

NSLS-II R&D FOR OPERATIONS AND BEAM STUDIES*

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Abstract

NSLS-II carries out facility-led accelerator R&D to improve present storage-ring operations, expand beamline capabilities, strengthen beam-study and optimization tools, and prepare for future upgrades. Recent work has supported high-current operation toward 500 mA, long-term orbit stabilization through Unified Orbit Feedback (UOFB), specialized high-current bunch patterns for time-resolved experiments, model-independent lattice characterization, nonlinear optics correction and optimization, and Complex Bend (CB) prototype beam commissioning. These activities span different technical areas, but share a common goal: improving the performance, flexibility, and future upgrade readiness of NSLS-II as a user facility. This paper summarizes selected R&D efforts and their impact on operations, user capabilities, beam studies, and next-generation light-source development.

NSLS-II SR STATUS OVERVIEW

NSLS-II [1, 2] is a 3 GeV synchrotron light source at Brookhaven National Laboratory supporting a broad user program that requires high reliability, excellent beam stability, flexible operating modes, and continuous improvement of accelerator performance [3]. In addition to routine operation, NSLS-II conducts accelerator R&D to improve present machine performance and developing tools and concepts for future light-source upgrades.

The R&D activities described in this paper are organized from four aspects. The first is improving present operations, including high-current performance, operational reliability, and orbit stability. The second is expanding user capabilities, particularly through specialized filling patterns, timing modes for time-resolved experiments. The third is strengthening beam-study and optimization tools through advanced diagnostics, lattice characterization, and nonlinear dynamics methods. The fourth is preparing for future upgrades through the development and beam commissioning of Complex Bend technologies. Although these activities span different technical areas, they share a common goal: improving the performance, flexibility, and future upgrade readiness of NSLS-II as a user facility. The following sections summarize selected recent accomplishments in each area.

R&D FOR PRESENT OPERATIONS

Studies Toward 500 mA Operation

A major operational R&D effort at NSLS-II has been the development of reliable 500 mA storage-ring operation [4]. Since first beam operation in 2014, NSLS-II has progressively increased beam current while integrating additional insertion devices and beamlines. High-current operation required systematic testing and improvement of several accelerator systems, including ceramic chambers, RF bellows, BPMs, RF systems, and vacuum-component heating diagnostics.

The original storage-ring design assumed bunch lengthening with harmonic cavities. Because these cavities were descope during facility construction, high-current operation required extensive studies to identify and mitigate impedance-induced heating. Significant heating was observed in ceramic chambers, RF bellows, and RF-contact regions. Temperature diagnostics and infrared monitoring were expanded, improved RF spring installation procedures were developed, and selected components were repaired or upgraded to improve high-current reliability.

The RF system was optimized to deliver increased power with improved stability and reliability. In addition, the HEX superconducting wiggler was tested at high current, which further reduces heating through bunch lengthening. These studies demonstrated the importance of bunch-lengthen for both high-current operation and future harmonic-cavity development.

Since August 2023, NSLS-II has conducted multiple 500 mA user-operation periods with progressively increased run time. Beamline feedbacks, as shown in Fig.1, demonstrated clear benefits from high-current operation: stronger signals were reported by 25 beamlines, improved signal-to-noise ratio by seven beamlines, and increased sample throughput by five beamlines. No beamlines reported sample-damage or optics-instability concerns. Although 500 mA operation has now been demonstrated for user experiments, simultaneous operation at 500 mA and very low vertical emittance remains limited by beam lifetime, motivating future third-harmonic cavity development.

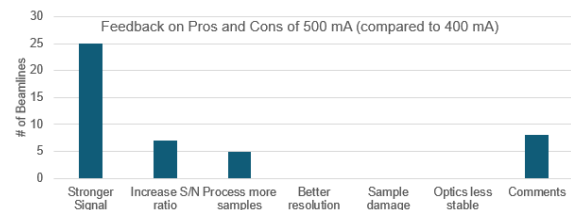


Figure 1: Beamline feedback during 500 mA operation.

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Unified Orbit Feedback for Beam Stability

Beam stability is a key performance metric for all NSLS-II beamlines. To improve both short- and long-term orbit stability, NSLS-II developed a Unified Orbit Feedback (UOFB) system [5, 6] that integrates slow orbit feedback, fast orbit feedback, RF frequency feedback, and local source-point control into a single operational framework.

