BNL-223411-2022-TECH

NSLSII-ASD-TN-378

Accelerator physics at NSLS-II: research accomplishments in 2021

V. Smaluk

December 2021

Photon Sciences

Brookhaven National Laboratory

U.S. Department of Energy

USDOE Office of Science (SC), Basic Energy Sciences (BES) (SC-22)

DISCLAIMER

NSLS-II TECHNICAL NOTE BROOKHAVEN NATIONAL LABORATORY	NUMBER **NSLSII-ASD-TN-378**
AUTHORS: V. Smaluk, G. Bassi, J. Choi, Y. Hidaka, D. Hidas, A. Khan, S. Kongtawong, Y. Li, F. Plassard, T. Shaftan, T. Tanabe, G. Wang, X. Yang, L.H. Yu	DATE 12/31/2021
Accelerator physics at NSLS-II: research accomplishments in 2021	

Accelerator physics at NSLS-II: research accomplishments in 2021

V. Smaluk, G. Bassi, J. Choi, Y. Hidaka, D. Hidas, A. Khan, S. Kongtawong, Y. Li, F. Plassard, T. Shaftan, T. Tanabe, G. Wang, X. Yang, L.H. Yu

Dec. 31, 2021

Abstract

Accelerator physicists provide scientific support for NSLS-II user operations, improvements, and developments including the HLA common tools program, improvement of the scientific computing environment, support of raytracing and radiation safety, routine lattice characterization, modeling beam dynamics with a superconducting wiggler for HEX beamline, development of high-chromaticity lattice options, improvement of beam stability and orbit feedbacks, online optimization of the Injector and Storage Ring, realistic modeling of the Storage Ring RF system. We also supported the EIC project. At the same time, the physicists are working on the following research activities: conceptual design options for NSLS-II upgrade, theoretical studies of free-electron lasers, development of novel methods for dynamic aperture optimization, advanced studies of nonlinear beam dynamics, collective effects and impedances, ultrafast electron diffraction and microscopy. Research accomplishments achieved in 2021, are summarized in this report.

1 Introduction

In 2021, the NSLS-II accelerator physicists working in the Accelerator Physics Group, Accelerator Coordination Group, and Insertion Devises Group were providing scientific support for the NSLS-II user operations, machine improvement, and development. This work includes the development of software tools for beam studies and operations, assessment of new insertion devices, improvement of beam quality for beamline users, and radiation safety.

Besides the support of operations and machine improvement, we work on several R&D projects and activities. In frameworks of the LDRD project 20-041 "Conceptual Design Options for Future Upgrade of NSLS-II Facility", the physicists are working on the lattice development and studies of beam dynamics and collective effects for the NSLS-II accelerator upgrade. A summary of the accelerator physics R&Ds needed for the NSLS-II upgrade has been written and included in the proposal to DOE.

Two new LDRD projects proposed by the Accelerator Physics Group members have been approved and funded: LDRD 22-028 "Assessment of FEL options for NSLS-II upgrade" and LDRD 22-029 "Towards ultrafast electron microscope with nanometer resolution". The accelerator physicists also contributed to the project of the BNL electron-ion collider.

To enhance scientific and technical qualifications, accelerator physicists attended an EPICS Training Course and a virtual Python tutorial organized by BNL. We have completed a summary of research accomplishments in FY17-FY21 for the DOE triennial review.

This is a list of major accelerator physics projects and activities:

- HLA common tools program
- Support of raytracing and radiation safety
- Lattice characterization and modeling
- Superconducting wiggler for HEX beamline
- Development of high-chromaticity lattice options
- Beam stability and orbit feedbacks
- Online optimization of the Injector and Storage Ring
- Realistic modeling of RF system
- Conceptual design options for NSLS-II upgrade
- Theoretical studies of free-electron lasers
- Novel methods of dynamic aperture optimization
- Advanced studies of nonlinear beam dynamics
- Collective effects and impedances
- Ultra-fast electron diffraction and microscopy
- Support of the EIC project

Highlights of the research and developments carried out by NSLS-II accelerator physicists in 2021 are summarized in the next chapters.

2 HLA common tools program

In 2017, we proposed the development of a Python Middle Layer (PyML) software package with the same or better functionality as Matlab Middle Layer (MML) used for accelerator controls at most of the light sources worldwide. As a first step, we initiated the HLA common tools program to develop a set of well-tested and documented high-level applications available for all Accelerator Division staff from a common tools collection. These functions are assumed to have an interface to EPICS process variables and to the virtual machine model. All accelerator physicists contribute to code development, testing, and debugging. Beam studies are allocated for testing the applications.

The HLA common tools program has been successfully completed [1]. After thorough testing and debugging, more than 20 ready-to-use applications have been uploaded to a GitLab-based library. The functions are logically divided into several blocks:

- Measurement and correction of orbit and linear optics [2, 3, 4, 5, 14, 15];
- Characterization of non-linear beam dynamics [13];
- Beam stability and feedbacks [8];
- Local bumps and feedforward tables for insertion devices [10, 11, 12];
- Optimization of injection [7, 17];
- Beam diagnostic tools [6, 9, 16].

Once each code is released, all NSLS-II accelerator physicists are trained on how to use the software. As a result, every physicist is now prepared for independent control and tune-up of the machine. A standard procedure of routine lattice characterization has been developed and implemented.

