INJECTION DYNAMICS FOR SIRIUS USING A NONLINEAR KICKER

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Abstract

The concept of injection using a single nonlinear kicker has been proposed and tested in several existing storage rings with reduction in the stored beam oscillations during the accumulation process. Despite the good results, this scheme has not yet been adopted for routine operation in these machines due to the reduced injection efficiency. The main cause for reduction in efficiency is precisely the nonlinearity of the kick at the injected beam position and the generally large injected beam size. In this paper we study the injection dynamics in the Sirius storage ring where beam accumulation is based only on the use of a nonlinear kicker. The whole injection system has been optimized from the start for high injection efficiency.

INTRODUCTION

With the advent of fourth generation storage rings such as Sirius in Brazil, with natural emittance of 0.25 nm.rad at 3 GeV [1], the requirement of beam position stability becomes very challenging. This is particularly true for perturbations on very short time scales (less than 0.1 ms) where even state-of-the-art beam position feedback systems are inefficient. In these cases, the amplitude of the perturbation itself has to be limited to tight tolerances in order to guarantee the stability requirement. One of the main sources of perturbation in this category arises from the top-up injection process. The common injection method requires a pulsed orbit bump that is localized in space. This pulse is generated by 3 or 4 dipolar kickers that have to be perfectly matched to make a completely closed bump. For the kickers, it turns out that the matching conditions in shape and amplitude are extremely difficult to fulfil from the technological point of view. In many laboratories, to manage this problem, a blanking signal is provided to the beamlines so that all data collected during injection can be disregarded [2].

A promising new injection approach has been recently proposed and tested in many laboratories [3,4], which consists in using a single nonlinear kicker magnet with a flat zero magnetic field in the center and a maximum value off-axis, close to the injected beam position. A significant reduction in the stored beam oscillations during the injection process has been observed with this scheme, yet it has not been adopted for routine operation in these machines due to the compromised injection efficiency. The main cause for reduction in efficiency is precisely the nonlinearity of the kick at the injected beam position and the generally large injected beam size.

In this paper we study the injection dynamics in the Sirius storage ring where beam accumulation is based solely on the use of a nonlinear kicker. The whole injection system has been optimized from the start for high injection efficiency.

INJECTION SYSTEM

The Sirius storage ring injection system is designed since early stage to operate with a single nonlinear kicker (NLK) scheme. In order to optimize the efficiency of the injection process, the Sirius Booster ring has been designed with a very low emittance of 3.5 nm.rad at 3.0 GeV. The large circumference booster (496.8 m) is concentric to and shares the same tunnel as the storage ring. The optics of the booster-to-storage ring transport line has been optimized taking into account the nonlinearity of the NLK field at the injected beam position by mismatching the phase ellipse. A tilted ellipse can partially compensate for the kick dependence on position at the NLK. A small horizontal beam size also helps to minimize the sampling of the nonlinear field. The nominal injected beam horizontal rms size at the NLK position is only 250 μm.

The injection straight section contains a NLK installed close to the section extremity, far from the septum, for off-axis injection and accumulation, and a dipole kicker for on-axis injection next to it, as shown in Fig. 1. The dipole kicker is installed for safety, to be used during the initial commissioning phase, when the dynamic aperture may not be large enough for off-axis injection. The injection point (IP) in the storage ring is defined at the end of the septum magnet.

The transverse cross-section of the injected beam geometry with respect to vacuum chamber apertures at IP is shown in Fig. 2. The 3.0 GeV beam from the Booster is injected from the inner side, with horizontal amplitude of x=-19.35 mm and angle of x'=2.84 mrad with respect to the storage ring coordinate system.

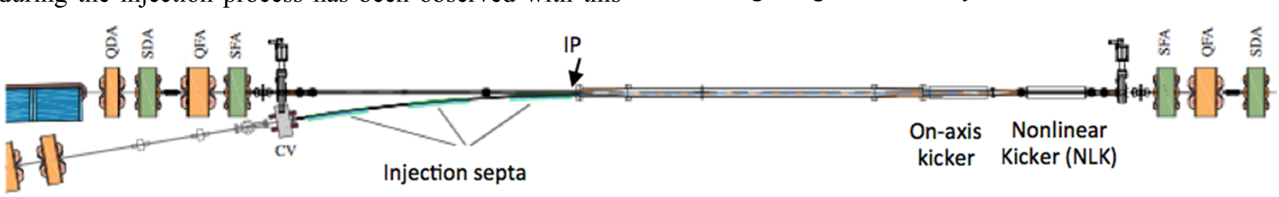

Figure 1: Layout of the Sirius storage ring injection straight section. The on-axis injection kicker and the nonlinear kicker are located downstream the injection point (IP), in the same straight section.

