BNL-225901-2024-TECH

NSLSII-ASD-TN-418

Accelerator Physics at NSLS-II: Research Accomplishments in 2023

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December 2023

Photon Sciences

Brookhaven National Laboratory

U.S. Department of Energy

USDOE Office of Science (SC), Basic Energy Sciences (BES)

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NSLS-II TECHNICAL NOTE BROOKHAVEN NATIONAL LABORATORY	NUMBER **NSLSII-ASD-TN-418**
AUTHORS: Smaluk, V., Bassi, G., Khan, A., Li, Y., Yang, X., Yu, L.H., Tiwari, G., Song, M., Wang, G., Choi, J., Hidaka, Y., Hidas, D., Tanabe, T., Sharma, S., Shaftan, T.	DATE 12/30/2023
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Dec. 30, 2023

Abstract

NSLS-II accelerator physicists provided operation support for user operations and machine start-ups, carried out routine lattice characterization, and produced regular reports on beam dynamics. The commissioning of a superconducting wiggler for the HEX beamline is complete, and the wiggler effects on beam dynamics have been studied. A Facility Improvement Project for absolute lattice characterization has been approved and funded. We implemented and tested a new orbit-based technique of lattice characterization and correction. We developed a theory to calculate the beam-induced power in ceramic vacuum chambers and a new convergence map technique for nonlinear lattice characterization. We continued working on the NSLS-II upgrade including lattice development, commissioning a low-energy complex bend prototype, analyzing beam sensitivity to various errors, implementing higher-harmonic RF cavities, studying collective effects, and assessing FEL options. We also supported lattice optimization and beam diagnostics development for the EIC project. Main research accomplishments achieved in 2023, are summarized in this report.

1 Introduction

In 2023, NSLS-II accelerator physicists provided scientific support for user operations, machine start-up after shutdowns and maintenance days, and the commissioning of a superconducting wiggler for the HEX beamline. Routine lattice characterization was continued to keep tracking the machine's status and performance. Our new colleagues were trained on the high-level applications for beam studies. We were also working on several development and R&D activities including design and optimization of the lattice and studies of collective effects for NSLS-II upgrade. Three LDRD projects led by the accelerator physicists have been completed: 20-041 "Conceptual Design Options for Future Upgrade of NSLS-II Facility", 22-028 "Assessment of FEL options for NSLS-II upgrade", and 22-029 "Towards ultrafast electron microscope with nanometer resolution". Several talks have been prepared and presented at the Retreat on Plans for NSLS-II Upgrade. We discussed the global landscape of light sources, scientific directions in the next decade, options for ring-based and FEL-based light sources, R&D directions for the next generations of insertion devices, and instrumentation for electron and X-ray beam stability. A new Facility Improvement Project for absolute lattice characterization has been approved and funded. A few student projects supervised by the group members have been completed. We participated in the BES Basic Research Needs Workshop for Accelerator-Based Instrumentation and contributed to developing the BRN report for DOE. We continued supporting the EIC project contributing to the development of beam diagnostics and optimization of the electron storage ring lattice.

This is a list of major projects and activities in 2023:

- NSLS-II operations and start-up
- Beam dynamics reports
- HEX SCW commissioning
- Facility Improvement Project for absolute lattice characterization
- Beam-induced heating of ceramic chambers
- Beam power loss in vacuum chamber components
- New techniques for lattice characterization
- Reducing beta functions in long straight sections
- Assessment of new insertion devices
- NSLS-II upgrade: lattice development
- NSLS-II upgrade: higher-harmonic RF cavities
- NSLS-II upgrade: collective effects
- NSLS-II upgrade: FEL options
- Complex bend magnet prototype
- Beam sensitivity to girder vibrations
- Novel technique for particle stability diagram
- Ultrafast Electron Microscopy
- Support of EIC project

2 Support of NSLS-II operations and start-up

Accelerator physicists participated in the machine start-up after shutdowns and maintenance periods. To keep track of the injector gun performance, several measurements of the gun charge at the end of the Linac were taken for a set of voltages and pulse widths. To improve injection efficiency, regular matching of the Linac-to-Booster transport line and Booster optimization were done. A software code based on the Robust Conjugate-Gradient Algorithm is now a regularly used tool for online optimization of the injection kickers to minimize the beam perturbation during injection [1]. We optimized the full set of kicker parameters, including the trigger timing, amplitude, and pulse width. The beam diagnostics systems including the bunch-by-bunch feedback, the pinhole camera, and the SLM camera were regularly checked and tuned.

