lattice. The horizontal $\beta$-function reaches a maximum of 29 m at the center of the injection straight which corresponds to the injection point where the NLKs will be inserted.

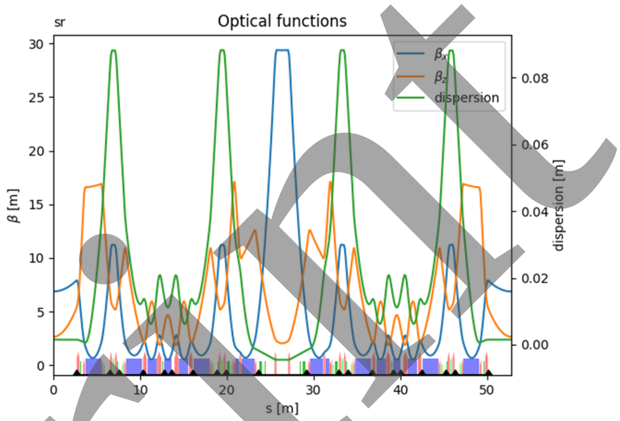

Figure 1: Optics functions of the NLK optics injections cells. The center of the straight is the injection point.

Table 1 summarizes the lifetime and dynamics aperture calculations with the standard lattice and the NLK lattice. A degradation of lifetime is observed. However, non-linear optimization were not performed prior these calculations and with a transparent injection scheme lower lifetime is acceptable since more frequent injection would be feasible to maintain current stability without affecting beamlines operation. Finally, it is planned to install a fourth harmonic cavity system for bunch lengthening at the ESRF-EBS which is expected to increase the lifetime by a factor of at least 2-3 [8]. The dynamic aperture on the other hand is significantly increased as expected and should allow for a horizontal offset of the injected beam of 8 mm. This corresponds to the distance for the NLK field to reach its peak and is achievable using standard manufacturing processes as described in the following section.

## NON-LINEAR KICKER AND POWER SUPPLY

The ESRF NLK design, described in Ref. [9] is based on the approach proposed in Ref. [10]. It consists of a $\sim$30 cm ceramic body where a total of 8 copper wires a glued to form the desired field shape. The conductors are placed such that

Table 1: Touschek lifetime (LT) and horizontal dynamic aperture (DA) at the injection point the the present lattice (STD) and the NLK lattice (NLK) with and without errors (average of 10 seeds). Non-linear dynamics optimization of the NLK lattice was not performed prior these calculations

| | **Lifetime [h]** | **Dynamics aperture [mm]** |
|---|---|---|
| STD w/o. errors | 35.3 | 9.9 |
| STD w. errors | 31.6 | 9.4 |
| NLK w/o. errors | 26.9 | 13.1 |
| NLK w. errors | 26.1 | 11.3 |

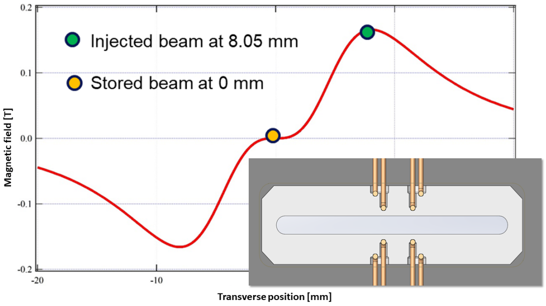

Figure 2: Field shape of the NLK and section view of the mechanical assembly.

the field and its derivative cancel on the magnetic center where the stored beam axis is located. The field reaches a maximum at 8 mm from the magnetic center such that the injected beam experiences a maximum deflection angle and a minimum gradient for a given en excitation current. Tight tolerances of ±20 µm are enforced on the machining of the grooves that host the conductors in order to minimize field errors.

This is illustrated in Fig. 2 where the NLK field shape and mechanical assembly are shown. It is seen that the injected beam sees the maximum field and no gradient. However, a strong sextupole remains which can affect injection efficiency in case the horizontal size of the injected beam is large compared to the field variation. This is the case at ESRF and special mitigation measures had to be implemented that will be discussed in the next sections.

