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Accelerator Physics at NSLS-II Research Accomplishments in 2016-2017

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Accelerator physics at NSLS-II: research accomplishments in 2016-2017

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Abstract

The main duty of the Accelerator Physics group at NSLS-II is to support user operations. At the same time, the accelerator physicists carry out a number of studies of topical accelerator physics problems. These studies cover a wide range of accelerator physics including advanced techniques of magnet lattice correction and optimization, nonlinear beam dynamics, collective effects and impedances, low-emittance upgrade options for NSLS-II, and new approaches to lattice design for circular accelerators. A review of recent accomplishments of the NSLS-II Accelerator Physics group is presented in this report.

1 Introduction

Now, NSLS-II is the brightest 3rd generation light source operating with the beam current of 350 mA in top-off injection mode and horizontal emittance of 0.9 nm·rad. The design values of beam stability have been achieved: less than 10% of r.m.s. beam size in position and less than 10% of r.m.s. beam divergence in angle. These achievements result from the continuous efforts of NSLS-II accelerator physicists and engineers.

At the same time, the members of the NSLS-II Accelerator Physics group carry out a number of studies of topical accelerator physics problems. These studies cover a wide range of accelerator physics including advanced techniques of magnet lattice correction and optimization, nonlinear beam dynamics, collective effects and impedances, low-emittance upgrade options for NSLS-II. A review of recent accomplishments of the NSLS-II Accelerator Physics group is presented in this report.

A list of major accomplishments is presented below.

- Increase of beam current.
- Diffraction-limited vertical emittance.
- Beam stability.
- Advanced techniques of lattice correction:
  - AC LOCO, a new fast and precise technique;

- Independent Component Analysis;
  - Driving-terms-based linear optics calibration;
  - Experimental crosscheck of lattice correction algorithms.

- Analysis of nonlinear dynamics by square matrix method.
- Real-time redistribution of fast correctors' strengths to slow correctors.
- Collective effects and impedances:
  - Self-consistent parallel tracking code;
  - Analysis of the coupled-bunch instability for arbitrary multibunch configurations;
  - Low-frequency quadrupole impedance of undulators and wigglers;
  - Studies of microwave instability;
  - Observation of ion-induced instabilities;
  - AC orbit bump method of local impedance measurement.
- High-brightness lattice upgrade options for NSLS-II.
- High-resolution gated mode of NSLS-II beam position monitors.
- Lower-energy operational modes of the NSLS-II injector.
- Radiation shielding analysis.
- Ultra-fast electron diffraction and microscopy.
- Simulation studies of beam-beam effects for the eRHIC project.

Some of the recent achievements of the NSLS-II accelerator physicists are discussed in the following chapters.

2 Increase of beam current

Overheating the ceramic vacuum chambers of the injection kickers was observed with the beam current exceeding 250 mA in the storage ring. Quadratic temperature dependence on the beam average current shows the heating is caused by the impedance-driven coherent loss of the beam energy. Using experimental data, an approximate analytical model was developed to understand the heating mechanism and to find an optimal thickness of the metal coating. Computer simulations of the chamber impedance were also carried out. The solution is to install new ceramic chambers with thicker and uniform titanium coating. As a temporary solution, cooling fans were installed on the ceramic chambers allowing a beam current of 400 mA to be achieved. The temperature and vacuum were monitored for 5 hours at that current, and no issues were observed [1].

To achieve the design beam current of 500 mA, the accelerator physicists carry out extensive studies of high-current effects. The stabilizing effect of positive chromaticity in combination with the transverse bunch-by-bunch feedback system was investigated. Analytical and numerical studies were done to predict the bunch lengthening caused by a 3rd-harmonic RF cavity. The conclusion is the installation of a 3rd-harmonic cavity is helpful to increase the beam lifetime and to mitigate collective effects resulting in the vacuum chamber overheating and collective instabilities.

3 Diffraction-limited vertical emittance

The NSLS-II design values of horizontal and vertical emittances are 0.9 nm·rad and 8 pm·rad, respectively. The vertical emittance is diffraction-limited at the photon energy of 12 keV. The 30-cell double-bend achromat lattice of the NSLS-II storage ring provides the horizontal emittance of 2 nm·rad. Further reduction of the emittance to 0.9 nm·rad is achieved by using three pairs of damping wigglers [2]. The effective vertical emittance determining the photon beam quality is affected by the electron beam dynamics and by the performance of subsystems such as fast orbit feedback, bunch-by-bunch feedback, wigglers and undulators, etc. To achieve the diffraction-limited emittance of 8 pm·rad, precise correction of the lattice functions and coupling was successfully done using advanced correction techniques. Several subsystems including the feedbacks and beam instrumentation were optimized too. As a result, the diffraction-limited vertical emittance was demonstrated with the operational lattice and beam current.