Regular measurements of seasonal variations of the ring circumference affecting the beam dynamics have been arranged since February 2023. We observed changes in the ring circumference from February to September, correlated with the average temperature.

A few training sessions were provided for our postdocs on how to use HLA common tools for lattice characterization and correction, and for measurement and analysis of dynamic aperture and tune shift with amplitude. MATLAB Middle Layer was supported and maintained, new functions were tested and implemented for lattice characterization and correction, and for parallel beam-based alignment. Participation of our accelerator physicists in the international collaboration on developing a new Python interface for accelerator controls has been reviewed and approved.

Several beam studies were carried out for the lattice characterization and correction including new optics feedforward tables compensating effects of the superconducting wiggler for HEX beamline. We also worked on the implementation of the lattice characterization tool based on a short diagnostics train and gated BPMs, and the Parallel Beam-Based Analysis technique.

3 Beam dynamics reports

Regular reports on beam dynamics are established to understand the long-term behavior of the accelerator systems. More than 20 reports with data analysis have been uploaded to a dedicated Sharepoint website [31]. Key beam parameters, such as emittance, energy spread, lifetime, injection transients, and others, are monitored using all available diagnostic tools including synchrotron light monitors, pinhole cameras, streak camera, beam position monitors, and bunch-by-bunch feedback system. The data analysis, correlations found, and possible reasons are summarized.

4 HEX SCW commissioning

In 2023, a superconducting wiggler (SCW) with a peak field of 4.3 T has been installed and commissioned. The wiggler generates a high-flux X-ray beam with a photon energy range from 20 keV to 200 keV for the High Energy Engineering X-ray Scattering beamline (HEX). This device induces significant distortions in the electron beam orbit and optics. We have corrected these adverse effects using feed-forward tables. We estimated the HEX SCW effects on the emittance, energy spread, bunch length, and synchronous phase as functions of the SCW current using analytical formulae and numerical simulations. Then we measured these beam parameters using optical diagnostic tools and compared the results with theory and simulations. The horizontal emittance decreased from 0.78 nm to 0.7 nm, the energy spread increased from 0.077% to 0.087%, and the bunch length increased from 13 ps to 15.5 ps when the HEX SCW current was ramped from zero to maximum. The calculations are in good agreement with the measurements. The impedance and beam-induced heating of the SCW vacuum chamber was also studied combining the contributions from both geometric and resistive-wall impedance including the cold liner, two warm tapered transitions, and two transitions from 300 K to 20 K. Since the SCW commissioning, no overheating issues were observed during regular operations with 400 mA and studies with 500 mA of the beam current. Results of the HEX SCW commissioning were presented at the 14th Int. Particle Accelerator Conf. (IPAC'23) [14, 21] and published in Nucl. Instrum. Meth. A [8].

5 Facility Improvement Project for absolute lattice characterization

Currently, the NSLS-II lattice functions are calibrated by measuring the beam oscillation amplitude by 180 beam position monitors (BPMs) when coherent betatron oscillations are excited by a pulse kick. The measured oscillation amplitude is proportional to the square root of the beta function but there is an intrinsic systematic error determined by the initial excitation amplitude, which makes impossible absolute calibration of beta functions. So, the present method is essentially model-dependent, and the measurement is invalid if the betatron coupling is strong. We proposed to install two extra button-type BPMs separated by a drift space and equipped with turn-by-turn or bunch-by-bunch data acquisition electronics and integrated into the NSLS-II control system. With these two BPMs, it is possible to calculate the transverse beam position and its momentum at the same location using a simple and accurate formula. So, we can provide an absolute and model-independent lattice characterization eliminating the systematic error, which is intrinsic to the method we are using now. Our Facility Improvement Project "Installation of a dedicated BPM pair for absolute and model-independent characterization of the storage ring" has been approved and funded. The procurements and electronics testing for two BPMs are going well. The BPM receivers are in the lab and the button assemblies are already installed in Cell 1. Beam testing is expected in the FY24 spring run.