A total deflection angle of ~11 mrad is required and is achieved using 3 NLKs powered with 3 independent power supplies. The required current for each of the power supplies is 7 kA and the pulse width is ~6.0 µs which correspond to two turn of the storage ring. This prevents the injected beam from experiencing a second kick when it comes back to the injection point. The selected topology will provide a half-sine pulse shape that can only be provide optimal injection efficiency for single pulse injection. The effective window for injection is reduced to ~0.5 µs and corresponds to only half a booster turn. Pulse distribution will have to be adapted to fit this window and injection duration will be lengthened. This could represent an issue in the case of a refill from scratch after a failure as it would also lengthen the recovery time and eventually the overall machine availability. This could be a major inconvenient for the project and will need careful evaluation to determine whether the half-sine pulse shape is adequate for USM operation.

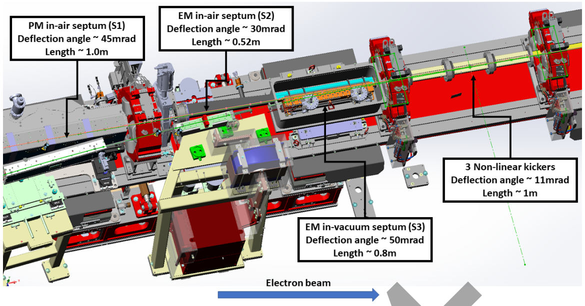

Figure 3: Mechanical layout of the end of TL2.

## TRANSFER LINE

To adapt to the modification of the storage ring layout and the reduction of the injected beam horizontal offset form 15 mm to 8 mm the end of the booster to storage ring transfer line (TL2) had to be modified. Below is the list of required modifications to the magnetic layout ordered following the direction of propagation of the electron beam:

- The angle of the last dipole of TL2 is reduced by ~15‰.
- The quadrupole layout was modified and 2 electromagnetic quadrupoles were replaced by more compact permanent magnets in order to avoid interference with storage ring magnets.
- All septum magnets are shifted toward the booster, the second in-air septum S2 is shortened and a new in-vacuum septum S3 with stronger deflection angle is required.
- The 3 NLKs are inserted are the injection point, i.e. in place of the present in-vacuum septum.

Figure 3 shows a top view of the mechanical layout of the end of the new transfer line TL2. The assembly is extremely dense, and avoiding interference with the storage ring is the main constraint to determine the pulsed magnets deflection angles and longitudinal positions and therefore their specifications. Full validation of this layout will be required once the conceptual design of new pulsed elements is advanced and the feasibility of the present specifications demonstrated. It should be noted that a permanent magnet option is under evaluation of the in-vacuum septum S3. Details on the status of the magnets design can be found in Ref [11].

Another difficulty associated with the NLK injection scheme relates to the non-linear nature of the kicker field. The injected beam will experience a strong sextupolar field that will in return affect the transfer efficiency of the particles located in the horizontal tails of the gaussian beam distribution and degrade the robustness of the storage ring injection against TL2 trajectory errors or fluctuations. To mitigate this effect it is planned to install a sextupole compensation magnet in TL2 at $\pi$ phase advance from the injection point.

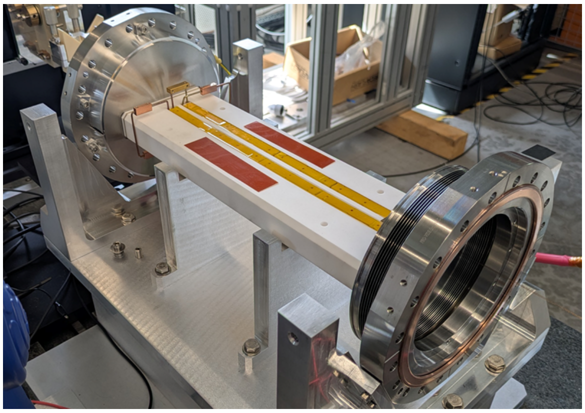

Figure 4: Prototype NLK installed on the ESRF pulsed magnets measurement bench.