4 Beam stability

A beam stability task force was established to develop and implement a program focused on continuous improvements of the electron and photon beam stability. The goal is to identify and diagnose all issues associated with beam stability. The results of the task force efforts are summarized in semiannual reports [3]. The short-term (10 sec and less) beam orbit stability in the storage ring meets the specifications: 10% of the r.m.s. beam size and 10% of the r.m.s. beam divergence for the positional and angular stability, respectively. The long-term (24 hours) positional/angular stability at ID source points is generally within 1 μm/1 μrad peak-to-peak. The orbit reproducibility after beam dumps or after machine shutdowns was found to be much worse and needs to be improved [4]. Several machine studies were performed by accelerator physicists and beamline scientists together. These studies resulted in improved local orbit bumps (well localized and compatible with the Fast Orbit Feedback) and improved orbit reproducibility after beam dumps.

Besides the beam stability task force, an RF frequency feedback was implemented to compensate daily variations of the storage ring circumference and therefore to improve the long-term stability; beam position monitors located close to the light-generating insertion devices were added to the Fast Orbit Feedback; a procedure of real-time redistribution of the fast correctors' strengths to slow correctors was developed to prevent saturation of the fast correctors.

5 Advanced techniques of lattice correction

5.1 AC LOCO, a new fast and precise technique

A novel advanced technique was developed to improve the precision and to shorten the measurement time of the LOCO (linear optics from closed orbits) lattice characterization [5]. This technique named AC LOCO is based on sine-wave (AC) beam excitation via fast correctors, which are typically installed at synchrotron light sources for the fast orbit feedback.

The beam oscillations are measured by all beam position monitors. The narrow-band signals used for the beam excitation and measurement allow us to improve the signal-to-noise ratio significantly and also opens the opportunity for simultaneous excitation of multiple correctors at different frequencies (multifrequency mode) [6]. The new technique was tested at NSLS-II and demonstrated better lattice correction and shorter measurement time than the traditional LOCO method.

5.2 Independent Component Analysis

The independent component analysis (ICA) method for simultaneous correction of linear optics and coupling using turn-by-turn data measured by beam position monitors (BPMs) was implemented at NSLS-II [7]. The ICA method is applied to find the amplitudes and phases of the projections of the normal oscillation modes on the turn-by-turn beam position measured by the BPMs. For the fitting, they are compared to their model-generated counterparts. The fitting scheme is similar to LOCO. The ICA-based method provides the accuracy of the BPM calibration and linear lattice correction comparable to the standard LOCO technique.

5.3 Driving-terms-based linear optics calibration

The Driving-Terms-Based Linear Optics Calibration (DTBLOC) algorithm was implemented in a Python code [8]. The input (observables) is: four frequency components extracted from turn-by-turn BPM data and from measured dispersion functions. The output (fitting parameters) is: normal and skew quadrupole errors, BPM errors (horizontal and vertical gain, roll, and deformation). Iterative least-square fitting is applied using singular-value decomposition with analytical Jacobian based on resonance driving terms. The method is very fast, it needs only about 5 minutes for the data acquisition, processing, and fitting at NSLS-II.

5.4 Experimental crosscheck of lattice correction algorithms

The performance, capabilities, and limitations of several algorithms for linear optics correction were studied experimentally at NSLS-II [9]. A crosscheck of four algorithms based on analysis of the turn-by-turn beam position measured by BPMs was done in comparison with the LOCO algorithm based on the orbit response matrix. For the correction, either iterative solving of the linear problem (matrix inversion with singular-value decomposition) or variational optimization was used. The measurement results show the turn-by-turn-based algorithms (weighted correction of betatron phase and amplitude, independent component analysis, model-independent analysis, and driving-terms-based linear optics characterization) provide almost the same correction quality as LOCO, but they are much less time-consuming.

6 Analysis of nonlinear dynamics by square matrix method

The nonlinear dynamics of a system with a periodic structure is analyzed using a square matrix [10, 11]. The square matrix provides a novel method to optimize the nonlinear dynamic system. The main feature of the new method is that high order can be achieved in one step. This is a significant advantage when compared with the canonical perturbation theory and normal form, where the calculation is carried out order-to-order by a complicated iteration. It was also shown the stability and precision of the Jordan decomposition is ensured by scaling the variables and by removing the high-power invariant monomial terms. Thus the analysis of a nonlinear dynamic system can be greatly simplified using linear algebra. The developed theory shows good potential in the theoretical understanding of a complicated dynamical system to guide the fast optimization of dynamic apertures in circular accelerators [12, 13]. The new method is general, and hopefully may be applied to other areas, for example, nonlinear dynamics in physics and astronomy.

