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A COMPACT TOP-OFF INJECTION WITH CASCADED NONLINEAR KICKERS FOR DIFFRACTION LIMITED STORAGE RINGS*

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Abstract

To address the stringent dynamic aperture (DA) constraints of diffraction-limited storage rings, we propose a compact top-off injection scheme based on cascaded nonlinear kickers (NLKs) strategically placed near the injection point. By optimizing phase advances and distributing kicks across multiple NLKs, the injected beam oscillations are effectively suppressed within a fraction of a turn. The NLK design preserves a field-free on-axis region, ensuring minimal perturbation to the stored beam and enabling transparent injection. A novel NLK geometry can reduce the peak field distance to the beam orbit from greater than 7 mm to less than 5 mm, improving injection efficiency and reducing stored-beam distortion. Particle tracking simulations using Accelerator Toolbox, incorporating realistic field maps, alignment tolerances, and injected beam errors, confirm >90% injection efficiency and support a relaxed DA requirement of 5 mm for the NSLS-II upgrade lattice.

INTRODUCTION

Next-generation synchrotron light sources (NG-SLSs), such as NSLS-IIU, use multi-bend achromat lattices to achieve ultra-low emittance. While this improves brightness, it drastically reduces the dynamic aperture (DA)—from ~15 mm in third-generation rings to as little as 1-2 mm in advanced upgrades like ALS-U [1, 2]—challenging conventional off-axis injection.

On-axis swap-out injection, used in APS-U and ALS-U [3, 4], addresses this by replacing full bunches but demands major injector upgrades, increasing cost and complexity. We propose an alternative: a compact, scalable top-off injection scheme using cascaded nonlinear kickers (NLKs) that enable off-axis injection even in tight DA and physical aperture (PA) conditions.

The NLK scheme uses sequential, phase-matched kickers to suppress oscillations within a turn. Two innovations enable this: a novel NLK geometry reducing field-to-beam distance (~5 mm), and a cascaded layout distributing moderate kicks to minimize orbit disturbance. Particle tracking simulations validate greater than 90% efficiency within the 5 mm DA in the NSLS-IIU lattice. A prototype is under development at NSLS-II under LDRD funding with the goal of establishing a robust, low-impact injection technique for future diffraction-limited storage rings in alignment with Basic Energy Sciences Advisory Committee (BESAC) – 24 priorities [5].

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SIMULATION AND RESULTS

Simulation

Simulations show that sequential NLKs can suppress injected beam oscillations within one turn while preserving a field-free on-axis region for the stored beam. This results in negligible perturbations to the beamlines. By distributing kicks across two NLKs, residual oscillations are reduced by a factor of 10 when using moderate magnetic fields.

Using Accelerator Toolbox (AT) [6], we placed NLK1 and NLK2 in adjacent straight sections (cells 1 and 2) of the NSLS-IIU lattice (see Fig. 1a). Simulated magnetic fields of 0.021 T and 0.014 T over 0.3 m were optimized for rapid oscillation damping and transparency. DA (Fig. 1d) and misalignment errors were incorporated into the analysis, confirming robustness down to 5 mm.

Figures 1 and 2 illustrate the phased kick sequence, beam envelope comparisons, and kicker field profiles. As shown in Fig. 2c, the peak of NLK2 cannot occur at 0.3 mm off-axis; therefore, the kick θ_2 from NLK2 follows the magnetic field slope. The close alignment of the stored and injected beam trajectories, with only small offsets observed in Fig. 2a, confirms that the operation has minimal impact.

Feasibility and Optimization

Design feasibility was evaluated through multi-turn tracking, considering injection offsets, field tolerances, and kicker placement. Optimized kick angles (θ_1, θ_2) were selected via a 2D scan (Fig. 3) to minimize residual beam motion. Results reveal a clear operating point that balances damping effectiveness with manageable field strength.

The modular simulation framework also supports adaptive optimization. If one kicker fails, remaining elements can be re-optimized to maintain performance—offering a resilient and scalable design for future upgrades.