Now, the HLA common tools program is further evolved to PyML. We are working on development, testing, and debugging Python functions using lattice models based on the input file in the ELEGANT format, with built-in help and a detailed manual for every function.

3 Support of raytracing and radiation safety

By a request from the raytracing workgroup, we reviewed and cross-checked the beam deviation envelope calculated in 2018 [18], the results are summarized in [19]. Now, we use an updated NSLS-II lattice with 17 installed insertion devices. The maximum beam deviation was estimated by particle tracking with the following assumptions: 1) damage can only be caused by the stored beam (closed orbit must exist in simulations); 2) the error sources are the orbit correctors and the RF frequency; 3) the beam is limited by the physical aperture of the vacuum chamber and the photon absorbers; 4) the beam is confined by the active interlock at the straight centers. No other possible reason for the orbit deviation was considered in the simulations. In conclusion, we confirmed the orbit envelope values listed in the technical note [18]. We also reviewed the fault simulation results and provided the total radiation power, maximum power density, and power profile of radiation emitted by the storage ring dipole magnets at 500 mA of the beam current. For the SR shielding design, we reviewed the fault simulations done in 2013 [20]. The requested tracking data for the whole Storage Ring supercell has been recovered and analyzed. We confirm the results published in [20] are only relevant for the first two dipoles after the injection straight section. The large beam phase space shown in this technical note will be much smaller after passing through subsequent magnets.

4 Lattice characterization and modeling

We continue the program of routine lattice characterization using HLA common tools to keep tracking the machine status and to let every accelerator physicist get their skills updated. Several beam study shifts for lattice characterization are scheduled every run. The stored data was helpful to analyze the long-term evolution of the amplitude-dependent shift of betatron tunes and to find its relation to seasonal variations of the Storage Ring circumference [21]. We discussed the problem of seasonal variations of the circumference and temperature with mechanical engineers and decided to measure the evolution of the storage ring radius during the year. This information will be useful to understand the observed seasonal variations of the beam orbit and nonlinear beam dynamics.

Following our previous simulations, we tried to apply the multi-frequency AC LOCO (Linear Optics from Closed Orbits) to measure the field errors of NSLS-II sextupole magnets. However, we found the use of the LOCO algorithm to study nonlinear beam dynamics is limited by the degeneracy of LOCO fitting parameters. So the absolute sextupole errors can not be identified with accuracy better than 10%. As an alternative, we decided to use a new LOCOM (Linear Optics from Closed Orbit Modulation) method [22] to overcome the degeneracy issue. This method uses a pair of correctors in each transverse plane to modulate the closed orbit. The orbit modulation data are fitted with a lattice model, from which the lattice errors can be determined and used for correction. This technique has some advantages compared to LOCO and to the methods that rely on turn-by-turn BPMs. The working principles of the method were confirmed by numerical simulations and we are going to test it experimentally. First beam studies are done with promising results. The AC beam excitation by fast correctors and BPM data collection were experimentally tested.

5 Superconducting wiggler for HEX beamline

We have completed the analysis of HEX superconducting wiggler (SCW) effects on the optics and orbit using magnetic measurement data provided by vendor [23]. The quadrupole errors result in the tolerable RMS deviations of beta functions of 0.2% (horizontal) and 0.3% (vertical), the maximal beta-beat values are 8 cm (horizontal) and 12 cm (vertical).

To estimate the skew quadrupole components, we carried out the global and local polynomial fitting of the magnetic measurement results because the vendor data are spiky and no measurement errors were provided. Assuming the worst-case scenario to estimate the effect of the skew quadrupole component on the beam optics and injection, we consider the installation of a dedicated skew quadrupole magnet to implement a local compensation. A magnet with the same configuration as the existing NSLS-II skew quadrupoles should be good enough.

The beam orbit distortion has been estimated using the dipole field errors. A maximum closed orbit distortion is about 0.1 mm, it can be corrected by the existing fast correctors, the needed kick strengths do not exceed 5 μrad (one third of the maximum). The characteristic time of the field drop caused by a quench is longer than 0.1 s, so the Fast Orbit Feedback should be able to correct dynamically the orbit distortion. We experimentally tested suppression of the dynamic orbit perturbation imitated by fast correctors. The maximum perturbation was about 300 μm peak-to-peak (100 μm expected from simulations). We demonstrated the Fast Orbit Feedback suppressed the perturbation down to 10 μm peak-to-peak.

We have completed a reassessment of the beam-induced heating of the HEX SCW vacuum chamber with a 1-inch wide 30-micron thick copper coating. The image current distribution in the SCW vacuum chamber has been estimated, our calculations confirm that most power is concentrated on the copper-coated strip. According to this estimate and to the experience of MAX-Lab, we should not expect serious issues with the beam-induced heat load.

6 Development of high-chromaticity lattice options

A high-chromaticity operation mode is being developed to provide operations with high-intensity bunches and reduced gain of the bunch-by-bunch feedback. The operational lattice with chromaticity +7/+7 was characterized using the diagnostic tools based on turn-by-turn BPM data and Linear Optics from Closed Orbits (LOCO). We confirmed the RCDS online optimization of this lattice effectively improves the injection efficiency above 90%. This lattice was repeatable in several beam study shifts.

