12th Int. Particle Acc. Conf. IPAC2021, Campinas, SP, Brazil JACoW Publishing
ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-WEPAB121

# DESIGN AND SIMULATION OF TRANSPARENT INJECTION UPGRADE FOR THE CLS STORAGE RING

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*Abstract*

The Canadian Light Source (CLS) synchrotron uses four fast kicker magnets to inject electrons into the storage ring from a 2.9 GeV booster ring. The injection occurs over several turns of the stored beam, which is also perturbed by the injection kickers. The resultant oscillations of the stored beam can negatively affect beamline experiments, so it is desirable to implement an injection scheme which does not disturb the stored beam. Transparent injection is desired for planned top-up operations of the CLS storage ring. Many alternative injection techniques were examined as they apply to the CLS storage ring. Pulsed multipole magnets and a non-linear kicker (NLK) are the most viable options for integration with the current ring. Non-linear kicker designs are also being considered for the proposed CLS2 and studying the NLK in the limitations of the current machine provides insight to guide the work on the new machine. Simulation with the accelerator code ELEGANT shows the viability of the non-linear kicker design as developed at BESSY, MAX IV and SOLEIL for transparent injection at the CLS.

## INTRODUCTION

The Canadian Light Source (CLS) presently uses a conventional four kicker injection scheme. The first two of these magnets bring the stored beam closer and parallel to the injected beam, reducing the separation of the injected and stored beams and allowing greater electron capture efficiency. The second pair of magnets bring the stored and injected beams back towards the design orbit, where they undergo betatron oscillations and damp down to the equilibrium emittance via synchrotron radiation. While this is effective in accumulating current in the storage ring it results in unwanted oscillations of the stored beam.

Ideally, the kicker magnets create a temporary "bump" in the stored beam's orbit near the injection point, and preserve the central orbit elsewhere around the ring. However, due to nonlinear elements (ie. sextupoles) between the kickers, timing or field errors, and other complications it is difficult to have a perfectly closed bump so the stored beam oscillates significantly after injection [1]. These oscillations are undesirable for users as it modulates the intensity of the photon beam they use in their experiments.

Many injection schemes have been developed to avoid this negative effect on experiments and we aim to find an additional injection technique for the CLS storage ring [1, 2]. This work uses the simulations in ELEGANT to evaluate alternate injection techniques for the CLS storage ring [3].

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## DESIGN ALTERNATIVES

Before evaluating alternative injection schemes, we characterized constraints of the CLS storage ring. One main constraint in this project is the available space to add an injection magnet, but we also consider the current injection point and design orbit as preset variables. In ELEGANT we simulated injection of 1000 particles with the four injection kickers disabled, but without otherwise adjusting the injection. The beam is completely lost within two turns, but the losses begin at s = 54.452 5 m (the superconducting wiggler for the Bio-Medical Imaging and Therapy beamline) which is after the available space to add an injection kicker magnet; the third and fourth straight sections shown in Fig. 1.

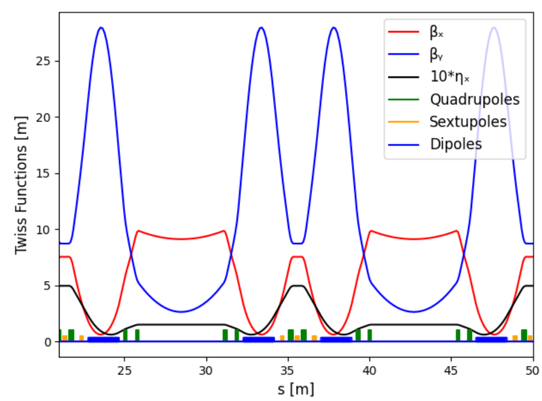


Figure 1: The horizontal and vertical beta functions and the horizontal dispersion (scaled by 10) of the available third and fourth straight sections in the CLS storage ring.

**Pulsed Multipole Injection (PMI) [1, 2, 4–7]** A pulsed multipole magnet (either quadrupole or sextupole) is placed at a location where the injected beam has a non-zero amplitude. The injected beam receives a kick to bring it within the acceptance of the ring where it then performs betatron oscillations as it damps down to the stored emittance. The stored beam passes through the center of the field and is less disturbed.

**Non-Linear Kicker (NLK) Injection [5, 8–11]** Similar to PMI, except the non-linear field is created by an array of pulsed current-carrying wires. The field is octupole-like on axis to minimize effect on the stored beam and has a field maximum at the location of the injected beam as shown in Fig. 2.

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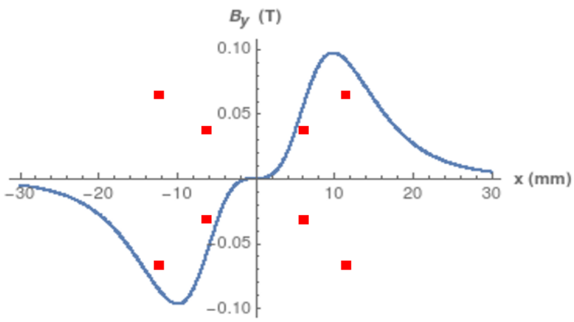


Figure 2: $B_y$ field in the horizontal plane for the NLK. The red points represent the layout of the conducting wires in the magnet. Conductor thickness not to scale.

