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Accelerator Physics at NSLS-II: Research Accomplishments in 2024

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Abstract

NSLS-II accelerator physicists advanced the operational performance and scientific capabilities of NSLS-II, providing regular lattice characterization and correction, injection optimization, vertical emittance control, and beam dynamics reports with correlation analysis. We further developed advanced lattice characterization techniques and studies on impedance, beam-induced heating, and higher-harmonic RF cavity effects to support NSLS-II and its high-brightness upgrade. The assessment of free-electron laser options for the NSLS-II upgrade has been completed. We carried out comprehensive studies focused on complex bend magnets and novel efficient injection schemes for next-generation low-emittance synchrotrons. We contributed to the Electron-Ion Collider project, including Electron Storage Ring lattice design, beam diagnostics, and injector studies. The physicists participated in international collaborations, including the development of Python-based Middle Layer software, and participated in key accelerator physics workshops and scientific meetings. The main research accomplishments achieved in 2024 are summarized in this report.

1 Introduction

In 2024, NSLS-II accelerator physicists provided scientific support for user operations, including start-up, routine lattice characterization, vertical emittance control, and beam dynamics reports. We worked on several accelerator development and improvement projects: high-intensity bunch pattern for time-resolved operations, FIP for model-independent lattice characterization, and design of low-beta straight section for NEXT-III beamlines. Our R&D efforts included NSLS-II upgrade, studies of multi-harmonic RF systems to mitigate high-intensity effects, development of novel techniques for lattice characterization and optimization, active control of magnet vibration, and ultrafast electron microscopy. We participated in the Scientific Meeting on the Strong-focusing Combined-function Magnets and in the NSLS-IIU Accelerator and Science Retreat. The physicists supervised summer and fall internship projects. Collaboration with the EIC project was focused on optimizing ESR straight sections, designing beam diagnostic systems, and developing the electron injector.

A list of major projects and activities is below.

- NSLS-II operations and start-up
- HLA common tools and Python Middle Layer development
- Beam dynamics reports
- Seasonal variation of the storage ring circumference and energy
- High-current bunches for time-resolved experiments
- Model-independent lattice characterization
- Straight section with reduced beta functions for NEXT-III
- Advancing methods of lattice characterization and correction
- Impedances, collective effects, and beam-induced heating
- Multi-harmonic RF system
- Active control of magnet vibrations
- Three-pole wigglers
- NSLS-II upgrade: lattice development, collective effects, injection
- Theoretical study of free electron lasers
- Ultrafast electron microscopy
- Support of EIC: beam diagnostics, lattice optimization, electron injector

2 NSLS-II operations and start-up

To enhance the Injector and Storage Ring performance, multiple beam studies were carried out, including minimization of injection transients, top-off injection troubleshooting, gun charge calibration, check-up and tuning beam diagnostics, and improvement of the injection efficiency and beam lifetime. To improve the routine lattice characterization and effectively track the machine status and performance, we updated our procedure and set up a shared folder for regular reports [43]. Each report includes measured emittance and energy spread; beta functions, betatron phases, and dispersion; linear coupling; chromaticity; amplitude-dependent tune shifts and dynamic aperture. Vertical emittance control using the bunch-by-bunch feedback system was implemented by accelerator physicists in collaboration with beam diagnostics experts. The required vertical emittance and beam lifetime were achieved by the combined use of the bunch-by-bunch feedback and coupling control by skew quadrupoles, with the feedback system contributing approximately half of the effect. We analyzed the effect of multipole errors of the IVU18 in Cell 9 (CDI beamline) on the nonlinear beam dynamics and found this device has a negligible effect on the dynamic aperture. A new method of beam-based alignment to determine the centers of multiple magnets simultaneously was preliminarily tested [21]. We arranged a tutorial on the beam diagnostic instrumentation (gated camera and streak camera) for accelerator physicists.

3 HLA common tools and PyML development

Together with control experts, the most severe issues of MATLAB Middle Layer incompatibility with the new versions of MATLAB have been solved. The recompiled basic functions work with both MATLAB 2014b and 2022a versions. We drafted a plan for the participation of NSLS-II accelerator physicists in the international collaboration for the development of a new Python-based Accelerator Toolbox and Middle Layer software. This collaboration has been screened and cleared for export control and the S&T Risk Matrix. We coordinated the plan with ESRF colleagues leading the project and participated in the Accelerator Middle Layer Workshops. We will update our HLA Common Tools following the selection of a Python Middle Layer option by the collaboration.

4 Beam dynamics reports

Biweekly beam dynamics reports were systematically generated using all available beam diagnostic instruments during the start-up periods, regular operations, and test operations with an increased beam current of 500 mA. All reports have been uploaded to a dedicated SharePoint website [42]. As a result of the correlation analysis of the measured data, we identified the adjustment of undulator gaps as the primary source of emittance and lifetime perturbations. The findings were presented and discussed with system engineers at Accelerator Coordination Meetings to address operational challenges and optimize performance.