We also experimentally tested a lattice with chromaticity +10/+10 optimized by computer simulations. We were able to improve the injection efficiency up to 70% by online optimization of sextupoles, but it is not sufficient for operation yet. Adjustment of the injection bump height did not result in further improvement. The effect of transport line correctors and injection kickers was not significant. It was observed the injection efficiency does not correlate well with the measured dynamic aperture, the reason is not known yet. The main problem is the real machine still differs from the simulation model even with all the kick maps of insertion devices included, we need to find the error sources.

7 Beam stability and orbit feedbacks

A program to simulate the NSLS-II fast orbit feedback (FOFB) system has been developed and experimentally validated [24]. The simulation closely follows each stage of the real system in the time domain and also includes the spatial domain, i.e. all beam position monitors and correctors. It can accept measured data or an artificial excitation from a model. The errors can be added to every stage of the calculation. The simulation results were compared with experimental data and showed a good agreement. This simulation code will be a useful tool for designing a future upgrade of the FOFB system.

8 Online optimization of the Injector and Storage Ring

The Facility Improvement Project (FIP) "Methods of online optimization of NSLS-II storage ring concurrent with user operations" was proposed and approved in 2018. Two main goals were set: 1) optimization of nonlinear beam dynamics in the Storage Ring to increase the injection efficiency and beam lifetime; 2) minimization of the user beam perturbations caused by the injection.

Applying the Robust Conjugate-Gradient Algorithm to online optimization of the NSLS-II sextupoles, we increased the horizontal dynamic aperture by 20% for the operational lattice. Using the same approach, we were able to double the injection efficiency and exceed 90% for the new high-chromaticity lattice developed to increase the single-bunch beam intensity and to improve the beam stability.

To minimize the perturbation of the stored beam during injection transient, we have optimized the matching of four Storage Ring injection kickers. First, we reduced the timing jitter by a factor of 5, down to 1 ns by the upgrade of the trigger boards for all kickers. Our simulation studies indicated that we need to adjust the pulse widths of all kickers with nanosecond precision for further reduction of the injection transient. So, the hardware modifications of the kicker power supplies have been done to provide adjustment of the kicker pulse width in the desired range of 70 ns with nanosecond precision. Finally, applying online optimization to the kickers' timing delay, pulse amplitude, and pulse width, we have minimized the RMS injection transient down to 70 μm, which is close to the limit of 60 μm determined by the off-axis injection scheme. Thus, the Facility Improvement Project is complete, the results have been summarized in a technical note [25], the optimized kicker settings are implemented in user operations.

9 Realistic modeling of the RF system

A realistic model of the NSLS-II RF system is being developed for reliable simulations of the longitudinal beam dynamics, studies of the system performance and stability with various beam currents, and optimization of the RF parameters. A model of the Low-Level RF system has been implemented in the SPACE simulation code and benchmarked against beam-based measurements. Several beam studies were carried out to characterize open- and closed-loop transfer functions of the RF cavities using the RF phase jump technique. For the two-cavity system (cavities C and D), good agreement between the model and the measurements was demonstrated. For the three-cavity system (including cavity A), more measurements are needed, the parameters of cavity A have been measured only in open-loop mode. A preliminary model of a longitudinal bunch-by-bunch feedback system has also been implemented in the SPACE code. Present results are included in a technical report of the APES Task Force.

10 Conceptual design options for NSLS-II upgrade

In frameworks of the LDRD 20-041 project "Conceptual Design Options for Future Upgrade of NSLS-II Facility", we are working on the lattice design, alignment and stability specifications, and collective effects studies for the low-emittance upgrade of the storage ring. Several lattice options are considered including MBA and Complex Bend lattices. We developed a hybrid multi-bend achromat lattice, which adopts a similar layout as the ESRF-EBS lattice, but the emittance was reduced to 28 pm, and the nonlinear beam dynamics were optimized to achieve a dynamic aperture sufficient for the off-axis injection scheme. We proposed a Hybrid Complex Bend Achromat lattice providing the emittance of 24 pm, dynamic aperture sufficient for the off-axis injection, and a momentum aperture large enough to result in a beam lifetime of several hours. We also developed a preliminary design of the HCBA lattice with a 2.2 T super-bend magnet in the middle of the complex bend. We analyzed the longitudinal beam dynamics in the DCBA 25pm lattice. For filling patterns with 5 and 10 bunch trains, a bunch lengthening by a factor of 3 is achievable, together with a moderate shift of bunch centroids and small non-uniformity of bunch lengths along the train. On-resonance and off-resonance approaches to obtain round beams in the NSLS-IIU were analyzed. We have reviewed alignment and stability specifications for ALS-U, APS-U, Diamond-II, ESRF-EBS, NSLS-II, SIRIUS, MAX IV, SOLEIL-II to figure out the future requirements for alignment and stability of the upgraded NSLS-II. A summary of the accelerator physics R&Ds needed for the NSLS-II upgrade has been written and included in the White Paper proposal to DOE.