Injection Efficiency and Sensitivity

Efficiency was evaluated based on a ±5 mm horizontal and vertical acceptance, using realistic beam emittances. The injected electron beam had horizontal and vertical emittances of 60 nm·rad and 6 nm·rad, respectively. Simulations showed 100% injection efficiency under ideal conditions. With position and angle errors, injection efficiency becomes highly sensitive, especially to angular offsets (Fig. 4) and position deviations that distort angular kicks due to NLK field gradients. These effects the importance of placing the injected beam at the off-axis field peak. Therefore, precise alignment and trajectory control are crucial for optimal performance.

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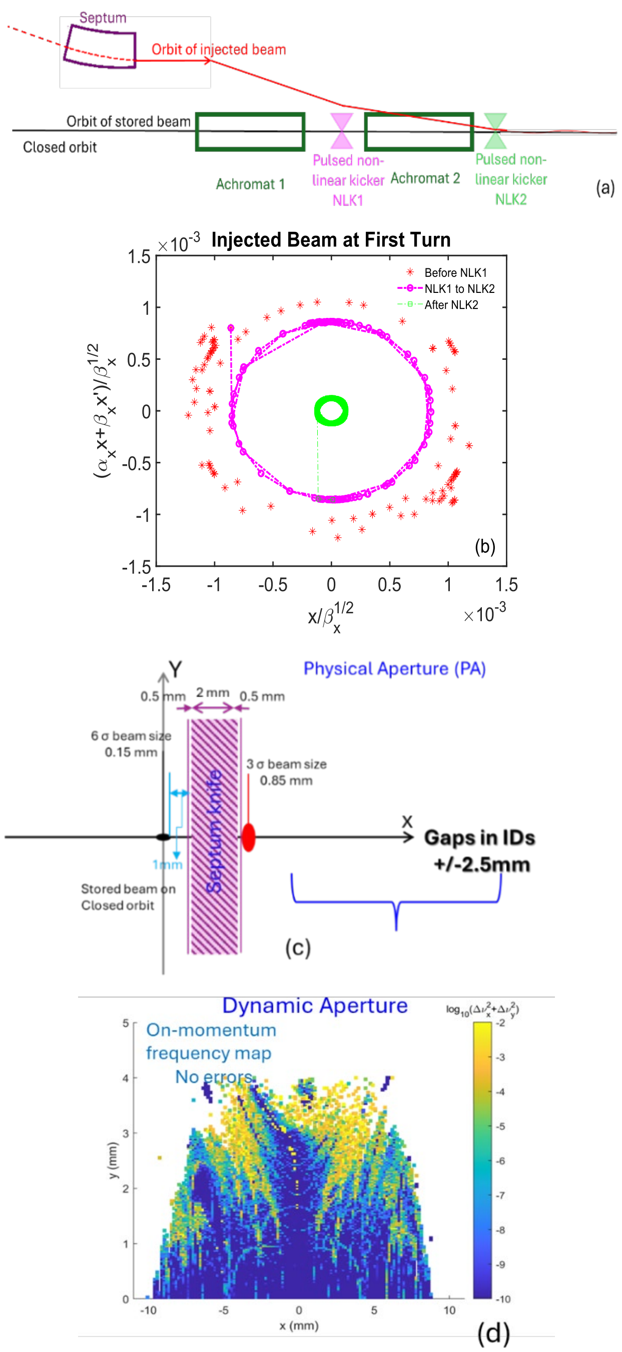

Figure 1: (a) Proposed NSLS-IIU injection system with septum and two NLKs in cells 1 and 2. (b) Injected beam phase space before and after kicks from NLK1 and NLK2. (c) Physical aperture showing beam sizes and septum clearance. (d) Ideal 9 mm DA for NSLS-IIU without errors.