5 Seasonal variation of the storage ring circumference and energy

We completed an analysis of seasonal variations in the NSLS-II ring circumference and energy using direct circumference measurements, archived data (RF frequency, magnet settings), and ID10 gap adjustments to maintain fixed photon energy for the IXS beamline. Taking into account that the tunnel motion is translated to the mezzanine with an amplification of about a factor of two, the seasonal variations of the ring circumference and energy show a good agreement. Adjustments to the RF frequency and horizontal orbit corrections partially mitigated these effects. Since the sum of quadrupole currents correlates with the energy, we identified those seasonal energy variations as the primary reason for regular lattice corrections required to keep stable performance for user operations. The main results were published in Nuclear Instruments and Methods in Physics Research, A [13].

6 High-current bunches for time-resolved experiments

Significant progress was made in optimizing the high-current single-bunch operations for time-resolved operation mode. The single-bunch top-off script was updated, tested, and implemented into the control system. We optimized single-bunch top-off injection using a special fill pattern of 15 equidistant high-charge bunches. We studied a few options with nominal and increased chromaticity. Additionally, nonlinear lattice optimization for high single-bunch current mode was applied, resulting in the accumulation of 67 mA in 15 bunches at the nominal chromaticity, with the injection efficiency improved to 70%. Two equidistant bunch configurations were tested for CHX beamline experiments: 15 bunches at 4 mA each and 30 bunches at 2 mA each. These developments enhance the NSLS-II capability for time-resolved experiments.

7 Model-independent lattice characterization

NSLS-II engineers and physicists completed the Facility Improvement Project "Installation of a dedicated BPM pair for absolute and model-independent characterization of the storage ring" [10, 19, 38]. A pair of new beam position monitors (BPMs) with bunch-by-bunch resolution were installed in a magnet-free section of the storage ring. We calibrated the BPMs using both the orbit-based technique and turn-by-turn data. Using the new BPM pair, we precisely measured the beam transverse Poincare map, derived linear one-turn matrices, and calculated 4-dimensional coupled Twiss parameters at the BPM locations. The global action-angle variables obtained by normalizing beam oscillation amplitudes with these Twiss parameters are used to measure the Twiss parameters independent of the lattice model at all other BPMs. This method is quite universal and especially effective if the real machine significantly deviates from its model.

8 Section with reduced beta functions for NEXT-III

Development of the NSLS-II lattice with reduced beta functions in a long straight section has progressed with the decision to retain the double-minimum beta option, as reducing the horizontal beta function is a low priority for beamlines. Further simulations confirmed that the horizontal beta function does not constrain brightness or beamline performance. A new section with a reduced vertical beta function in Cell 26 (ARI and TXN beamlines) was designed and integrated into the lattice model. The nonlinear lattice configuration was modified to reduce the strength of resonances observed in the previous version, resulting in improved performance. A comprehensive report was completed for the mini-beta section in Cell 26, detailing linear lattice matching, nonlinear optimization, impedance-driven heating estimates, multi-particle simulations with errors and apertures, and brightness calculations for new undulators [37]. The report also outlined the requirements for implementing the lattice, including new quadrupole magnets, vacuum chambers, and power supplies. Following the successful CD-1 review for NEXT-III, we explored the feasibility of the double-mini-beta modification in Cell 26 for ARI/TXN beamlines. The layout for the double-mini-beta cell was reviewed with beamline scientists to align design priorities, ensuring compatibility with beamline performance goals.

9 Methods of lattice characterization and correction

For precise characterization of chromatic sextupoles in a storage ring, we implemented the Linear Optics from Closed Orbit Modulation (LOCOM) method with two options: 1) Independent Component Analysis (ICA) of measured turn-by-turn beam position and 2) Nonlinear Optics from off-Energy Closed Orbits (NOECO) [12, 20]. Both techniques applied to the NSLS-II storage ring demonstrated quite good accuracy, with RMS residual errors below 1%. LOCOM-NOECO, providing higher precision of beam position measurements, is preferred for accurate studies of nonlinear beam dynamics, while ICA-NOECO provides much faster analysis.

We expanded the NOECO technique to include harmonic sextupoles, addressing a limitation in the original method developed for chromatic sextupoles only. The proof of concept was validated through numerical simulations and beam measurements on the NSLS-II storage ring [1, 30]. With a vertical dispersion generated using skew quadrupoles, we measured hybrid dispersive orbits. Analyzing the measured data, we observed measurable chromatic function distortions caused by harmonic sextupoles. This expanded method offers practical benefits, such as generating significant vertical dispersion with weak skew quadrupoles while maintaining lattice optics properties due to weak coupling. Although our study focused on sextupole corrections, future investigations could extend this approach to higher-order nonlinear magnets like octupoles, provided their chromatic function dependencies are sufficiently strong.

We applied approximate entropy analysis to characterize chaos in nonlinear beam dynamics, using the NSLS-II electron storage ring as a real example [3, 33]. This technique quantifies the regularity and unpredictability of time-series data, such as turn-by-turn beam position, and serves as a chaos indicator for nonlinear lattice optimization. Relatively low computational demand makes this method particularly useful for screening lattice configurations in early design stages and potentially for online optimization if the measurement resolution is sufficient. This approach could be extended to advanced beam dynamics studies in other circular accelerators, such as hadron colliders, together with alternative entropy algorithms.