Before UOFB, local long-term stabilization was available only for a limited number of sensitive insertion-device beamlines. Interactions among local bump agents, bending-magnet source control, RF frequency feedback, and fast orbit feedback could create conflicts or require disruptive feedback resets. UOFB resolves these conflicts by continuously shifting accumulated fast-corrector strengths to slow correctors while maintaining the fast orbit feedback reference orbit and compensating ring-circumference changes through RF frequency feedback.

The system supports three types of local source-position control: insertion-device RF-BPM bumps, bending-magnet source bumps, and insertion-device bumps based on X-ray photon BPMs [7, 8]. UOFB was successfully deployed into normal operation in July 2022. Since deployment, it has provided long-term sub-micron orbit stability across insertion-device straights and bending-magnet sources, significantly improving beam stability for routine user operation, as shown in Fig. 2. The system also provides flexible local source-point adjustments in response to beamline requests without interrupting global orbit stabilization.

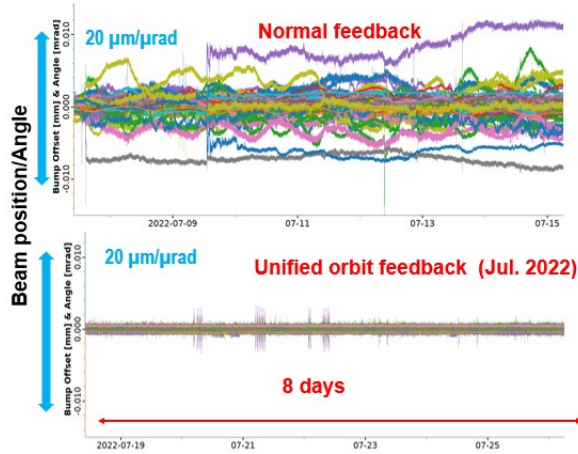


Figure 2: Unified Orbit Feedback improvement of beam stability.

R&D EXPANDING USER CAPABILITIES: HIGH-CURRENT BUNCHES AND TIMING MODES

Time-resolved experiments require well-defined X-ray pulse structures, synchronized timing signals, detector gating, and flexible filling patterns. In March 2020, NSLS-II formed a Time-Resolved Capabilities Taskforce to evaluate scientific requirements and accelerator feasibility for specialized timing modes [9]. The taskforce included

scientists from multiple beamlines, accelerator physicists, and control-system experts.

The team defined specialized operating modes, including uniform singlet-bunch patterns, high-current bunch trains, and hybrid filling patterns. These modes are intended to support studies of dynamical behavior on picosecond-to-nanosecond time scales. Required supporting infrastructure includes accelerator timing signals, beamline timing signals, detector gating, and tunable delay capabilities.

Significant progress has been made in high-current bunch operation. A special pattern of 15 equidistant high-charge bunches was studied, and nonlinear lattice optimization enabled accumulation of 67 mA in 15 bunches with approximately 70% injection efficiency. Timing experiments were also performed with the CHX beamline using specialized filling patterns, as shown in Fig. 3. These studies expand the available operating modes for time-resolved science while providing important information on single-bunch and multi-bunch intensity limits.

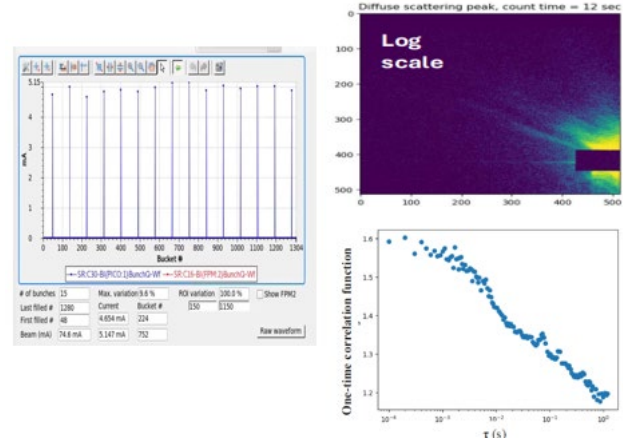


Figure 3: Bunch filling pattern and CHX Timing mode correlation experiments with Ag.