**Longitudinal Injection [7, 12]** The beam is injected on-axis with a time offset from the circulating bunches. The bunch is injected between two circulating bunches and then merges with them via synchrotron radiation damping. However, for the 500 MHz RF frequency used in the CLS storage ring this method requires an extremely fast magnet pulse of approximately 1 ns. As a result of the very strict pulse length requirements, as well as the complexity of aligning the injected beam in longitudinal phase-space we eliminated this alternative.

**Off-Momentum Injection [7]** Similar to PMI, except the beam is injected with a momentum offset onto the associated off-momentum closed orbit. As the momentum offset is damped the injected beam blends into the stored beam. However, it was eliminated as we constrained the design to methods that do not alter the injected beam from the CLS's 2.9 GeV booster ring.

**Swap-Out Injection [7, 13, 14]** This method utilizes on-axis injection and replaces either an individual bunch or the entire beam at once. Individual bunch swap-out requires very fast magnet pulses so adjacent bunches are not disturbed, and full charge bunches to replace those that deteriorate. For full beam swap-out the larger issue is that it would require a secondary storage ring to accumulate the replacement beam for swap out. For these reasons it was also eliminated.

## SIMULATION OF ALTERNATIVE INJECTIONS

After narrowing the options to PMI and NLK injection we simulated these remaining techniques in the CLS storage ring using the tracking code ELEGANT [3]. PMI is further separated by the type of magnet being used. We first examined a pulsed quadrupole magnet (PQM), guided by the methodology used at the Photon Factory Advanced Ring to find the optimal location and strength [1]. The approach assumes the betatron oscillations are linear and represents the beam with a single particle. The representative particle is described in a normalized phase-space where it progresses around a circular invariant until acted upon. We evaluated the available straights 3 and 4 (machine functions in Fig. 1) and possible locations for the quadrupole were found only in straight 3. The PQM strength is minimized, and therefore optimized, at the end of this straight. For a 0.3 m long PQM placed at the end of the third straight (s = 29.216 5 m) the optimal quadrupole geometric strength is calculated to be K1 = 0.69 m$^{-2}$. Simulating the injection of 1000 particles the actual optimal strength was K1 = 0.85 m$^{-2}$, at 93.1% capture efficiency for a kick on a single turn.

The second approach to PMI utilizes a pulsed sextupole magnet (PSM), where the zero field gradient on-axis reduces stored beam disturbance. This technique has been successfully implemented for top-up injection at the Photon Factory storage ring and many other synchrotrons have considered it as well [2, 4–7]. Using a similar approach to finding the optimal PQM strength above, we found the ideal location within our available space is also the end of straight 3 [1, 2, 4–6]. The calculated sextupole geometric strength for this location is K2 = −112.1 m$^{-3}$. Simulating PSM injection for one thousand particles, we found that peak injection efficiency of 67.3% was actually at K2 = −186 m$^{-3}$.

The difference between the theoretical ideal strength and simulation for both the pulsed quadrupole and sextupole can be attributed to the significant injected beam width; it samples a broad range of the kicker field and receives varying kick strengths across its width as illustrated in Fig. 3.

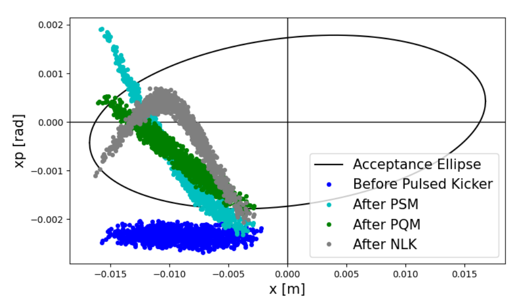


Figure 3: Beam distribution in horizontal phase space before and after a single kick from each alternate injection scheme. In each case a 30 cm magnet is placed at s = 29.216 5 m, the end of the third straight section.

The final method considered is a pulsed NLK magnet. The design was orignially developed for the BESSY II storage ring and similar designs have been considered for other facilities' storage ring injections [8–10]. The array of conductors produces zero field and field gradient at the magnet center (Fig. 2) and has minimal impact on the stored beam. An important feature is that the peak of the field is at a greater radial distance than the location of the inner wires which limits how close to the axis the peak field can be. It has been shown that, for the NSLS-II storage ring, injection can be performed at a location closer to the axis, with non-zero gra-

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dient rather than at the peak field [10]. However, as shown in Fig. 3, the relatively large emittance of the CLS's injected beam makes that an impractical option for CLS.