We studied the effects of the sextupole magnet offsets on the NSLS-II storage ring linear optics. Sextupole offsets can cause complex perturbations in the storage ring optics, including orbit distortion, quadrupole kicks, and couplings. The offsets in chromatic sextupoles can affect the correction of chromaticity, too. We found a reasonable solution that can explain the deviation in horizontal and vertical phase advances using the quadrupole field errors and sextupole horizontal offsets [27].

10 Collective effects and Impedances

We completed theoretical and experimental studies on the impedance and beam-induced heating of titanium-coated ceramic vacuum chambers used in the NSLS-II injection kickers [11, 16]. Using field-matching theory and numerical simulations, we characterized the impedance and demonstrated that power dissipation occurs predominantly in the titanium coating. We derived an analytical expression for the longitudinally averaged two-dimensional power density [35] and calculated the beam-induced power, taking into account realistic nonuniform coating thickness and temperature-dependent resistivity. Using the calculated power, we simulated temperature distribution along the ceramic chambers. We measured the beam-induced heating of two ceramic chambers using thermal sensors installed along the chamber and compared the measurement results with the simulations. Our measurements and simulations show a decent agreement within 2%-8%. The error sources include the thermosensors calibration and measurement accuracy of thickness, resistivity, and film coefficients. This study contributes to a better understanding of beam-induced heating and is helpful for a more predictable and reliable design of ceramic vacuum chambers for accelerator facilities.

We carried out a detailed analysis of the impedance and kick factors of an NSLS-II in-vacuum undulator (IVU) by numerical simulations and beam-based measurements [18]. Using the ECHO3D code, we simulated the full 3D IVU structure, including geometric and resistive-wall contributions. Comparisons with measurements showed better agreement for shorter bunch lengths covering a wider bandwidth of beam-induced fields in simulations. Bigger discrepancies were observed at larger IVU gaps, likely due to measurement uncertainties and limitations in the simulation model. Both measurement techniques and computational models need to be improved for accurate calculation of low-gap undulator impedances.

11 Multi-harmonic RF system

We started to study bunch lengthening in low-emittance rings induced by higher-harmonic RF cavity (HHC) systems combining active cavities of different orders [15]. In 4th-generation light sources, short bunch lengths resulting from small momentum compaction in low-emittance lattices severely limit the beam quality due to strong collective effects such as intra-beam and Touschek scattering. HHC systems provide an effective solution by increasing the equilibrium bunch length and, thereby, improving beam lifetime, mitigating collective instabilities, and reducing beam-induced heat load. However, present systems based on same-order HHCs can provide limited bunch lengthening, which is not sufficient for the NSLS-II high-brightness upgrade. Our study demonstrated that the maximum bunch lengthening is achieved using a combined HHC system of orders 2 and 3. The simulations show a bunch lengthening factor greater than 10 under optimal conditions for the ring parameters.

12 Active control of magnet vibrations

The mechanical vibrations of magnets are a major factor contributing to electron beam stability in a storage ring. We completed beam-based measurements and computer simulations of the effect of magnet vibrations on the electron beam orbit in the NSLS-II storage ring [17]. We created a MATLAB-based computer model and validated it using collected accelerometer data. To study the magnet vibration effect on the electron beam, we induced controlled vibrations of one girder supporting the magnets by use of electromagnetic actuators and collected data at different frequencies and different powers to check the vibration amplitudes. The spatial distribution of beam oscillations was measured by beam position monitors distributed in the storage ring. We found that low-power audio speakers are sufficient as a counteractive vibration source, providing the required vibration amplitude. As a next step to the active control of girder vibrations, we are developing a test assembly, which is currently under manufacturing. This work is ongoing to enhance beam stability in NSLS-II and its future upgrade via advanced techniques of active vibration suppression.

13 Three-pole wigglers

Six three-pole wigglers have been constructed at the NSLS-II IDs Lab and successfully commissioned at NSLS-II storage ring. These devices are used to produce broadband radiation with lower angular power density and to monitor the electron beam emittance and energy spread. We completed R&D activities focused on developing the required magnetic and mechanical designs, magnetic field optimization, and the final magnetic measurements. The magnetic properties of the devices have been studied and found to satisfy the specification requirements as well as the electron and photon beam performances. The results are summarized in the article published in NIM A [14].