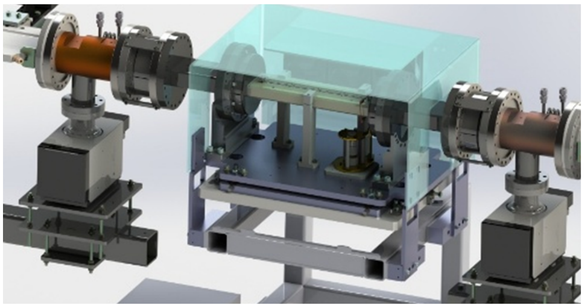

Figure 5: Mechanical assembly of the prototype test at ESRF-EBS.

With he sextupole compensation included sufficient operational margin is provided with an injection efficiency greater than 90 %. Details on the tracking simulations and results can be found in Ref. [12].

## PROTOTYPE AND EXPERIMENTAL VALIDATION

A prototype non-linear kicker was manufactured and delivered to ESRF for experimental validation in the storage ring. The goal of the beam experiments is to demonstrate transparency for the beam lines and validate its compatibility with USM operation. Beam induced heating of the titanium coated ceramic chamber is of particular concern an will have to be validated for all ESRF running modes.

Figure 4 shows the ESRF prototype NLK installed on the pulsed magnet measurement bench. The assembly and gluing of the conducting wires on the ceramic chamber was done at ESRF. The magnet will undergo a magnetic measurement campaign and fiducialization before being coated, still at ESRF. Details on the measurement bench can be found in Ref. [13].

Figure 5 and Fig. 6 shows the mechanical assembly and thermal simulations for the prototype beam experiment foreseen at ESRF-EBS. Beam induced heating is critical at ESRF where high bunch current modes are operated and substantial energy can be deposited by the beam in vacuum vessel in case they are not correctly optimized for impedance. Titanium coated ceramic chamber are particularly sensitive to this effect as they can break in case of overheating. The beam induced heating is determined in this case by the thickness of the coasting. Beam coupling impedance were conducted for the NLK chamber considering a coating thickness of 1 µm and used as input for the thermal simulations. Using cooling fan, the predicted temperature rise was estimated to 10 °C for a maximum temperature on the the body of 35 °C. However, a safety margin of a factor 2 is assumed for the coating and 2 µm thickness will be deposited on the ceramic. Installation will take place in May 2026 and beam experiments during summer 2026 and represent the final major milestone before validation of the concept for ESRF-EBS.

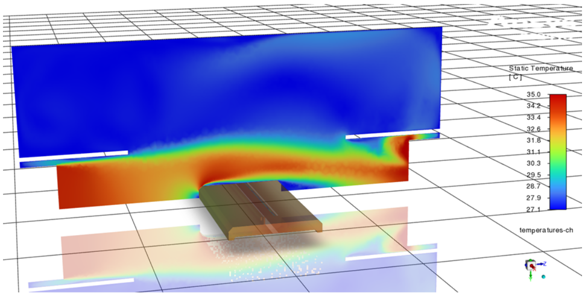

Figure 6: Thermal simulations of the NLK chamber for prototype test.

## SUMMARY

Some of the ESRF-EBS beamlines operation is presently affected by injection perturbation. The injection time has to be excluded from data acquisition and this represents a loss of effective beam time and an additional constraint when scheduling experiments. The NLK injection scheme was found to be a good candidate to solve this long standing issue and the development of non-linear kickers was launched for validation at ESRF-EBS. The conceptual design is ready and prototype was manufactured and beam experiments to validate it for operation and demonstrate transparency for the beamlines are scheduled. Although the non-linear kicker injection scheme would result in transparent injection it also represents a major change in the operation of the storage ring potentially more complex and less stable tuning of the injection system and increased injection time after a failure. Once the concept has been validated experimental a full review of the project with risks assessment is foreseen to evaluate these issues.

## ACKNOWLEDGMENTS

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