The end of straight 3 (s = 29.216 5 m) is again the optimal available place for the injection magnet. The injected beam is furthest from the central axis, closest to the peak of the NLK field without altering the injection point. The inner (outer) wires are placed 6 mm (12 mm) from the x and y axes (Fig. 2), which was determined to be the minimum spacing before the out-of-vacuum magnet would reduce the vertical acceptance. This arrangement of wires was simulated in RADIA, and the peaks were located at ±10 mm (Fig. 2) [15]. Through tracking in ELEGANT we found to better align the injected beam with this peak an injection angle of 0.174 mrad could be introduced with a minor adjustment to the septum current. The change is small enough that it was deemed acceptable within the constraints discussed earlier.

The peak simulated injection efficiency for the NLK with this injection angle is 98.3%. This was achieved with a current pulse of 2.2 kA at the time of the kick. The pulser used at SOLEIL and MAX IV provides a 7.7 kA, 3.5 µs half-sine pulse [11]. The CLS storage ring has a much shorter revolution period at 0.57 µs and thus the injected beam would receive multiple kicks from a pulse even half this length. However, the strength of the kick required for injection at the CLS is also much lower, and we can take advantage of this by not using the peak value of the half-sine pulse. For a 3.5 µs pulse of 4.5 kA peak amplitude, the amplitude 0.57 µs from the end of the pulse is then the required 2.2 kA, and the pulse will end before a second kick is applied.

To make the comparison between the three methods valid we also simulated PQM and PSM injection with the 0.174 mrad angle on the injected beam. For the PQM this increased the single turn injection efficiency to 98.1% ($K1 = 0.6\ m^{-2}$), and for the PSM we find 74.6% capture efficiency ($K2 = -120\ m^{-3}$). In both cases the additional amplitude of the beam at the kicker moves it to a higher strength region of the field, and thus the peak efficiency is achieved with lower kick strength.

We also considered the effects of slower pulses by simulating a kick over multiple turns, and in all cases a second, partial kick drastically reduced the injection efficiency. This reinforces the importance of strict pulser requirements in our 170.88 m ring.

### *Effect on the Stored Beam*

While injection efficiency is important it is not the reason for the considered upgrade. Thus, we strongly consider the effect of each injection on the stored beam. The magnitude of the stored beam's oscillation after a regular injection is about 2 mm peak-to-peak, and each of the alternate approaches improve on this. PQM and PSM injection reduce the magnitude of the oscillations to 0.2 mm and 0.7 mm respectively. The NLK has the greatest reduction, down to 40 µm, which is a factor of 50 improvement as shown in Fig. 4. There is also an effect on the size of the stored beam as it also has non-zero width and interacts with the field near the axis. The average beam size over the 1000 turns after injection is summarized in Table 1, which shows PSM is on par with 4-kicker injection, PQM doubles the size, and the NLK reduces the blow up by a factor of 3.

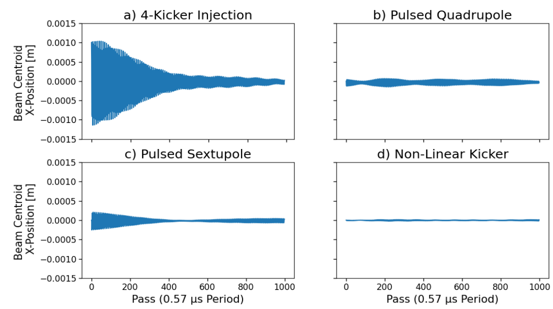


Figure 4: Comparison of stored beam position oscillations following injection for (a) standard 4-kicker, (b) pulsed quadrupole, (c) pulsed sextupole, and (d) NLK injection.

Table 1: Comparison of Injection Techniques' Efficiency for a Single Kick and Effect on the Stored Beam, as Simulated In ELEGANT [3]

| Injection Method | Simulated Capture Efficiency (%) | Stored Beam Oscillation (mm) | Stored Beam Average Width, 1000 turns (mm) |
|---|---|---|---|
| 4-Kicker | 100 | 2 | 6.52 |
| PQM | 98.1 | 0.2 | 10.73 |
| PSM | 74.6 | 0.7 | 6.53 |
| NLK | 98.3 | 0.04 | 2.04 |

## CONCLUSION

This study shows that the NLK is by far the best at minimizing the effect on the stored beam at CLS, but this comes at the cost of a reduced injection efficiency, as shown in Table 1. While on the surface 98.3% efficiency is viable, our simulations did not robustly account for variation in the injected beam. As illustrated in Fig. 3 the large injected beam interacts with a significant region of the field, so any variation in the shape or position of the beam will drastically reduce injection efficiency as less of the beam receives the ideal kick. This means that more refined injection simulations and likely adjustment to the NLK design to broaden the peak field are required to make NLK a viable option for transparent injection into the current CLS storage ring.

## ACKNOWLEDGEMENTS

This work benefited greatly from Ward Wurtz's original modelling of the CLS storage ring in ELEGANT [3].

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