6 Beam-induced heating of ceramic chambers

We completed our theoretical and experimental studies of the impedance and beam-induced heating of titanium-coated ceramic vacuum chambers used in the NSLS-II injection kickers. Through analytical calculations and numerical simulations, we have characterized the impedance of the two-layer electromagnetic system and demonstrated that for the coating thickness of a few microns, the beam-induced power is mostly dissipated in the titanium coating [10]. As we found the longitudinally averaged two-dimensional power density is independent of the vertical coordinate and its horizontal distribution is Gaussian with a standard deviation equal to the thickness of the ceramics, we developed a simplified model for ANSYS simulations. For a few values of the NSLS-II beam current, we measured the beam-induced heating of two ceramic chambers and compared the measurement results with the simulations.

7 Beam power loss in vacuum chamber components

By requests from the Vacuum Group and ID Group, the impedance and beam-induced power were calculated for new vacuum chambers: 1) A custom chamber with a mirror for extraction of infrared radiation for INF beamline. This chamber is designed to fit inside a standard-gap dipole magnet. The conclusion is the chamber's geometry and mirror position have a low contribution to the beam-induced power. 2) A vacuum chamber for the ALS-U bellows test. A sharp resonance peak, which seems like a trapped mode, was found to contribute about 20% to the total power of 27 W. 3) A chamber for the adaptive gap undulator. The total power loss from geometric and resistive wall impedance is about 130 W.

8 New techniques for lattice characterization

We are working in collaboration with SLAC experts on the implementation of novel techniques of lattice characterization and correction: Linear Optics from Closed Orbit Modulation (LOCOM) and Nonlinear Optics from Off-Energy Closed Orbits (NOECO). LOCOM is essentially an improvement of a previously used Linear Optics from Closed Orbits (LOCO) technique but instead of fitting individual closed orbits, the improved method decomposes the orbit oscillation data into two orthogonal modes and fits the amplitudes of the modes at all beam position monitors. The improved method greatly reduces the number of data points and allows a substantially larger collection of orbits to be used in fitting. This is especially useful for the AC version of LOCOM case when the two modulating correctors are driven by sine signals and the BPM data are taken at the same frequency, then a large number of modulated orbits can be read in a short period (e.g., 10000 orbits in 1 s for NSLS-II). We benchmarked the LOCOM technique with the well-established Independent Component Analysis (ICA) and confirmed a good agreement between LOCOM and ICA [5, 16].

We also continued the development of the ICA-based NOECO tool. Numerical simulations predict a possibility for the calibration of chromatic sextupoles with an accuracy of about 1-2%. This could potentially resolve the long-standing discrepancies between the NSLS-II design and measured nonlinear parameters such as tune shift with amplitude. To test the ICA-NOECO technique, we applied a 10% error to one of 5 power supplies of one chromatic sextupole family and were able to measure it with an accuracy of about 1%.

A technique characterizing Nonlinear Optics from Off-Energy Closed Orbits (NOECO) was developed at MAX-IV and applied to correct the chromatic sextupole errors. However, it does not apply to harmonic sextupoles, which are widely used for the optimization of dynamic aperture. We extended this technique to characterize harmonic sextupoles in storage rings [9, 13]. Through generating vertical dispersion with chromatic skew quadrupoles, a measurable dependence of nonlinear optics on harmonic sextupoles can be observed from hybrid horizontal and vertical dispersive orbits. The expanded technique for measuring nonlinear optics distortions from off-energy orbits taking into account the harmonic sextupole contribution, was tested by simulations and beam measurements at the NSLS-II storage ring. The main results of this work were presented at the IPAC'23 conference and the 67th ICFA Advanced Beam Dynamics Workshop on Future Light Sources (FLS 2023).

We studied a systematic error in the quadrupole beam-based alignment caused by a nonzero dipole component existing after the variation of the quadrupole strength [25]. Analytical formulae for this error and its amplification factor with respect to the magnetic center motion have been derived and confirmed with simulations. We demonstrated the significance of this error, potentially on the order of hundreds of microns, through both simulations and experiments.

We are developing a technique for sextupole beam-based alignment, the first measurements of sextupole offsets have been done [26]. Although the measured results do not give accurate numbers, unlike the quadrupole offset measurements, we were able to get some ideas about sextupole offsets.