7 Real-time redistribution of fast correctors' strengths to slow correctors

We developed and tested a method of real-time redistribution of the correction strength from fast correctors to slow correctors, with the closed loop of fast orbit feedback (FOFB) [14]. The strength of the fast correctors is limited by their power supplies that can saturate if a local orbit bump is applied by a beamline request. The slow correctors are able to provide much larger corrections without saturation of their power supplies. The fast-to-slow corrector shifting matrix is calculated using the lattice model of the NSLS-II storage ring. This method was experimentally tested, the results are repeatable and the method is robust. We are able to reduce the maximum current of fast correctors from 0.45 A to 0.04 A with the orbit perturbation within ± 1 μm. The method is now routinely used during user operations of NSLS-II to prevent saturation of the fast correctors resulting in degradation of the machine performance.

8 Lossless crossing of the half-integer resonance

We carried out a study focused on beam dynamics in a storage ring featuring a large chromatic tune footprint that can span across major resonances [15]. Such a property of the ring lattices has been recently identified during the design of the new Multi-Bend Achromat lattices proposed for the next generation of synchrotron light sources. We found both by calculation and by experiment, it is possible to achieve the storage ring conditions where the beam crosses the half-integer resonance without particle loss. This can be accomplished if the resonance stopband is narrow due to small residual field errors in the ring magnets, and is further controlled by accurate cancellation of the harmful harmonic of the field errors around the ring. The combination of the small stopband width with a large magnitude of nonlinear chromaticity leads to the rapid crossing of the resonance, which does not cause loss of the particles as demonstrated by our experiments [16, 17].

9 Collective effects and impedances

9.1 Self-consistent parallel tracking code

A new parallel tracking code SPACE (self-consistent parallel algorithm for collective effects) has been developed at NSLS-II [18]. SPACE is a code to simulate the collective effects of beam dynamics driven by short- and long-range wakefields. For multibunch simulations, the long-range interaction is efficiently computed by a novel algorithm based on the expansion of the long-range wake function in the Taylor series, allowing the calculation of the coupled-bunch interaction via storing few moments of the bunch densities. The code has the following general features and capabilities: efficient simulation of the short- and long-range wakefield effects in 6D phase space; head-tail effects and coupled-bunch instabilities; passive higher harmonic cavity effects with arbitrary fill pattern; microwave instability; efficient density estimation from particles. The SPACE code was benchmarked with the ELEGANT tracking code and experimental data measured at the Advanced Photon Source (ANL) [19]. Development and implementation of new features, such as modeling of a transverse feedback system [20], RF system, ion effects, are in progress.

9.2 Analysis of the coupled-bunch instability for arbitrary multibunch configurations

Coupled-bunch instabilities were studied at NSLS-II theoretically and experimentally [18, 21]. An analytical treatment of the coupled-bunch instability for arbitrary filling patterns has been developed. The intensity-dependent complex frequency shifts have been derived starting from a system of coupled Vlasov equations. The analytical formulae and numerical simulations confirm that the analysis is reduced to the formulation of an eigenvalue problem based on the known formulae for the uniform filling pattern. The numerical solution of the eigenvalue problem is used to study instability thresholds via the determination of the eigenvalue with the largest imaginary part. The analysis is general and can be applied, for example, to study the stability of a multibunch beam with the various number of particles per bunch, or to find the most stable multibunch configuration.

9.3 Low-frequency quadrupole impedance of undulators and wigglers

Analytical expressions of the low-frequency quadrupole impedance contributed by undulators and wigglers were derived and benchmarked against beam-based impedance measurements [22, 23]. The theoretical model is valid for an arbitrary number of electromagnetic layers with parallel geometry. We formulated general equations describing the impedance for arbitrary frequencies and for arbitrary electric permittivity and magnetic permeability.

An explicit formula has been derived for the quadrupole impedance at zero frequency assuming general magnetic properties of the magnets. The formula describing the quadrupole impedance as a function of the magnet gap was found to be in good agreement with the measurements.