R&D TOOLS FOR BEAM STUDIES AND OPTIMIZATION

Model-Independent Lattice Characterization

Accurate characterization of the real storage-ring lattice is essential for beam studies, optics correction, injection optimization, and future upgrade preparation. NSLS-II completed a Facility Improvement Project to install a dedicated pair of bunch-by-bunch BPMs in a magnet-free section of the storage ring. These BPMs enable absolute and model-independent characterization of the ring by measuring the transverse Poincare map, deriving linear one-turn matrices, and extracting Twiss parameters without relying directly on the lattice model.

This capability is especially valuable when the real machine differs from the design model or when high-precision optics characterization is needed. The new instrumentation improves the ability to benchmark lattice models, diagnose optics errors, and support advanced beam studies.

Nonlinear Optics Characterization and Correction

NSLS-II has also developed and applied methods for nonlinear optics characterization and correction. One example is Nonlinear Optics from Off-Energy Closed Orbits (NOECO), which applies linear optics tools to nonlinear optics characterization. This method has been used to characterize chromatic sextupoles and support nonlinear correction of the storage ring.

Dynamic-aperture measurements with ICA-NOECO correction have been applied to improve injection efficiency and storage-ring performance. These studies provide practical tools for diagnosing nonlinear lattice errors and optimizing the machine under operational conditions.

Nonlinear Lattice Optimization

Nonlinear dynamics strongly affects storage-ring dynamic aperture, injection efficiency, and beam lifetime. NSLS-II has developed new methods to characterize and optimize nonlinear beam dynamics, including convergence-map techniques and machine-learning-based chaos indicators.

The convergence-map approach provides information about on-momentum and off-momentum phase space, including stability boundaries of the dynamic aperture. Compared with conventional frequency-map analysis, the method can be 10 to 50 times faster, making it effective for nonlinear lattice optimization. Data-driven chaos indicators based on the prediction accuracy of machine-learning surrogate models are also being explored as metrics for nonlinear motion and dynamic-aperture optimization.

R&D TOWARD FUTURE UPGRADES: COMPLEX BEND PROTOTYPE BEAM COMMISSIONING

NSLS-II has proposed the Complex Bend [10, 11] concept as a path toward future low-emittance storage-ring upgrades. The concept uses compact, high-gradient combined-function permanent-magnet elements to provide strong focusing and bending within a compact lattice cell. This approach can enable ultra-low-emittance lattices while preserving straight-section space for insertion devices.

To demonstrate the feasibility of this concept, a prototype Complex Bend beamline was developed and commissioned using the NSLS-II linac diagnostic beamline. The prototype consisted of compact Halbach permanent-magnet quadrupole elements with gradients of approximately 140 T/m. Nine prototype poles were fabricated, with eight used in the beamline test, as shown in Fig. 4.

Beam commissioning was carried out in two phases from January 2023 to June 2024 [12, 13]. In the first phase, the CB elements were used as strong periodic focusing quadrupoles with the beam passing near the magnetic centers. In the second phase, the permanent-magnet quadrupoles were transversely offset to demonstrate

combined focusing and bending. The measured beam trajectory and focused beam size showed good agreement with theoretical expectations, validating the feasibility of the Complex Bend concept for future storage-ring upgrades.

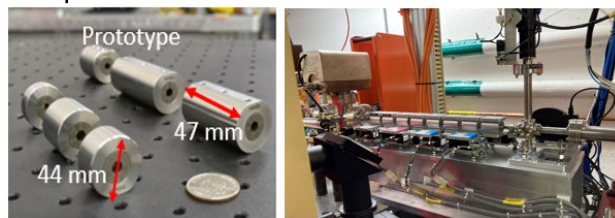


Figure 4: CB poles and installation in NSLS-II LN.

SUMMARY AND OUTLOOK

NSLS-II accelerator R&D supports present operation, user capability expansion, beam-study tool development, and future upgrade readiness. High-current studies have enabled extended 500 mA operation and identified the importance of bunch lengthening for future operation at high current and low vertical emittance. Unified Orbit Feedback has improved long-term orbit stability across insertion-device and bending-magnet beamlines, directly benefiting user experiments.

Specialized filling-pattern studies are expanding timing-mode capabilities for time-resolved experiments. New bunch-by-bunch BPM instrumentation, nonlinear optics characterization methods, and nonlinear lattice optimization tools are improving the ability to diagnose, correct, and optimize the storage ring. In parallel, Complex Bend prototype commissioning has demonstrated a key technology for future low-emittance storage-ring upgrades.

Together, these R&D efforts improve current NSLS-II beam performance, broaden experimental capability, and provide a strong foundation for future NSLS-II upgrade development.

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