11 Theoretical studies of free-electron lasers

A new LDRD project 22-028 "Assessment of FEL options for NSLS-II upgrade" has been approved for funding in FY22. Taking into account a world trend to combine synchrotron and free-electron laser (FEL) sources on the same site (PETRA-III and EuroXFEL in Germany, SPring-8 and SACLA in Japan, ELETTRA and FERMI in Italy), we are working on the assessment of an FEL project using a low-emittance electron beam of NSLS-IIU. The advantage of a storage ring FEL compared to a linac-based one is much better pulse-to-pulse beam stability. We consider two options of an FEL synergetic with the routine operation of the NSLS-IIU storage ring: 1) hard X-ray free-electron laser oscillator (XFELO) [26], and 2) soft X-ray echo-enabled high harmonic generation (EEHG). The main feature of the XFELO is its extremely narrow bandwidth compared to the linac-based FELs. The XFELO option of the NSLS-II upgrade could provide the brightness at 10 keV of photon energy by more than three orders of magnitude higher than that attainable at synchrotrons. The FEL based on EEHG provides very high peak intensity radiation, temporally coherent emission across the full range of emitted photon energies, and Fourier-limited pulses and pulse trains.

We contributed to the studies of the generation of intense few-femtosecond superradiant extreme-ultraviolet FEL pulses carrier out at FERMI@ELETTRA (Italy). The FEL pulses four times shorter, and with higher peak power than in the standard high-gain harmonic generation mode have been achieved [27].

12 Novel methods of dynamic aperture optimization

We developed a new technique to obtain a "convergence map" characterizing the nonlinear beam dynamics in the same way as the known frequency map but much faster [28]. The technique is based on the square matrix method, convergence maps are obtained from the iterative solving of the nonlinear equation of motion using the perturbation method and the convergence analysis. The map provides information about the on-momentum and off-momentum phase space, and stability border of dynamic aperture. We compared the convergence map technique with particle tracking, a standard way to get frequency maps. The results agree well with tracking including dynamic aperture, tune footprint, phase space trajectory, and frequency spectrum. The new method has an advantage of much higher (10 to 50 times) calculation speed and it can be effectively applied in nonlinear lattice optimization.

A novel data-driven chaos indicator concept is introduced to characterize the degree of chaos for nonlinear dynamical systems [29]. The indicator is represented by the prediction accuracy of surrogate models established purely from data. It provides a metric for the predictability of nonlinear motions in a given system. When applied to particle transportation in a storage ring, as particle motion becomes more chaotic, its surrogate model prediction accuracy decreases correspondingly. Therefore, the prediction accuracy, acting as a chaos indicator, can be used directly to optimize the dynamic aperture of storage rings. This method was successfully applied to optimize dynamic aperture and momentum acceptance of the Hybrid Multi-Bend Achromat lattice option for the NSLS-II upgrade.

13 Advanced studies of nonlinear beam dynamics

We developed a perturbation theory of nonlinear dynamics on resonances based on using the linear combination of left eigenvectors in the degenerate Jordan chains of a square matrix as the zeroth-order approximate action-angle variables to find a highly accurate approximation of the KAM invariants [30]. The solution is not in the form of a power series, but in the form of an exponential function with rational function as its exponent, more like a Laurent series rather than a Taylor series. The required power order for the action-angle variables in the exponent is much less stringent than the required power order for the power series expansion to achieve the same precision. The Henon map was revisited by linking the nonlinear perturbed orbit to a rigid rotation by an iteration procedure following the spirit of KAM theory [35]. The square matrix presents an essential tool to enable this method to converge near the major resonances.

We developed a new technique for simultaneous correction of high-order geometrical driving terms using octupoles [31, 32]. We designed an algorithm for the optimal positioning of octupoles with respect to the sextupoles present in the lattice. This technique provides a local and simultaneous compensation of all fourth-order on-momentum phase- and amplitude-dependent driving terms, using only three families of octupoles. This nonlinear correction method has been demonstrated on a simplified FODO model and on a realistic low-emittance design, optimized in the framework of the NSLS-II upgrade.

We developed a numerical method to design nonlinear double- and multi-bend achromat (DBA and MBA) lattices with approximate invariants of motion [33, 34, 36]. The search for such nonlinear lattices was motivated by Fermilab's Integrable Optics Test Accelerator, whose design is based on an integrable Hamiltonian system with two invariants of motion. While it may not be possible to design a DBA or MBA lattice with exact invariants of motion, we demonstrated that it is possible to optimize the sextupoles and octupoles to produce approximate invariants. The resulting lattices share some important features with integrable ones, such as a large dynamic aperture, trajectories confined to invariant tori, robustness to resonances and errors, and a large amplitude-dependent tune spread.

14 Collective effects and impedances

From the beginning of the NSLS-II project, the impedance of vacuum chamber components was calculated analytically (if possible) and numerically using the GdfidL 3D electromagnetic code. The design of each component was individually optimized to minimize the beam-induced heating and to prevent single-bunch and coupled-bunch instabilities. As a result of this extensive research and engineering effort, the design beam current of 500 mA has been accumulated in NSLS-II without any major problem caused by the collective effects. The total longitudinal impedance budget of the NSLS-II storage ring is now complete [37].

We have completed theoretical, numerical, and experimental studies of the combined effect of chromaticity and feedback on transverse head-tail instability, which is a major limitation for single-bunch beam intensity in circular accelerators [38, 40]. We considered several processes that suppress this type of instability, such as fast chromatic damping and Landau damping due to machine nonlinearity together with beam-based feedback providing active suppression of the beam oscillations. Results of experimental studies carried out at NSLS-II were compared with the theoretical and numerical models. For electron storage rings, the combination of positive chromaticity and resistive feedback is the most effective.