9.4 Studies of microwave instability

The microwave instability of an electron beam circulating in the NSLS-II storage ring was studied [24, 25]. The energy spread as a function of single-bunch current was measured using two independent techniques: 1) analysis of the spectrum of the photon beam generated by an in-vacuum undulator, and 2) measurement of the transverse beam size by a synchrotron light monitor installed in a dispersive section. The measurements were carried out for the lattice options with and without damping wigglers. In addition, the beam oscillation spectra were measured by a spectrum analyzer connected to a button pickup. The measured data show a non-monotonous growth of the energy spread as a function of the single-bunch beam current, in particular, local minima of the energy spread were observed. All the measurement results were compared with numerical simulations and analytical formulae.

9.5 Observation of ion-induced instabilities

Fast ion instability was observed in the NSLS-II storage ring at various vacuum conditions, beam current and filling patterns, chromaticities, and insertion device settings [26]. Two signature features of fast ion instability are always present: 1) unstable modes move up in frequency at higher bunch currents and 2) these modes tend to have a broadband "hump" spectral feature, presumably due to the beam size (and hence the corresponding ion frequency) variation around the ring, as well as due to multiple ion species involved in the instability. The bunch-to-bunch tune shift, lifetime increase along the bunch train, ion intensity with a probe bunch in the gap, and vertical oscillation developing along the bunch train captured with a streak camera, have been studied.

9.6 AC orbit bump method of local impedance measurement

An advanced technique of local impedance measurement was developed and tested at NSLS-II [27, 28]. The technique is based on the excitation of an AC orbit bump in the vacuum chamber section, the impedance of which is measured. Four fast orbit correctors adjacent to the section are excited by an in-phase sine-wave driving signal, the beam oscillations are measured by beam position monitors and the oscillation amplitudes are obtained by synchronous detection. The narrow-band signals allow us to improve significantly the accuracy of the conventional orbit bump method. The use of the coreless fast correctors completely eliminates the systematic error caused by magnet hysteresis. The systematic error caused by orbit drifts is also eliminated because the measured signal is not affected by the orbit motion outside the excitation frequency range. A proof-of-principle experiment carried out at NSLS-II demonstrated the measurement resolution good enough to measure the orbit distortion of the order of 0.1 μm, which is an order of magnitude smaller than the sensitivity of the conventional bump method.

10 High-brightness lattice upgrade options for NSLS-II

NSLS-II is now one of the brightest sources of X-rays worldwide. However, there are several new or upgrade projects promising much brighter beams than NSLS-II is able to provide today. In order to maintain the competitiveness of NSLS-II, we explore possible ways to increase the brightness of NSLS-II, with the constraint of not having to replace a large fraction of the magnets.

One of the possible solutions is the conversion of current Double-Bend Achromat lattice to a 4-Bend Achromat by replacement of the existing dipole magnets. Possible upgrade of NSLS-II will double the number of dipoles with the hardware changes minimized to only 2 girders per cell and without major changes outside of the dipole girders. The emittance can be reduced by a factor of 2 and three damping wigglers give an additional factor of 1.5. Taking into account the effects of other insertion devices, the emittance can be reduced to about 300 pm·rad.

The other option is a modification of NSLS-II lattice to redistribute the damping partitions. The horizontal emittance is inversely proportional to the horizontal damping partition number, which is close to 1 for a storage ring like NSLS-II built with pure dipole magnets with no gradient in their magnetic field. To decrease the emittance, the horizontal damping partition should be significantly greater than 1; this can be achieved by introducing a gradient in the bending magnets, but replacing the dipoles would be very expensive. Alternatively, a dipole magnetic field with gradient components can be introduced into the lattice by operating the ring with an off-center beam orbit.

11 High-resolution gated mode of NSLS-II beam position monitors

Single-bunch resolution of NSLS-II beam position monitors was improved by an order of magnitude to about one-micron turn-by-turn at 1 nC/bunch by special processing of ADC signals [29]. The new capability of resolving turn-by-turn signals from up to 8 bunches stored in the ring is useful for sensitive measurements of collective effects [30] or single-particle dynamics [31]. It allows us to simultaneously measure bunches with different charges (or kick amplitudes) thus eliminating the harmful effects of machine drifts. ADC processing is presently done off-line but will be implemented in FPGA, so that improved resolution will be available through the NSLS-II control system.