14 NSLS-II upgrade: lattice development

We continued our effort on the lattice design for the high-brightness upgrade of NSLS-II [8, 26, 41]. We formulated requirements for the magnetic field characterization for curved and combined-function magnets. Using the complex bend field data provided by magnet experts, we computed the sextupole and octupole harmonics; the higher-order multipoles are weak. We ran the simulations to check their impacts on nonlinear beam dynamics; no big impact on dynamic aperture and momentum acceptance was observed. We found that hard-edge models might not be sufficiently accurate for complex bend magnet modeling and integration into simulations. We are working with magnet experts, developing new numerical methods, and adopting other newly developed techniques. Studying the complex bend field map, we found the sagitta is too big for the specified good field region. The large sagitta is an issue for modeling complex bends using built-in ELEGANT elements. The matrix approach looks good enough for linear lattice studies. We calculated the NSLS-IIU lattice functions using transport matrices extracted from 3D field maps of the side complex bends. The tune shifts were quite significant; the magnets could need shimming to compensate for vertical focusing. We may attach thin multipoles to every pole of the complex bend magnet to estimate nonlinear effects. We carried out nonlinear optimization of the Complex Bend lattice for the NSLS-II upgrade, improving the on-momentum dynamic aperture. We have also done the first simulations of linear optics correction for the NSLS-IIU complex bend lattice with field errors and implemented a preliminary set of undulators for simulations of collective effects. The most recent results were presented at the 9th Low Emittance Rings Workshop [28, 29].

15 NSLS-II upgrade: collective effects

We carried out convergence studies of two electromagnetic solvers, GdfidL and ECHO3D, simulating the geometric impedances of several vacuum chamber components to test the consistency and precision of the models. We reviewed bench-based measurements of impedances at several facilities and formulated our preliminary requirements for the instrumentation of our future impedance measurement lab. Due to the complex geometry of in-vacuum undulators and the lack of accurate formulas, full 3D simulations are challenging and need extensive memory and processor time, particularly when simulating the wakefields induced by short electron bunches. We explored the applicability of Machine Learning (Gaussian process regression) to model the impedance of an in-vacuum undulator, the first results look encouraging. For a complex bend lattice designed for the high-brightness NSLS-II upgrade, we studied the emittance scaling with the beam intensity and energy, considering the effects of intrabeam scattering, beam-impedance interaction, and bunch lengthening by higher-harmonic RF cavities [34]. For any lattice, there is a specific energy where the intensity-dependent emittance reaches a minimum due to the interplay of the quadratic increase of zero-intensity emittance with energy and IBS-induced blow-up at lower energies. We found that more efficient bunch lengthening moves the optimal energy down.

16 NSLS-II upgrade: injection

The magnet lattices of low-emittance synchrotrons, such as NSLS-II upgrade, are inherently nonlinear, resulting in a much smaller dynamic aperture compared to previous-generation synchrotrons. Achieving the unprecedented brightness and ultrahigh stability of NSLS-IIU photon beams demands efficient top-off injection with a limited dynamic aperture. We reviewed injection schemes of the most recent low-emittance synchrotron projects. Existing injection methods, such as on-axis swap-out (APS-U and ALS-U) or off-axis linac-based techniques (Spring-8-II and MAX-IV), need substantial injector upgrades or increased operational complexity and costs. As a cost-effective and innovative alternative, we propose an injection scheme utilizing multiple nonlinear kickers that provide successive kicks to the injected beam during its first turn, effectively reducing the beam offset to near zero. This scheme significantly reduces dynamic aperture requirements and minimizes perturbations to the stored beam.

17 Theoretical studies of free electron lasers

We completed data analysis and published results of the recently completed LDRD project on exploring FEL options for the NSLS-II upgrade. We proposed an integration of high harmonic generation (HHG) seeding for echo-enabled harmonic generation (EEHG) to develop a storage-ring-based free-electron laser (FEL) capable of generating coherent X-ray pulses in the tender to hard X-ray spectrum [7]. Implementing the proposed HHG-seeded EEHG scheme into the low-emittance upgraded NSLS-II ring, we will be able to generate ultrashort, high-brightness X-ray pulses with narrow bandwidths. This approach offers a cost-effective and efficient alternative to traditional FEL designs, potentially enhancing the capabilities of synchrotron light sources by providing femtosecond-level temporal resolution for advanced scientific applications.

We derived a small-gain formula for an X-ray free-electron laser oscillator (XFELO) based on a medium-energy (3-4 GeV) storage ring [9, 40]. We modified existing small-signal low-gain formulas, eliminating the “no focusing approximation” and accommodating strong focusing and harmonic lasing, essential for achieving hard X-ray FEL operation within this energy range. To maximize FEL performance, we applied our formula to the lattice designed for NSLS-II upgrade and carried out multiparameter optimization with collective effects taken into account.

We analyzed power loss in the optical cavity of a 10 keV X-ray Free-Electron Laser Oscillator (XFELO) [36]. We focused on the effects of refractive lenses and Bragg crystals on a monochromatic Gaussian radiation beam. X-ray power outcoupling efficiency and intra-cavity reflectivity were estimated to assess the feasibility of achieving efficient X-ray power outcoupling in XFELO systems. We also studied the focusing behavior and the effects of the curvature of compound refractive lenses on X-ray beam propagation in an optical cavity [31].

18 Ultrafast electron microscopy

We completed data analysis and published the results of a few recently completed LDRD projects on ultrafast electron diffraction and microscopy. We developed an analytical model to determine the optimal electron beam energy for in situ imaging of large biological samples, up to 10 μm thick, achieving nanometer-scale resolution [6, 32]. This model, based on elastic and inelastic scattering angles, was validated through Monte Carlo simulations. Our findings indicate that to maintain a beam size below 10 nm throughout the sample, an electron energy of at least 10 MeV is necessary.