Although impedance modeling for particle accelerators has improved over the years, it is still a challenge to predict collective effects in real machines. We reviewed a general approach to the impedance modeling and the subsequent simulations of collective effects [39]. We considered a proper choice of the electrodynamic simulation codes and the required computing resources for modeling the geometric and resistive wall impedances, their comparison with analytical formulae, and simulating the collective effects using multi-particle tracking. In addition to instability calculations, we analyzed beam-induced heating as another issue that may limit beam intensity.

We studied the combined effect of the intrabeam scattering (IBS) and impedance on the longitudinal beam dynamics [41]. We measured the NSLS-II electron beam emittance, bunch length, and energy spread depending on a single-bunch current. A monotonic growth of the horizontal emittance and the energy spread dependence on the single bunch current below the microwave instability threshold can be explained by the IBS effect. Varying the vertical emittance, we experimentally observed the IBS results in a bunch lengthening and in increasing the threshold current of microwave instability. To compare with experimental data, we carried out multi-particle tracking simulations with the ELEGANT code, including IBS and the total longitudinal wakefield calculated by the GdfidL code.

15 Ultra-fast electron diffraction and microscopy

The LDRD project 19-016 "Demonstration of feasibility of sub-nm, picosecond electron microscope for the life sciences" is close to its final stage. For the magnet system of the UEM instrument, magnetic field specifications are driven by the performance requirements. The ultimate resolution of the UEM depends on how well we can optimize the design of beam focusing magnets via minimizing the spherical and chromatic aberrations. The tolerances of manufacturing and field measurement are specified via the start-to-end simulation. Three quintuplets, Objective, Projector 1, and Projector 2, contain a total number of fifteen permanent-magnet quadrupoles (PMQs). All the PMQs have been measured and meet the specification [44, 45].

The UEM facility has been designed, manufactured, and assembled ready for commissioning. We have developed a detailed plan of the UEM Phase-I Commissioning, the goal of which is to determine whether the ATF electron beam quality meets the specifications of the UEM LDRD project. We have established a step-by-step beam quality control including the measurement of transverse emittance and relative energy spread in the single-shot mode, and the shot-to-shot energy jitter and spatial-pointing jitter in the accumulation mode. Unfortunately, the beam quality provided by ATF is not good enough yet to start the UEM commissioning.

We explored the possibility of visualizing the lattice dynamics behavior by acquiring a single time-resolved mega-electron-volt ultrafast electron diffraction (UED) image [42, 46]. For a conventional UED, multiple shots with varying time delays are needed to map out the entire dynamic process and the measurement precision is limited by the timing jitter, intensity fluctuation of probe pulses, and the sample damage. We found the full lattice dynamic process can be obtained in a single electron pulse by converting the longitudinal time of an electron pulse to the transverse position of a Bragg peak on the detector. The main advantage of our novel time-resolved single-shot UED is to maximize the signals for visualizing the lattice dynamical behavior and minimize the sample damage induced by the pump laser; this will help in having all the data taken for the entire dynamic process with much fewer laser pumping than multiple-shot time-resolved techniques.

We demonstrated a Machine Learning (ML) approach as the single-shot real-time diagnostics of the transverse electron beam parameters such as emittance, energy spread, spatial-pointing jitter, and shot-to-shot energy fluctuation [43]. To maintain the long-term stability and to achieve a high single-shot quality of the electron beam in the constantly drifting UED/UEM, the ML technique is essential to provide good conditions for the machine startup and also to give real-time information of the electron beam parameters for online optimization.

16 Support of the EIC project

In the frameworks of MOUs with the Electron-Ion Collider Directorate, the NSLS-II we studied lattice optimization and longitudinal beam dynamics for the future electron-ion collider [47, 48]. By using the Multi-Objective Genetic Algorithm (MOGA) we showed that the high-order chromaticity of the EIC electron ring can be controlled below 1%, which agrees with results obtained by other methods. This study suggests a new linear lattice for the spin rotator is needed. For the lattice version 5.4, several straight sections were designed with quadrupoles unified into a few families with a smaller number of power supplies reducing the cost of the project.

We carried out beam dynamics studies of transient beam loading effects in the EIC electron storage ring. The time-dependent Vlasov-Fokker-Planck simulations were performed with the parallel particle tracking code SPACE for arbitrary multi-bunch configurations to determine stable RF cavity settings under heavy beam loading. We also studied the option to operate with a passive, third-harmonic cavity system for bunch lengthening, addressing both stability and the performance limitation due to a gap in the uniform filling pattern for ion clearing.

17 Summary

In 2021, the accelerator physicists were providing scientific support for NSLS-II operations and developments including the HLA common tools program [1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17]; support of raytracing and radiation safety [19]; lattice characterization and modeling [21, 22]; feasibility studies of swapping dipole magnets for INF beamline; assessment of a superconducting wiggler for HEX beamline [23]; realistic modeling of the RF system. The Facility Improvement Project (FIP) "Methods of online optimization of NSLS-II storage ring concurrent with user operations" has been successfully completed [25].