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The beam reaches the NLK with an amplitude of x=-8.4 mm, where it receives the kick and is captured into the storage ring acceptance. To maximize the injection efficiency the magnetic field shape has been optimized with its maximum as close as possible to the position where the injected beam receives the kick. This property of the NLK turns out to be very challenging to achieve, because of the compromise between the horizontal position of the field maximum and the vertical aperture for the beam. At the center, where the stored beam passes, the field B_y and its derivative dB_y/dx are required to vanish so as to not perturb the stored beam.

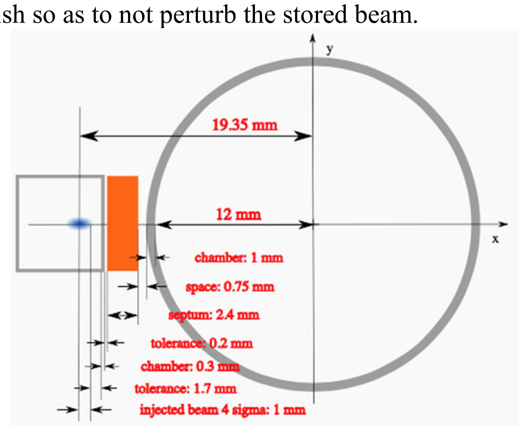

Figure 2: Schematic representation of the transverse cross section at the storage ring injection point.

Figure 3 shows the injected beam trajectory and the ±4-sigma beam envelope. After the nonlinear kick the amplitude of the oscillations is reduced and the beam is captured inside the storage ring acceptance. To minimize the distortion to the beam phase-space due to the nonlinear kick, and thus maximize capture efficiency, it is important to have simultaneously a small injected beam size and a flat magnetic field at the injected beam position. Figure 4 shows the distortion of the injected beam phase-space, as simulated with 1000 Gaussian-distributed particles, right after the nonlinear kick pulsed with optimal strength.

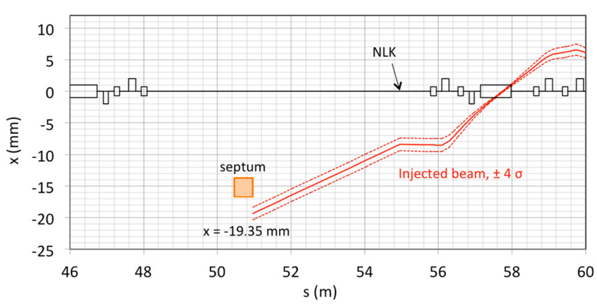

Figure 3: Injection into the storage ring using a NLK. The trajectory of the injected beam centroid in the horizontal plane is shown in solid red curve. The dashed curves represent $\pm 4\sigma_x$ beam envelope.

Once kicked, the injected beam was tracked for 213 turns, corresponding to a complete synchrotron oscillation period. Most of the kicked beam falls within the ring acceptance. A nominal injection efficiency of 99% is achieved. Fig. 5 displays the tracking data for the injected beam.

The small angular spread of the kicked beam obtained with the current nominal model of NLK implies that the expected pulse-to-pulse variations are inconsequential, as can be seen in Fig. 6. As for the stored beam, the NLK integrated dipolar field at x=0 mm has to be smaller than 3.7 G.cm so that the induced horizontal oscillation amplitude does not exceed 5% of the beam size.

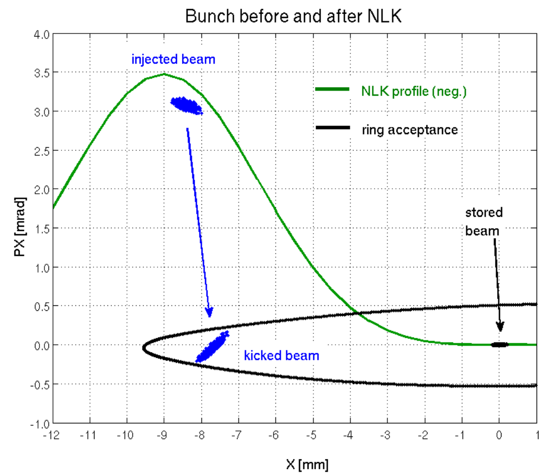

Figure 4: Phase space around the NLK position. Blue dots are 1000 particles representing the injected beam before and after the nonlinear kick. Green curve represents the negative of the NLK profile. Black dots correspond to the stored beam at x=0 mm and the ellipse is the nonlinear acceptance of the storage ring defined by an average dynamical aperture of 9.5 mm in the horizontal plane calculated from 20 simulated machines with realistic random errors.