We carried out detailed Monte Carlo simulations to study the interaction of MeV electrons with thick, frozen biological samples in scanning transmission electron microscopy (STEM) [4]. We analyzed single and multiple elastic and inelastic scattering events to understand electron trajectories, beam profiles, and intensity variations. We proposed a novel MeV-STEM designed to image thick frozen biological samples, addressing the sample thickness limitations of conventional transmission electron microscopes [5]. Our design integrates advanced electron optics and detection systems to achieve nanometer-scale resolution, enabling detailed visualization of thicker samples and promising significant improvements in imaging quality and depth for biological specimens. A novel miniature flux concentrator-based solenoid lens system was developed for MeV ultrafast electron diffraction and ultrafast electron microscopy applications [22]. Our design achieves a 2-Tesla magnetic field with 10 ppm stability and looks promising for developing high-strength focusing elements essential for achieving atomic-level resolution in ultrafast microscopy using MeV beams.

19 Support of EIC

We contributed to the Electron-Ion Collider project in frameworks of a few MOUs focused on the lattice design, development of beam diagnostic instrumentation, and design of the electron injector [23, 24, 25, 39].

We completed optimizing the EIC Electron Storage Ring (ESR) straight sections. We contributed to developing the coupling correction strategy, including determining the number and placement of skew quadrupoles and coupling measurement techniques. Synchrotron Radiation Workshop simulations were finalized for the EIC ESR Synchrotron Light Monitor at 18 GeV for two candidate locations, with simulations at 5 GeV and 10 GeV planned next. We explored the feasibility of employing undulator radiation for optical diagnostics in the EIC Hadron Ring and found that undulator radiation could be used for non-invasive proton beam diagnostics [39].

We proposed a design of a 3 GeV Booster for the EIC electron injector, estimated beam intensity limitations in the Booster, and discussed the results with collaborators. A set of lattices for the EIC Rapid Cycling Synchrotron (RCS) was prepared to study tolerances and polarization sensitivity to magnet misalignments. A cost-saving alternative arc cell design based on combined-function magnets was proposed for RCS. We participated in the EIC Virtual Machine Advisory Committee Meeting and the EIC Rapid Cycling Synchrotron Workshop. Our MOU with EIC was renewed for continued collaboration in FY25.

20 Summary

In 2024, NSLS-II accelerator physicists continued efforts to support the NSLS-II operations and start-ups, including injection transient minimization, top-off injection troubleshooting, gun charge calibration, diagnostics tuning, and lattice correction. The routine lattice characterization procedure was updated; a shared folder was established for regular reports [43]. Vertical emittance control was successfully implemented using bunch-by-bunch feedback and coupling correction by skew quadrupoles. A new method for parallel beam-based alignment was tested [21]. A plan for our contribution to the international collaboration for the development of a new Python-based Middle Layer software was developed. Regular beam dynamics reports were generated and uploaded to a dedicated Sharepoint website [42]; the primary sources of emittance and lifetime perturbations were identified. The analysis of seasonal variations of the NSLS-II circumference and energy is complete; the results have been published [13].

For the time-resolved experiments, we optimized the high-current single-bunch operations, improving injection efficiency, a few tests with CHX beamline were done. The Facility Improvement Project "Installation of a dedicated BPM pair for absolute and model-independent characterization of the storage ring" has been successfully completed [10, 19, 38]. For NEXT-III, we developed an NSLS-II lattice option with reduced beta functions in Cell 26 [37] and reviewed the layout and performance with beamline scientists.

We developed and implemented advanced methods of lattice characterization and correction: Linear Optics from Closed Orbit Modulation (LOCOM) [12, 20], Nonlinear Optics from off-Energy Closed Orbits (NOECO) for harmonic sextupoles [1, 30], and approximate entropy analysis to characterize chaos in nonlinear beam dynamics [3, 33].

Our studies of the impedance and beam-induced heating of titanium-coated ceramic chambers are complete [11, 16]; an analytical expression for the beam-induced power density was derived [35]. Numerical simulations and beam-based measurements of the in-vacuum undulator impedance and kick factor are done [18]. We studied bunch lengthening by higher-harmonic RF cavities of different orders [15], essential for the NSLS-II upgrade. The effect of magnet vibrations on the electron beam orbit was studied numerically and experimentally to assess the possibility of active vibration suppression [17].

We continued our effort on the NSLS-II upgrade, including lattice development and optimization, estimation of higher-order multipoles on nonlinear beam dynamics, accurate complex bend magnet modeling, and implementation of a preliminary set of undulators for simulations of collective effects. We studied the emittance scaling with the beam intensity and energy, taking into account intrabeam scattering, beam-impedance interaction, and bunch lengthening by higher-harmonic RF cavities [34]. We reviewed injection schemes of the most recent low-emittance synchrotrons and proposed an injection scheme using multiple nonlinear kickers.

We studied high harmonic generation seeding for the echo-enabled harmonic generation to develop a ring-based free-electron laser in the tender to hard X-ray range [7]. The possibility of designing an X-ray free-electron laser oscillator based on a medium-energy storage ring has been explored [9, 40], including the analysis of compound refractive lenses and power loss in the optical cavity [31, 36].