In frameworks of the LDRD 20-041 project "Conceptual Design Options for Future Upgrade of NSLS-II Facility", we were working on the low-emittance upgrade of the storage ring.

The UEM facility designed, manufactured, and assembled under the LDRD project 19-016 "Demonstration of feasibility of sub-nm, picosecond electron microscope for the life sciences", is ready for commissioning.

Two new LDRD projects, one on the FEL options of NSLS-II upgrade and another on the UEM with nanometer resolution, have been approved and funded.

The accelerator physicists were studying the following R&D topics: theoretical studies of free-electron lasers [26, 27]; development of novel methods of dynamic aperture optimization [28, 29]; advanced studies of nonlinear beam dynamics [30, 35, 31, 32, 33, 34, 36]; study of collective effects and impedances [37, 38, 40, 39, 41].

Under MOUs with the Electron-Ion Collider Directorate, we studied lattice optimization and longitudinal beam dynamics for the EIC project [47, 48].

The main results have been published in peer-reviewed journals and remotely presented at the 12th International Particle Accelerator Conference. Figure 1 shows the statistics of journal articles and conference reports published by NSLS-II accelerator physicists in FY14-FY21.

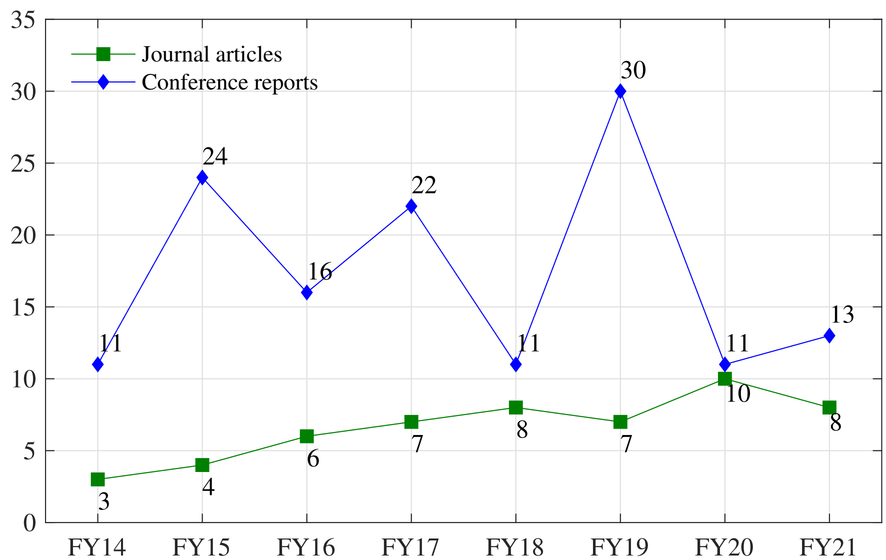

Figure 1: Number of journal articles and conference reports published in FY14-FY21

References

[1] V. Smaluk, T. Shaftan, G. Wang, *Program on development of standard High Level Application (HLA) common tools for beam studies and operations*, BNL-221682-2021-TECH (NSLSII-ASD-TN-365), 2021.

[2] Y. Li, *NSLS-II APHLA Optics Correction Tools*, BNL-221453-2021-TECH (NSLSII-ASD-TN-349), 2021.

[3] Y. Li, *NSLS-II APHLA Orbit Correction Tools*, BNL-221454-2021-TECH (NSLSII-ASD-TN-350), 2021.

[4] Y. Li, *NSLS-II APHLA Linear Coupling Correction Tools*, BNL-221455-2021-TECH (NSLSII-ASD-TN-351), 2021.

[5] Y. Li, *NSLS-II APHLA Optics Correction with Gated BPM Tool*, BNL-221456-2021-TECH (NSLSII-ASD-TN-352), 2021.

[6] Y. Tian, V. Smaluk, X. Yang, *Implementing HLA common tool - AC-Local-Bump for impedance measurements and for FOFB compatible user operation mode*, BNL-221563-2021-TECH (NSLSII-ASD-TN-355), 2021.

[7] X. Yang, A. Derbenev, *Implementing HLA common tool - Injector Energy Tuning Application*, BNL-221564-2021-TECH (NSLSII-ASD-TN-356), 2021.

[8] Y. Tian, X. Yang, *Implementing HLA common tool - FOFB Interface Application*, BNL-221565-2021-TECH (NSLSII-ASD-TN-357), 2021.

[9] R. Fliller, R. Smith, *Active Interlock Automatic Testing Program*, BNL-221567-2021-TECH (NSLSII-ASD-TN-358), 2021.

[10] Y. Hidaka, Y. Hu, B. Podobedov, R. Smith, Y. Tian, G. Wang, *Fast-Orbit-Feedback-Compatible ID Local Bumps with RF and X-ray BPMs at NSLS-II*, BNL-221576-2021-TECH (NSLSII-ASD-TN-353), 2021.

[11] Y. Hidaka, Y. Hu, B. Podobedov, R. Smith, Y. Tian, G. Wang, *Local Bump Agents (Feedback) at NSLS-II*, BNL-221577-2021-TECH (NSLSII-ASD-TN-354), 2021.

[12] Y. Hidaka, Y. Li, *A High-Level Application Tool for Generation and Validation of Insertion Device Orbit Feedforward Tables at NSLS-II*, BNL-221578-2021-TECH (NSLSII-ASD-TN-359), 2021.