9 Reducing beta functions in long straight sections

By request from the Photon Division, a working group has been formed for the development of an NSLS-II lattice with reduced beta functions in long straight sections for some of the new NEXT-III beamlines. Originally, we considered two options: 1) lattice with one single-minimum cell and 2) lattice with one double-minimum cell. The scope of work included linear lattice matching; simulations of dynamic aperture limiting injection and momentum aperture limiting beam lifetime, without and with errors; determining the range of in-vacuum undulator gap limited by the beam stay-clear; estimation of the beam-induced heating of small-gap undulators. We found the single-minimum option will not work for one or two undulators because of the beam stay-clear limitation. For the double-minimum option, the vertical beta function in each minimum can vary from 0.6 m to 2.5 m to meet the existing beam stay-clear requirements. The most recent lattice solution provides a minimum of 0.8 m. We expect 6.3 m of free space available for undulators, symmetric around the middle of the straight section.

10 Assessment of new insertion devices

We completed an assessment of beam dynamics effects for a future high-field 3-pole wiggler, considering the maximum field from 1 to 4 Tesla. The physical aperture data were checked and the beam stay-clear was re-computed by incorporating the beta function in the vertical plane. The conclusion is that the vertical aperture is limited at the edges of damping wigglers. If the location of a high-field 3-pole wiggler is the same as of the present 3PWs, the vertical beam stay-clear should be larger than ± 9 mm. We also calculated the radiation power distribution using a field map. For a 2-Tesla 3-pole wiggler, the total radiation power is about 720 W. We also considered accelerator physics issues of the installation of the APS SCU18 as a second undulator in Cell 10, including optics correction, longitudinal location, impedance modeling, and heat load estimate. By request from the Radiological Control Division, a top-off safety analysis has been completed for the updated ARI/SXN beamline in cell 29.

11 NSLS-II upgrade: lattice development

In 2023, we completed the LDRD 20-041 project "Conceptual Design Options for Future Upgrade of NSLS-II Facility". We continued working on the lattice design for the high-brightness upgrade of NSLS-II assuming the following key features: fitting to the existing tunnel and X-ray ports; sufficiently long straight sections for undulators; lowest possible emittance and optimal beta functions for high brightness; reasonable energy spread and bunch length; large dynamic aperture for off-axis injection; large momentum aperture for beam lifetime; sufficient space for vacuum and diagnostics components.

The design of the hybrid MBA lattice candidate for the NSLS-II upgrade is complete. This lattice with longitudinal gradient dipoles and reverse bending provides a reasonably small emittance of 28 pm, close to 25 pm of the optimized APS-U lattice scaled to the NSLS-II energy and circumference. With harmonic sextupoles and octupoles, the dynamic aperture is large enough for off-axis injection.

The most recent version of the complex bend achromat lattice with the emittance of 23.5 pm includes one of 15 supercells with high beta functions for injection and all other supercells with low and/or double low beta functions for light-generating insertion devices.

12 NSLS-II upgrade: higher-harmonic RF cavities

A common feature of low-emittance lattices is the small momentum compaction resulting in a short equilibrium bunch length. A short bunch interacting with the vacuum chamber impedance leads to significant beam-induced heating of the chamber components. A short bunch length combined with the small transverse emittances causes strong intra-beam scattering resulting in severe beam quality degradation. Higher-harmonic RF cavity (HHC) systems increasing the bunch length without increasing the energy spread are used to mitigate the above adverse effects. For the MBA lattice option of the NSLS-II low-emittance upgrade, we carried out numerical simulations of beam dynamics with a passive 3rd-harmonic cavity system, addressing both stability and the performance limitation due to a gap in the uniform filling pattern for ion cleaning [11]. For these simulations, we used a time-dependent Vlasov-Fokker-Planck equation solver implemented in the SPACE code, which allows for the self-consistent computation of short- and long-range wakefield effects. As it was found, the present bunch fill pattern with a single gap used for the NSLS-II operations significantly reduces the harmonic cavity performance, but it can be greatly improved by operating with a few bunch trains separated by smaller gaps. In the framework of the BNL summer internship program, we also carried out analytical studies of bunch lengthening caused by a combination of two harmonic RF cavities with different harmonic numbers.