A model of wave function collapse in a quantum measurement of spin as the Schrödinger equation solution of a system with a simple harmonic oscillator in a bath has been developed [2]. This analysis contributes to the ongoing debate on the foundations of quantum mechanics regarding the true nature of the quantum state.

As a part of theoretical studies of ultrafast electron microscopy, we analyzed imaging of large biological samples to find the optimal electron beam energy [6, 32], studied the interaction of MeV electrons with thick samples in scanning transmission electron microscopy [4], and proposed a novel MeV-STEM addressing the sample thickness limitations of conventional transmission electron microscopes [5, 22].

Our support of the Electron-Ion Collider project included the Electron Storage Ring lattice design, the development of beam diagnostic instrumentation, and studies of the electron injector [23, 24, 25, 39], the MOUs with EIC were renewed for FY25.

The physicists participated in the Accelerator Middle Layer Workshop, EIC Rapid Cycling Synchrotron Workshop, EIC Injector Review, USPAS 2024 winter session, Scientific Meeting on the strong-focusing combined-function magnets, and NSLS-IIU Accelerator and Science Retreat. Figure 1 shows the statistics of journal articles and conference reports published from FY14 to FY24.

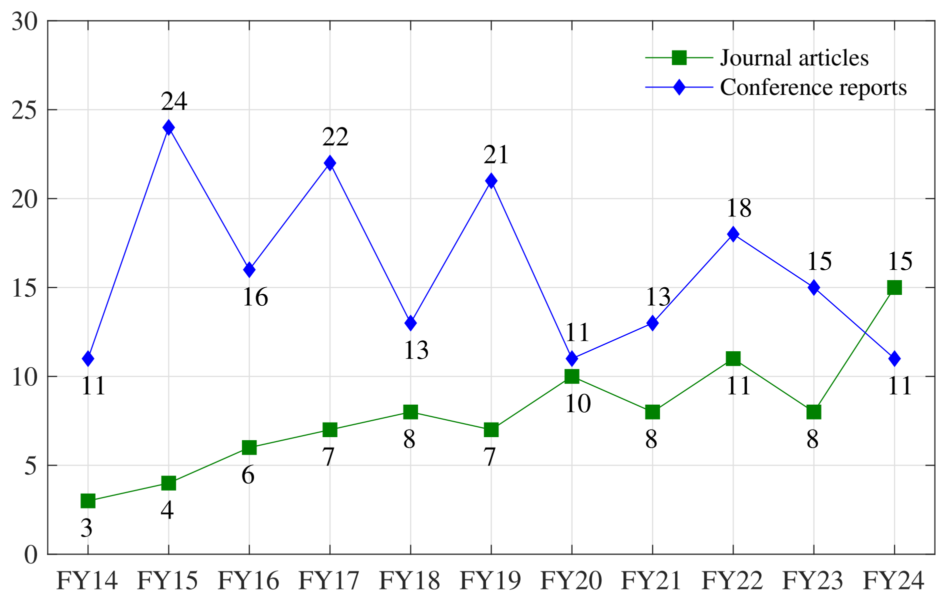

Figure 1: Journal articles and conference reports

References

Journal articles

[1] Y. Li, D. Xu, V. Smaluk, R. Rainer, *Nonlinear optics from hybrid dispersive orbits*, Nucl. Instrum. Meth. A 1060 (2024) 169032.

[2] L.H. Yu, *A model of wave function collapse in a quantum measurement of spin as the Schroedinger equation solution of a system with a simple harmonic oscillator in a bath*, Int. J. of Quantum Foundations 10, 1 (2024), pp. 1-25.

[3] Y. Li, R. Rainer, *Approximate entropy analysis for nonlinear beam dynamics*, Phys. Rev. Accel. Beams 27 (2024) 011601.

[4] L. Wang, X. Yang, *Monte Carlo Simulation of Electron Interactions in an MeV-STEM for Thick Frozen Biological Sample Imaging*, Appl. Sci. 14 (2024) 1888.

[5] X. Yang, L. Wang, J. Maxson, A. Bartnik, M. Kaemingk, W. Wan, L. Cultrera, L. Wu, V. Smaluk, T. Shaftan, S. McSweeney, C. Jing, R. Kostin, Y. Zhu, *Towards Construction of a Novel Nanometer-Resolution MeV-STEM for Imaging Thick Frozen Biological Samples*, Photonics 2024, 11(3), 252.

[6] X. Yang, L. Wang, V. Smaluk, T. Shaftan, *Optimize Electron Beam Energy toward In Situ Imaging of Thick Frozen Bio-Samples with Nanometer Resolution Using MeV-STEM*, Nanomaterials 2024, 14, 803.

[7] X. Yang, L.H. Yu, V. Smaluk, T. Shaftan, *HHG seeding EEHG toward a storage ring based tender and hard X-ray Free Electron Laser*, Instruments 2024, 8(2), 35.

[8] M. Song, T. Shaftan, *Design study of a low emittance complex bend achromat lattice*, Phys. Rev. Accel. Beams 27 (2024) 061601.