[13] Y. Hidaka, *A Multi-Shot Measurement Tool for 1-D Dynamic Aperture and Tune Shift with Amplitude based on Turn-by-Turn BPM Data at NSLS-II*, BNL-221579-2021-TECH (NSLSII-ASD-TN-360), 2021.

[14] Y. Hidaka, Y. Hu, R. Smith, Y. Tian, G. Wang, *Vertical Emittance Control Application for NSLS-II Operation*, BNL-221580-2021-TECH (NSLSII-ASD-TN-361), 2021.

[15] G. Bassi, *HLA Common Tools: Tune Correction, Chromaticity Measurement and Chromaticity Correction*, BNL-221581-2021-TECH (NSLSII-ASD-TN-362), 2021.

[16] J. Choi, *Beam Based Alignment and Response Matrix Measurement*, BNL-221582-2021-TECH (NSLSII-ASD-TN-363), 2021.

[17] J. Choi, *Injector High-Level Applications*, BNL-221583-2021-TECH (NSLSII-ASD-TN-364), 2021.

[18] W. Guo, *Reasonable Beam Deviation Envelope For Ray-tracing*, BNL-211206-2019-TECH (NSLSII-ASD-TN-269), 2018.

[19] Y. Li, *Review and Double-check of technote "Reasonable Beam Deviation Envelope for Ray-tracing"*, BNL-222770-2022-TECH (NSLSII-ASD-TN-373), 2022.

[20] Y. Li, S. Seletskiy, *Analysis of Mis-steered Electron Beam in the NSLS-II Storage Ring*, BNL-211118-2019-TECH (NSLSII-ASD-TN-122), 2013.

[21] L.H. Yu, G. Bassi, Y. Hidaka, B. Podobedov, V.V. Smaluk, G.M. Wang, X. Yang, *Amplitude-dependent Shift of Betatron Tunes and Its Relation to Long-term Circumference Variations at NSLS-II*, in Proc. of the 12th Int. Particle Accelerator Conf. (IPAC'21), Campinas, Brazil, 2021, MOPAB039.

[22] X. Huang, *Linear optics and coupling correction with closed orbit modulation*, Phys. Rev. Acc. Beams 24 (2021) 072805.

[23] Y. Li, T. Tanabe, V. Smaluk, X. Yang, K. Ha, Y. Tian, *Effects of HEX SCW field errors on linear optics and orbit*, BNL-221297-2021-TECH (NSLSII-ASD-TN-348), 2021.

[24] S. Kongtawong, Y. Tian, L.H. Yu, X. Yang, G. Wang, K. Ha, T. Shaftan, *Numerical simulation of NSLS-II fast orbit feedback system*, Nucl. Instrum. Meth. A 997 (2021) 165175.

[25] X. Yang, V. Smaluk, G. Wang, L.H. Yu, T. Shaftan, Y. Li, F. Plassard, S. Buda, Y. Hidaka, O. Ewart, D. Durfee, Y. Tian, Y. Hu, K. Ha, S. Ibrahim, A. Derbenev, B. Bacha, C. Danneil, D. Padrazo, *Online Optimization of NSLS-II Dynamic Aperture and Injection Transient (Facility Improvement Project)*, BNL-222523-2021-TECH (NSLSII-ASD-TN-372), 2021.

[26] L.H. Yu, *Gain of Hard X-ray FEL at 3 GeV and Required Parameters*, in Proc. of the 12th Int. Particle Accelerator Conf. (IPAC'21), Campinas, Brazil, 2021, MOPAB040.

[27] N.S. Mirian, M. DiFraia, S. Spampinati, F. Sottocorona, E. Allaria, L. Badano, M.B. Danailov, A. Demidovich, G. DeNinno, S. DiMitri, G. Penco, P.R. Ribic, C. Spezzani, G. Gaio, M. Trovo, N. Mahne, M. Manfredda, L. Raimondi, M. Zangrando, O. Plekan, K.C. Prince, T. Mazza, R.J. Squibb, C. Callegari, X. Yang, L. Giannessi, *Generation and measurement of intense few-femtosecond superradiant extreme-ultraviolet free-electron laser pulses*, Nature Photonics 15 (2021) 523-529.

[28] L.H. Yu, Y. Hao, Y. Hidaka, F. Plassard, V. Smaluk, *Convergence Map With Action-angle Variables Based on Square Matrix for Nonlinear Lattice Optimization*, in Proc. of the 12th Int. Particle Accelerator Conf. (IPAC'21), Campinas, Brazil, 2021, MOPAB041.

[29] Y. Li, J. Wan, A. Liu, Y. Jiao, R. Rainer, *Data-driven Chaos Indicator for Nonlinear Dynamics and Applications on Storage Ring Lattice Design*, BNL-222439-2021-TECH (NSLSII-ASD-TN-369), 2021.

[30] L.H. Yu, *A new method to probe the boundary where KAM tori persist by square matrix*, Advances in Physics and Astronomy: An International Journal. 2021;2(1):9, 82-107.

[31] F. Plassard, G. Wang, T. Shaftan, V. Smaluk, Y. Li, Y. Hidaka, *Simultaneous correction of high order geometrical driving terms with octupoles in synchrotron light sources*, Phys. Rev. Acc. Beams 24 (2021) 114801.