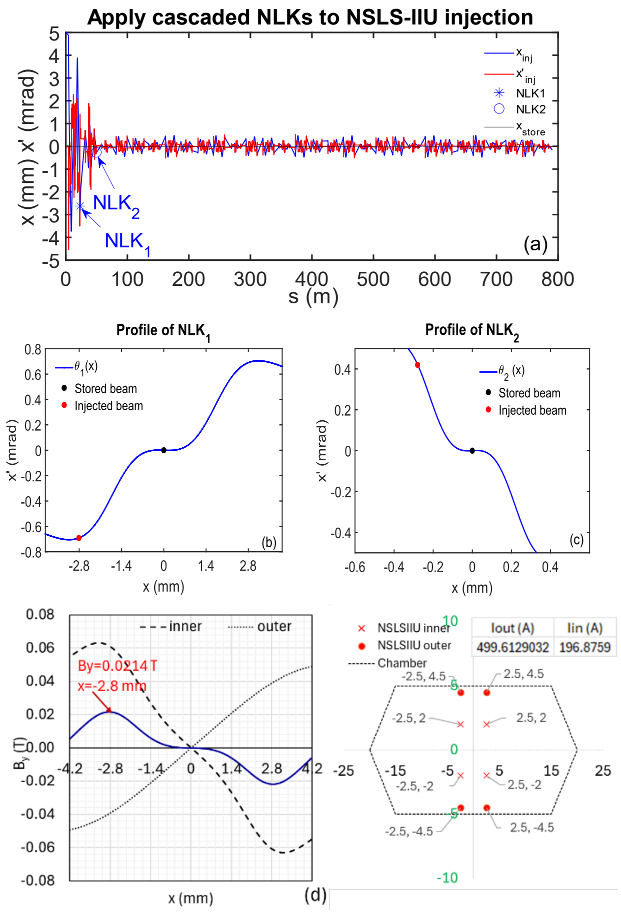

Figure 2: (a) First-turn trajectories of the injected (blue) and stored (black) beams around the ring, along with the first-turn angle of the injected beam (red), are shown. (b), (c) Simulated transverse field profiles of NLK1 and NLK2 with zero on-axis field. (d) Eight-wire NLK1 design generating the profile in (b). It is impossible to have the peak at 0.3 mm off-axis (c), as the kick θ_2 from NLK2 can only be aligned along the slope of the magnetic field profile.

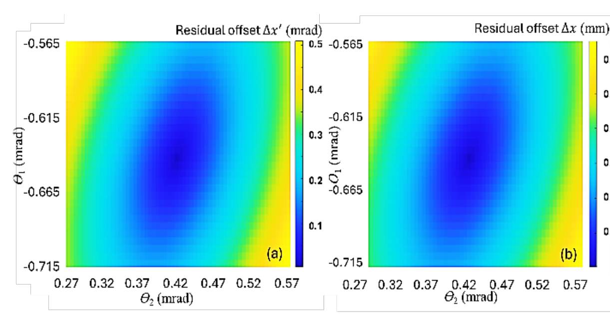

Figure 3: Optimization of cascaded NLK1 (cell 1) and NLK2 (cell 2) via 2D scan of kicks θ_1 and θ_2, minimizing injected beam oscillation in angle (a) and position (b).

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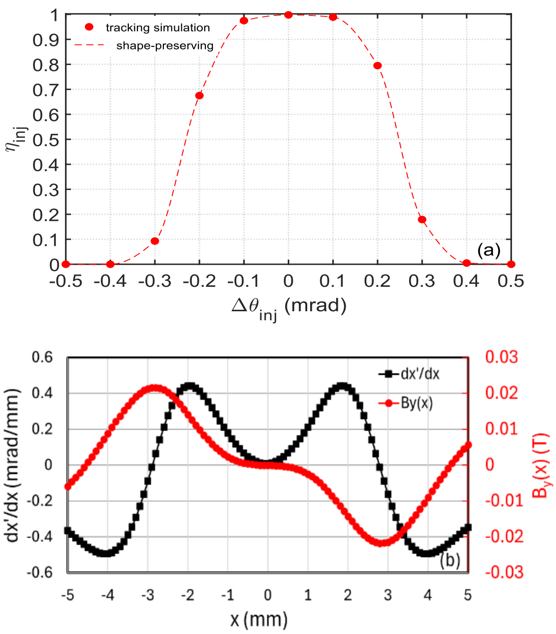

Figure 4: (a) Injection efficiency vs. beam angle offset, highlighting sensitivity to angular alignment. (b) Field profile (red) and angular kick derivative (black) vs. x offset, showing how position errors lead to angular deviations in the NLK.