13 NSLS-II upgrade: collective effects

Intra-beam scattering (IBS) is one of the adverse collective effects of beam dynamics resulting in a significant intensity-dependent growth of the emittance, energy spread, and bunch length. Although this effect is partially mitigated by the bunch lengthening caused by the longitudinal impedance, higher-harmonic cavity systems are essential. They are needed to provide bunch lengthening sufficient to keep the emittance low enough for achieving the designed brightness at operational beam intensity. For a hybrid MBA lattice of the ESRF-EBS type considered as an option for the NSLS-II upgrade, we studied a combined effect of the IBS, impedance, and harmonic cavities using a parallel version of the ELEGANT tracking code [12]. We modeled the longitudinal impedance by a broadband resonator with its parameters determined based on prior experience at NSLS-II. We incorporated IBS and a 3rd harmonic cavity into our analysis using built-in elements of ELEGANT and the beam parameters determined by the lattice model. To obtain realistic vertical and horizontal emittances, we implemented betatron coupling driven by skew quadrupoles. For three energy options of NSLS-II upgrade, 3, 3.5, and 4 GeV, we completed multi-particle simulations of the combined effect of IBS and impedance, with and without 3-rd harmonic cavities. The results are quite consistent with the high-energy approximation IBS formulae.

14 NSLS-II upgrade: FEL options

In 2023, we completed the LDRD project 22-028 "Assessment of FEL options for NSLS-II upgrade". The project goals were to explore two options: 1) hard X-Ray Free-Electron Laser Oscillator (XFELO) based on the upgraded low-emittance NSLS-II storage ring with beam energy as low as 3 GeV; and 2) soft X-ray generation by Echo-enabled Harmonic Generation (EEHG) on the upgraded NSLS-II storage ring. Possible scientific cases for both FEL options were figured out together with NSLS-II beamline scientists. For the XFELO option, the main challenges of the NSLS-II upgraded lattice are the low energy of 3 GeV and large energy spread of 10^{-3}. We developed an accurate gain formula including harmonic lasing, strong focusing, and vertical dispersion. A one-dimensional theory of harmonically seeded free-electron laser has been analyzed [6]. We studied possible X-ray mirrors and focusing lenses for the optical cavity and confirmed a total X-ray cavity loss of 5% is feasible. We optimized the XFELO parameters taking into account collective effects and bunch lengthening by a higher-harmonic cavity [18]. We found the higher-energy options of 3.5 GeV and 4 GeV are feasible providing the FEL gain of 6% and 12%, respectively. For the energy of 3 GeV, a local coupling correction scheme was proposed to keep large coupling outside the FEL section for mitigation of intrabeam scattering and correct coupling in the FEL section to a minimum value for maximum gain. For the EEHG option, we have developed a software tool to design a compact EEHG beamline using two straight sections of a storage ring. We optimized the energy modulation to maximize coherent radiation output and mitigate de-bunching induced by the beam energy spread [15]. Our standardized EEHG beamline design covers the photon energy ranges of soft X-ray (1.25 - 2.5 nm) and EUV (2.5 - 50 nm). We optimized two-stage separation to minimize energy modulation and mitigate ISR effects. A twin-pulse seeding scheme was developed to enable pump-probe capabilities [3]. A cascaded EEHG has been proposed to extend the short wavelength limit to tender and hard X-rays [7]. The results of the LDRD project were presented at the IPAC'23 conference and the American Physical Society Meeting, and published in Review of Scientific Instruments, Scientific Reports, Phys. Rev. Accel. Beams, and J. Synchrotron Rad.

15 Complex bend magnet prototype

To prove the feasibility of the complex bend concept, a low-energy prototype with a quadrupole gradient of 140 T/m has been designed, fabricated, installed, and commissioned at NSLS-II linac beamline with a beam energy below 200 MeV [19]. This beamline commissioning was split into two consecutive phases. In phase I, the beam passes through the center of the complex bend magnet, which, in this case, functions as a set of strong periodic focusing quadrupoles. In phase II, the beam passes through the complex bend with a transverse offset, so the complex bend functions as both a bending and focusing element. The beam diagnostics includes three flags to measure the beam profile and beamline optics. One high-resolution (a few microns) flag was installed to characterize the beam focusing after the complex bend. By applying Robust Conjugate Direction Search (RCDS) online optimization with a proper target function, the complex bend was tuned to focus the beam at three diagnostic flags. The initial beam commissioning results show quite good agreement with the model.