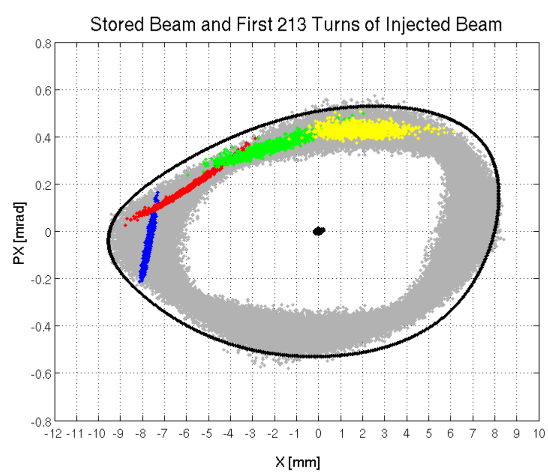

Figure 5: Phase space right pass the NLK with tracking data of the injected beam. In blue, 1000 particles representing the injected beam right after the nonlinear kick. In red, green and yellow, the injected beam after one, two and three turns around the storage ring, respectively. Depicted in grey is the beam in the next 210 turns.

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Ultimately, black dots at the origin of the phase space represent the damped beam.

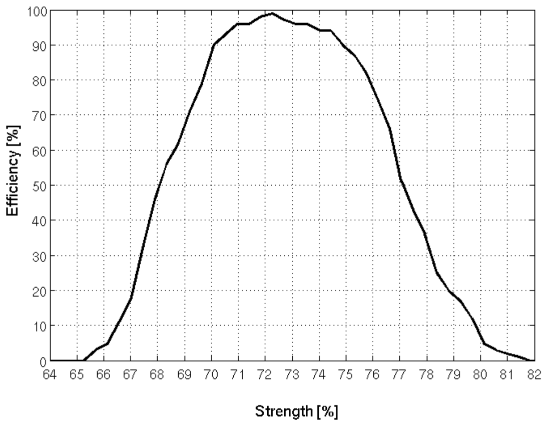

Figure 6: Injection efficiency as a function of the NLK strength calculated by particle tracking.

DESIGN OF THE NONLINEAR KICKER MAGNET

A nonlinear kicker based on current-driven wires to excite the magnetic field has been designed and simulated in order to produce a peak field around 9 mm and amplitudes of the order of 107 mT. A prototype is currently being analysed. The magnetic field shape is similar to that achieved at Bessy-II [3] but with the field peak closer to the center. Its design is based on eight 0.5 mm-diameter copper wires, two on each transverse quadrant carrying opposite currents. The locations and current polarizations of the wires display mirror symmetry about both planes. The symmetry about y=0 mm enforces B_x=0 T on the mid-plane, whereas the symmetry about x=0 mm leads to B_y=0 T at x=0 mm, at the horizontal center.

The two independent (x,y) locations of the wires in a quadrant are optimized so that the field quadrupolar components at x=0 mm and x=-9 mm are minimized and the field dipolar component is maximized at x=-9 mm. Once the optimal locations are found, the current that excites all eight wires in series is calculated from the desired nominal kick at the injected beam position. Minimizing the gradient at x=-9 mm allows for a flat zero field region around the position where the injected beam comes in. Figure 7 shows the calculated magnetic field profile of the NLK model.

An alumina tube developed in collaboration with a Brazilian company (ENGECER) will be used for the Sirius nonlinear kicker [1]. A pulser circuit has been designed to provide a half-sine pulse with fall time of 1.64 µs, shorter than the storage ring revolution period of 1.73 µs.

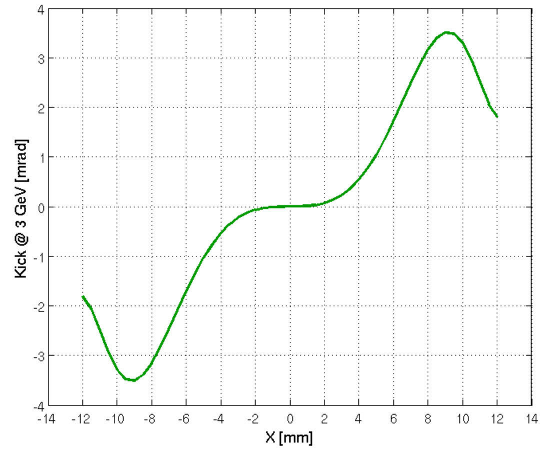

Figure 7: Calculated nonlinear kick profile. A peak kick of 4.8 mrad is obtained at around x=-9 mm. This kick corresponds to a field of 107 mT for the 0.45 m-long kicker model excitated with a current of 1850 A.

CONCLUSION

A nonlinear kicker for Sirius injection system has been designed and simulated. Tracking calculations show that the nominal injection efficiency is high and robust against expected pulse-to-pulse strength variations.

A prototype kicker based on the model described in this paper has been build and preliminary field measurements shows that the expected pulsed field amplitude and field profile were achieved. The nonlinear kicker prototype is still a work in progress.

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