Risk Management

Two kicker designs are under study: a proven eight-wire configuration [4, 7] and a novel in-vacuum NLK (INV-NLK) [7, 8]. The eight-wire version is lower risk but less effective at close beam separations. The INV-NLK offers stronger localized kicks at <5 mm separation, suitable for ultra-low DA but brings thermal and impedance challenges. A comparative risk analysis will inform the final design and be further developed in future research.

Prototype Development and Operational Benefit

A prototype NLK will be built for NSLS-II to validate the injection scheme experimentally. Prior tests using a repurposed pinger [9, 10] demonstrated the value of sequential kicks, boosting efficiency from ~80% to nearly 100% by complementing existing bump magnets, as well as reducing injected beam oscillations (Fig. 5).

The prototype will be installed in a spare straight section and tested with available diagnostics. It will guide integration into NSLS-IIU and immediately benefit NSLS-II by enhancing injection efficiency, reducing collective effects, and improving orbit stability.

CONCLUSION

We propose a compact, robust top-off injection method using cascaded NLKs that achieve efficient off-axis injection with minimal disturbance. This technique addresses critical challenges posed by reduced DA in NG-SLSs without requiring swap-out infrastructure.

A prototype kicker will be tested at NSLS-II, advancing both near-term operations and the NSLS-IIU upgrade. The effort includes simulation, magnet design, integration, and beam commissioning—offering a scalable path for next-generation low-emittance light sources.

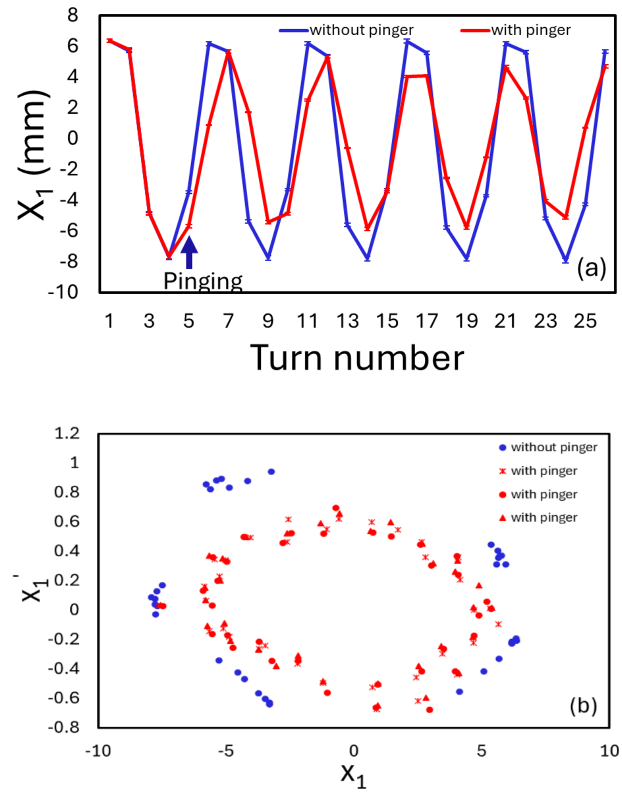

Figure 5: (a) The injected beam angle peaked at turn 4 (-0.47 mrad) when an optimal kick from the one-turn pinger reduced the injected beam oscillation, as shown by the transition from blue to red. (b) A timed pinger reduces oscillations (blue to red), boosting injection efficiency from 74% to 95%, with 5% loss before pinger activation.

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