16 Beam sensitivity to girder vibrations

Magnet alignment and mechanical stability are essential to the performance of modern light sources. Modeling the sensitivity to various errors is an important part of the low-emittance ring design, which includes studies to identify the error sources and to develop adequate correction systems [2]. We proposed, planned, and carried out an experiment with forced girder vibration to measure the NSLS-II beam sensitivity to the girder vibrations. A SULI Internship project "Measuring and modeling the effect of magnet vibrations on electron beam stability in storage rings" has been proposed and approved. The goal was to measure the response of an electron beam orbit to magnet vibrations excited by controlled shaking of specific girders and the development of a reliable computer model based on the measured data. A computer model based on Simulation Commissioning Tool, a part of MATLAB Accelerator Toolbox, has been developed to simulate girder vibrations affecting the beam orbit in several ways, depending on the location and orientation of the girders, as well as on the frequency and amplitude of the vibrations. Using controlled girder shaking by powerful speakers, we have measured beam sensitivity to the girder vibration at several frequencies, the first results of the measurements look quite consistent with the model. The student project is complete, and the results have been presented at the SULI Internship Session.

17 Novel technique for particle stability diagram

To analyze nonlinear dynamic systems, we developed a new technique based on the square matrix method. We applied this technique called the "convergence map" to generate particle stability diagrams similar to the frequency maps widely used in accelerator physics to estimate dynamic aperture. So, the convergence map provides similar information as the frequency map calculated by particle tracking but in a much shorter computing time. Hence the convergence map is suitable for the nonlinear optimization of storage ring lattices, and in particular, for the study of the very long-term beam evolution in a ring with a large number of sextuples or higher-order multipoles. Using the NSLS-II lattice as an example, we carried out an extensive comparison of the convergence map with the traditional tracking method. Our comparison of the computation speed and data quality shows that the convergence map method is 30 to 300 times faster than tracking, depending on the size and the complexity of the lattices. The computation speed ratio is larger for complex lattices with low symmetry, such as particle colliders. The method and its applications are summarized in an article published in Phys. Rev. Accel. Beams [4].

18 Ultrafast Electron Microscopy

In 2023, we completed the LDRD project 22-029 "Towards ultrafast electron microscope with nanometer resolution". The main goal was a pre-conceptual design of a MeV ultrafast electron microscope (UEM) with a magnification of 10000 and nanometer resolution. To achieve the project goal, addressing the following challenges is essential: aberration control; energy spread reduction; imaging of thick bio-samples; mechanical and RF stability. We consider a compact UEM consisting of a sample stage, a detector, a condenser lens, and an imaging system composed of three quintuplet lenses, with a total length of about 2 m. To estimate the UEM performance, the start-to-end computer simulation from the gun to the detector taking into account all potential errors, is required. We completed measurements of the ATF-UED beam jitter and concluded that the present quality of the ATF beam is not adequate for the UEM commissioning because of two major issues: 1) the energy jitter is too large; 2) occasional large spatial pointing perturbations. We found that a MeV-UEM can image bio-samples not thicker than 1 μm. For imaging bio-samples with a thickness of $1 - 10$ μm, we completed the preliminary design of a MeV-STEM with nm resolution based on two options of electron sources: 1) a DC gun and 2) a superconducting RF gun. We specified the source parameters by simulations of beam dynamics. We also simulated the interaction of 3 MeV electrons with 1-μm-thick amorphous ice using multi-slice wave-optics code. We theoretically estimated the transmitted signal as a function of sample thickness up to 10 μm. We also analyzed the possibility of prediction of MeV electron beam parameters using machine learning [17] and improved the formula to calculate the elastic scattering of electrons [20]. The results of the LDRD project were presented at the IPAC'23 conference, Workshop on Cold Copper Accelerator Technology and Application, Workshop on Photocathode Physics for Photoinjectors, and LANL UED workshop.

19 Support of EIC project

We continued support for the Electron-Ion Collider (EIC) project in the frameworks of two MOUs with the EIC Directorate. Non-collision straight sections for the EIC electron storage ring have been re-matched. The optimized straight sections have been integrated into the latest lattice version. We completed several simulations for beam diagnostics in EIC (MOU): propagation of Cherenkov radiation to measure bunch length in the Linac; SRW simulations for the Linac-to-RCS transport line, RCS, and ESR for longitudinal and transverse beam size measurements including estimation of the photon yield for a streak camera and diffraction effects for accurate transverse size measurements. The results were included in the EIC reports presented at the IPAC'23 conference [22, 23, 24].