[32] F. Plassard, Y. Hidaka, Y. Li, T. Shaftan, V. Smaluk, G. Wang, *Simultaneous Compensation of Phase and Amplitude Dependent Geometrical Resonances Using Octupoles*, in Proc. of the 12th Int. Particle Accelerator Conf. (IPAC'21), Campinas, Brazil, 2021, TUPAB227.

[33] Y. Li, K. Hwang, C. Mitchell, R. Rainer, R. Ryne, V. Smaluk, *Design of double- and multi-bend achromat lattices with large dynamic aperture and approximate invariants*, Phys. Rev. Acc. Beams 24 (2021) 124001.

[34] Y. Li, R.S. Rainer, V.V. Smaluk, K. Hwang, C.E. Mitchell, R.D. Ryne, *Design of Double- and Multi-Bend Achromat Lattices with Large Dynamic Aperture and Approximate Invariants*, in Proc. of the 12th Int. Particle Accelerator Conf. (IPAC'21), Campinas, Brazil, 2021, TUPAB223.

[35] Y. Hao, K.J. Anderson, L.H. Yu, *Revisit of Nonlinear Dynamics in Henon Map Using Square Matrix Method*, in Proc. of the 12th Int. Particle Accelerator Conf. (IPAC'21), Campinas, Brazil, 2021, THPAB016.

[36] Y. Li, K. Hwang, C. Mitchell, R. Rainer, R. Ryne, V. Smaluk, *Design of double- and multi-bend achromat lattices with large dynamic aperture and approximate invariants*, BNL-222440-2021-TECH (NSLSII-ASD-TN-370), 2021.

[37] A. Blednykh, G. Bassi, C. Hetzel, B. Kosciuk, V. Smaluk, *NSLS-II Longitudinal Impedance Budget*, Nucl. Instrum. Meth. A 1005 (2021) 165349.

[38] V. Smaluk, G. Bassi, A. Blednykh, A. Khan, *Combined effect of chromaticity and feedback on transverse head-tail instability*, Phys. Rev. Acc. Beams 24 (2021) 054401.

[39] A. Blednykh, G. Bassi, V. Smaluk, R. Lindberg, *Impedance modeling and its application to the analysis of the collective effects*, Phys. Rev. Acc. Beams 24 (2021) 104801.

[40] V.V. Smaluk, G. Bassi, A. Blednykh, A. Khan, *Effect of Chromaticity and Feedback on Transverse Head-Tail Instability*, in Proc. of the 12th Int. Particle Accelerator Conf. (IPAC'21), Campinas, Brazil, 2021, WEPAB239.

[41] A. Blednykh, B. Bacha, G. Bassi, T.V. Shaftan, V.V. Smaluk, M. Borland, R.R. Lindberg, *Combined Effect of IBS and Impedance on the Longitudinal Beam Dynamics*, in Proc. of the 12th Int. Particle Accelerator Conf. (IPAC'21), Campinas, Brazil, 2021, THPAB240.

[42] X. Yang, J. Tao, W. Wan, L. Wu, V. Smaluk, T. Shaftan, Y. Zhu, *Visualizing lattice dynamic behavior by acquiring a single time-resolved MeV diffraction image*, Journal of Applied Physics 129 (2021) 054901.

[43] Z. Zhang, X. Yang, X. Huang, J. Li, T. Shaftan, V. Smaluk, M. Song, W. Wan, L. Wu, Y. Zhu, *Accurate prediction of mega-electron-volt electron beam properties from UED using machine learning*, Scientific Reports 11 (2021) 13890.

[44] X. Yang, C. Spataro, L. Doom, F. Lincoln, V. Smaluk, T. Shaftan, *Magnets for the UEM instrument*, BNL-222522-2021-TECH (NSLSII-ASD-TN-371), 2021.

[45] G. Andonian, T.J. Campese, I.I. Gadjev, M. Ruelas, M.G. Fedurin, K. Kusche, X. Yang, Y. Zhu, C.C. Hall, *High Resolution Imaging Design Using Permanent Magnet Quadrupoles at BNL UEM*, in Proc. of the 12th Int. Particle Accelerator Conf. (IPAC'21), Campinas, Brazil, 2021, MOPAB139.

[46] X. Yang, T.V. Shaftan, V.V. Smaluk, J. Tao, L. Wu, Y. Zhu, W. Wan, *Visualizing lattice dynamic behavior by acquiring a single time-resolved MeV diffraction image*, in Proc. of the 12th Int. Particle Accelerator Conf. (IPAC'21), Campinas, Brazil, 2021, TUXC06.

[47] D. Marx, Y. Li, C. Montag, S. Tepikian, F.J. Willeke, Y. Cai, Y.M. Nosochkov, G.H. Hoffstaetter, J.E. Unger, *Dynamic Aperture Optimization in the EIC Electron Storage Ring with Two Interaction Points*, in Proc. of the 12th Int. Particle Accelerator Conf. (IPAC'21), Campinas, Brazil, 2021, TUPAB235.

[48] C. Montag, et al., *Design Status Update of the Electron-Ion Collider*, in Proc. of the 12th Int. Particle Accelerator Conf. (IPAC'21), Campinas, Brazil, 2021, WEPAB005.