[9] L.H. Yu, V. Smaluk, T. Shaftan, G. Tiwari, X. Yang, *3D small-gain formula allowing strong focusing and harmonic lasing for a ring-based x-ray free electron laser oscillator*, Phys. Rev. Accel. Beams 27 (2024) 060702.

[10] Y. Li, K. Ha, D. Padrazo, B. Kosciuk, B. Bacha, M. Seegitz, R. Rainer, J. Mead, X. Yang, Y. Tian, R. Todd, V. Smaluk, W. Cheng, *Dedicated beam position monitor pair for model-independent lattice characterization at NSLS-II*, Nucl. Instrum. Meth. A 1065 (2024) 169557.

[11] A. Khan, G. Bassi, B. Kosciuk, R. Todd, V. Smaluk, B. Bacha, P. Palecek, C. Hetzel, *Simulation and measurement of beam-induced heating of ceramic vacuum chambers*, Phys. Rev. Accel. Beams 27 (2024) 084501.

[12] X. Yang, X. Huang, Y. Hidaka, V. Smaluk, G. Wang, *Implementing Nonlinear Optics From Off-energy Closed Orbit at NSLS-II*, Nucl. Instrum. Meth. A 1065 (2024) 169743.

[13] V. Smaluk, L.H. Yu, C. Yu, S. Sharma, A. Suvorov, Y.Q. Cai, *Measurement of seasonal variations of the NSLS-II circumference and energy*, Nucl. Instrum. Meth. A 1069 (2024) 169858.

[14] M. Musardo, T. Tanabe, J. Rank, Y. Hidaka, D. Hidas, T. Corwin, C. Kitegi, *Three-pole wigglers at NSLS-II*, Nucl. Instrum. Meth. A 1059 (2024) 169008.

Conference reports

[15] G. Bassi, A. Khan, V. Smaluk, *Bunch lengthening induced by a combination of higher-harmonic cavities of different order in low-emittance rings*, Proc. of 15th Int. Particle Acc. Conf. (IPAC2024), Nashville, THBD2.

[16] A. Khan, G. Bassi, B. Kosciuk, V. Smaluk, R. Todd, B. Bacha, *Beam-based measurements of titanium coated ceramic chambers at NSLS-II*, Proc. of 15th Int. Particle Acc. Conf. (IPAC2024), Nashville, THPC47.

[17] A. Khan, J. Gomprecht, C. Yu, S. Sharma, V. Smaluk, G. Wang, *Measurements and computer simulations of the effect of magnet vibrations on the electron beam orbit in the NSLS-II storage ring*, Proc. of 15th Int. Particle Acc. Conf. (IPAC2024), Nashville, WEPG07.

[18] A. Khan, M. Seegitz, V. Smaluk, X. Yang, *Comparison of simulation and measurement of an in-vacuum undulator coupling impedance at NSLS-II*, Proc. of 15th Int. Particle Acc. Conf. (IPAC2024), Nashville, THPC46.

[19] K. Ha, B. Bacha, D. Padrazo Jr, J. Mead, V. Smaluk, Y. Li, Y. Tian, W. Cheng, S. Kongtawong, *NSLS-II bunch by bunch BPM development and beam operation*, Proc. of 15th Int. Particle Acc. Conf. (IPAC2024), Nashville, WEPG08.

[20] X. Yang, Y. Hidaka, V. Smaluk, G. Wang, X. Huang, *Implementing NOECO at NSLS-II*, Proc. of 15th Int. Particle Acc. Conf. (IPAC2024), Nashville, WEPC27.

[21] M. Song, X. Yang, J. Choi, Y. Hidaka, G. Wang, X. Huang, *Test of parallel beam-based alignment at NSLS-II*, Proc. of 15th Int. Particle Acc. Conf. (IPAC2024), Nashville, THPC83.

[22] C. Jing, G. Chen, A. Kanareykin, A. Simmonds, K. Kusche, M. Palmer, M. Fedurin, X. Yang, Y. Zhu, E. Dosov, E. Knight, P. Avrakhov, Y. Zhao, E. Montgomery, S. Antipov, *Development of a flux-concentrator-based 2-Tesla solenoid as a round lens for ultrafast microscopy*, Proc. of 15th Int. Particle Acc. Conf. (IPAC2024), Nashville, TUPR77.

[23] C. Montag, A. Zaltsman, A. Fedotov, B. Podobedov, B. Parker, C. Folz, C. Liu, D. Marx, D. Weiss, D. Xu, D. Kayran, D. Holmes, E. Aschenauer, E. Wang, F. Willeke, F. Meot, G. Wang, G. Mahler, G. Robert-Demolaize, H. Huang, H. Lovelace III, H. Witte, I. Pinayev, J. Berg, J. Kewisch, J. Tuozzolo, K. Smith, K. Drees, M. Sangroula,