20 Summary

In 2023, accelerator physicists supported NSLS-II operations and start-ups [1]; carried out routine lattice characterization; established regular reports on beam dynamics [28]; and completed the commissioning of a superconducting wiggler for the HEX beamline [8, 14, 21]. Our studies of seasonal variation of the NSLS-II circumference showed a significant residual change in the beam energy. We developed a theory to calculate the beam-induced power in ceramic vacuum chambers [10], the theoretical results are consistent with the measurements. Our proposal for a Facility Improvement Project for absolute lattice characterization has been approved and funded. In collaboration with SLAC, we implemented a novel LOCOM technique of lattice characterization and correction [5, 16]. We made an assessment of an NSLS-II lattice with reduced beta functions in long straight sections for new beamlines.

We continued working on the NSLS-II upgrade including lattice development, implementation of higher-harmonic RF cavities [11], studying a combined effect of the intrabeam scattering, impedance, and harmonic cavities [12], and assessment of two FEL options: XFELO [6, 18] and EEHG [3, 7, 15]. We participated in the commissioning of a low-energy complex bend prototype providing optimization of the beamline [19]. We analyzed beam sensitivity to various errors [2] and carried out numerical and experimental studies of girder vibrations. The development of a new convergence map technique for nonlinear lattice characterization is complete [4]. We extended the NOECO technique to characterize harmonic sextupoles [13]. For ultrafast electron microscopy, we applied machine learning to a prediction of MeV electron beam parameters [17] and reviewed an electron elastic scattering formula [20].

In frameworks of MOUs with the Electron-Ion Collider Directorate, we supported lattice optimization and beam diagnostics development for the EIC project [22, 23, 24].

The main results have been published in peer-reviewed journals and presented at the 14th International Particle Accelerator Conference, 67th ICFA Advanced Beam Dynamics Workshop on Future Light Sources, Workshop on Cold Copper Accelerator Technology and Application, Workshop on Photocathode Physics for Photoinjectors, LANL UED workshop, and American Physical Society Meeting. Figure 1 shows the statistics of journal articles and conference reports published in FY14-FY23.

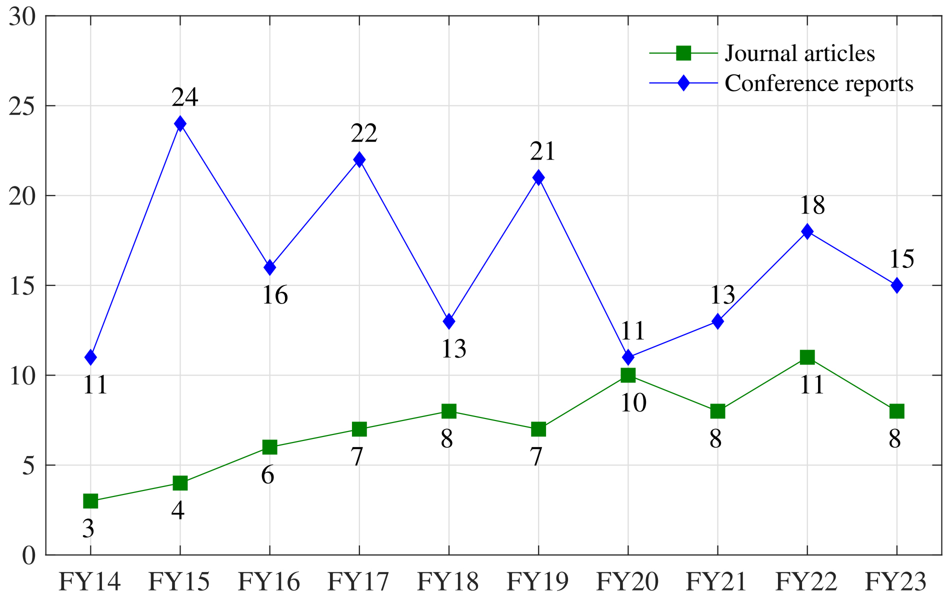

Figure 1: Journal articles and conference reports

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