M. Blaskiewicz, M. Minty, Q. Wu, R. Gupta, R. Than, S. Seletskiy, S. Peggs, S. Tepikian, S. Nayak, W. Xu, W. Bergan, W. Fischer, X. Gu, Y. Li, Y. Luo, Z. Conway, A. Blednykh, C. Hetzel, D. Gassner, J. Jamilkowski, N. Tsoupas, P. Baxevanis, S. Nagaitsev, S. Verdu-Andres, V. Ptitsyn, V. Ranjbar, V. Shmakova, A. Seryi, B. Gamage, E. Nissen, E. Daly, K. Deitrick, R. Rimmer, S. Philip, S. Benson, T. Michalski, T. Satogata, D. Sagan, G. Hoffstaetter, J. Unger, M. Signorelli, E. Gianfelice-Wendt, F. Lin, V. Morozov, G. Stupakov, J. Qiang, M. Sullivan, Y. Cai, Y. Nosochkov, Y. Hao, *The EIC accelerator: design highlights and project status*, Proc. of 15th Int. Particle Acc. Conf. (IPAC2024), Nashville, MOPC67.

[24] D. Marx, C. Montag, D. Xu, D. Holmes, E. Aschenauer, J. Berg, J. Kewisch, K. Hamdi, S. Tepikian, Y. Li, Y. Luo, Z. Zhang, B. Gamage, D. Gaskell, B. Bhandari, E. Link, M. Signorelli, *Design Updates to the EIC Electron Storage Ring Lattice*, Proc. of 15th Int. Particle Acc. Conf. (IPAC2024), Nashville, MOPC73.

[25] Y. Nosochkov, Y. Cai, C. Montag, D. Marx, H. Witte, J. Berg, J. Kewisch, S. Peggs, S. Tepikian, Y. Li, G. Hoffstaetter, J. Unger, M. Signorelli, *Dynamic aperture of the EIC electron storage ring*, Proc. of 15th Int. Particle Acc. Conf. (IPAC2024), Nashville, MOPC82.

[26] M. Song, T. Shaftan, *Design of the low-emittance complex bend lattice*, Proc. of 15th Int. Particle Acc. Conf. (IPAC2024), Nashville, THPC82.

[27] J. Choi, Y. Hidaka, G. Wang, *Sextupole Offset Effects on the Storage Ring Linear Optics*, Proc. of 15th Int. Particle Acc. Conf. (IPAC2024), Nashville, THPC04.

[28] Y. Li, et al., *Complex bend lattice design for NSLS-II upgrade*, 9th Low Emittance Rings Workshop, Geneva, 2024.

[29] T. Shaftan, et al., *Magnetic designs and tests of the Complex Bend approach at NSLS-II*, 9th Low Emittance Rings Workshop, Geneva, 2024.

Technical notes

[30] Y. Li, D. Xu, V. Smaluk, R. Rainer, *Nonlinear optics from hybrid dispersive orbits*, BNL-225110-2023-TECH.

[31] G. Tiwari, L. Yu, X. Yang, T. Shaftan, V. Smaluk, *Compound refractive lenses for X-rays*, BNL-225130-2023-TECH.

[32] X. Yang, V. Smaluk, T. Shaftan, *Optimize electron beam energy toward in-situ imaging of large thick bio-samples with nanometer resolution*, BNL-225131-2023-TECH.

[33] Y. Li, R. Rainer, *Approximate Entropy Analysis for Nonlinear Beam Dynamics*, BNL-225182-2024-TECH.

[34] V. Smaluk, T. Shaftan, *Electron beam emittance at operational intensity in fourth-generation synchrotron light sources*, BNL-225308-2024-TECH.

[35] G. Bassi, *Power Dissipation on the Metallic Coating of a Ceramic Chamber in Planar Approximation*, BNL-225654-2024-TECH.

[36] G. Tiwari, L.H. Yu, X. Yang, T. Shaftan, V. Smaluk, *Power loss analysis for optical cavity of X-ray free-electron laser oscillator at 10 keV*, BNL-225541-2024-TECH.

[37] Y. Li, Y. Hidaka, A. Khan, M. Song, D. Hidas, O. Chubar, V. Smaluk, *Reducing beta functions in the NSLS-II long straight section for NEXT-III beamlines*, BNL-225564-2024-TECH.

[38] Y. Li, K. Ha, D. Padrazo, B. Kosciuk, B. Bacha, M. Seegitz, R. Rainer, J. Mead, X. Yang, Y. Tian, R. Todd, V. Smaluk, *Dedicated beam position monitor pair for model-independent lattice characterization at NSLS-II*, BNL-225900-2024-TECH.

[39] I. Pinayev, G. Bassi, *Optical Diagnostics with Undulator Radiation for EIC Hadron Ring*, BNL-225694-2024-TECH.

[40] L.H. Yu, V. Smaluk, T. Shaftan, G. Tiwari, X. Yang, *Feasibility study of a hard x-ray FEL oscillator at 3 to 4 GeV based on harmonic lasing and transverse gradient undulator*, arXiv:2310.15307.

[41] M. Song, T. Shaftan, *Design study of a low emittance complex bend achromat lattice*, arXiv:2310.20010.

Web resources

[42] BNL SharePoint: Beam Dynamics Reports

[43] BNL SharePoint: NSLS-II Lattice Characterization Reports