12 Lower-energy operational modes of the NSLS-II injector

The NSLS-II Injector is operated in a top-off mode delivering an electron beam to the NSLS-II Storage Ring. The Booster synchrotron is designed to accelerate the beam from 200 MeV to 3 GeV. Frequent failures of the linac klystrons were observed at the standard injection energy of 200 MeV. To mitigate this issue and to improve the NSLS-II reliability, a series of beam studies were carried out with the goal of developing new operation modes with the Booster injection energy from 100 MeV to 170 MeV. This would allow us to lower the klystron power, to prevent their failures, and to extend the klystron lifetime. The ultimate value of 100 MeV was chosen to provide the emergency operation mode of the Injector with a single klystron instead of the regular two-klystron operation. The impact of lowering the booster injection energy down to 90 MeV on the supplemental radiation shielding was analyzed too [32]. Using a decremented approach with intermediate energies from 170 MeV to 115 MeV and applying online optimization of the Booster parameters, the Injector modes with the energies of 170 MeV, 150 MeV, 130 MeV, 115 MeV, and 100 MeV were developed [33]. The 170 MeV operation mode is now implemented for NSLS-II user operations. Overall beam transfer efficiency from the gun to the storage ring is the same as for the nominal 200 MeV injection energy. After the implementation of this new mode, substantially fewer klystron failures and less frequent interruptions of the top-off injection are observed. This helps to increase the NSLS-II operational reliability for the users.

13 Radiation shielding analysis

Operations of modern high-brightness light sources with low-emittance and high-current beams lead to higher beam loss rates compensated by full-energy top-off injection. To predict the dose rates outside the tunnel requires a detailed description of the geometry and materials that the beam losses will encounter inside the tunnel. An analytic shielding model is shown to be inadequate because of its lack of geometry specification for the process of particle shower below the neutron production threshold. To predict the dose rates outside the tunnel, Monte-Carlo codes like FLUKA are used. The FLUKA code can handle this geometric description of the radiation transport process in sufficient detail, allowing accurate predictions of the dose rates expected and the ability to show weaknesses in the design before a high radiation incident occurs. Implementation of the graphical interface of FLAIR to FLUKA made the effective shielding process for NSLS-II quite accurate and reliable [34].

High-energy neutrons produced by the injected beam losses in the top-off mode are a major component of the dose rate outside the shield walls of the tunnel. A circular shield wall design has been proposed to decrease substantially the dose rate compared to the conventional ratchet walls [35]. The circular shield wall is cost-effective because of the reduced volume of concrete and has additional advantages such as simpler construction and better access to the insertion devices and in-tunnel beamline components.

Radiation shielding analysis for a new NYX beamline (ID-19) was carried out [36]. Extensive FLUKA simulations were done to guide the adequate radiation shielding design and to prepare for NYX Instrument Readiness Review (IRR). This work includes creating complex geometry for FLUKA (based on engineering design drawings) and performing simulations of primary gas bremsstrahlung, secondary gas bremsstrahlung, and synchrotron radiation. The top-off safety analysis was also completed. The NYX beamline successfully passed its IRR.

14 Ultra-fast electron diffraction and microscopy

An LDRD project entitled “100 fs single-shot electron beam slicing technology towards ultra-fast imaging” has been approved and funded. This is an inter-disciplinary and cross-department R&D program involving NSLS-II, Condensed Matter Physics Department, and ATF-II. A bunch compressor was proposed to upgrade the existing facility for the ultra-fast electron diffraction (UED) and ultrafast electron microscopy (UEM) experiments. The expected intensity will be several orders of magnitude higher than the previously achieved using present technology (about $10^4 - 10^5$ electrons). A new concept of minimization of the time jitter between the electron bunch and the pump laser was proposed to realize an unprecedented level of 10 femtoseconds, which is much lower than achieved before (about 130 fs).

For this project, the following steps are already complete: model analysis and optimization of the beamline [37]; specifications for the magnets and the vacuum chamber; procurement of the magnets; design, installation, and commissioning of the optical diagnostic system.

15 Simulation studies of beam-beam effects for the eRHIC project

An LDRD project “Strong-Strong Beam-Beam Interaction Studies for a Ring-Ring Based Electron-Ion Collider” has been approved and funded. The outcome of the study is expected to provide solid information on the stability of electron-hadron collisions in eRHIC and whether the anticipated high luminosities are achievable. This study will thus contribute to the decision on the optimum design for the electron-ion collider at BNL. Coherent and incoherent beam-beam effects in eRHIC were simulated using weak-strong (SimTrack) and strong-strong codes (BBSS and BeamBeam3D). To verify the simulation code, a series of simulations were done for HERA parameters and compared with experimental data. For the strong-strong case, optimal simulation parameters were found by comprehensive convergence studies. The betatron tunes were optimized using weak-strong and strong-strong simulations. The threshold intensity of coherent instability was also found. The results of these studies are included in the eRHC Conceptual Design Report, presented at the eRHIC Design Choice Validation Review and reported at the IPAC-2017 [38] and NAPAC-2016 [39] conferences.

16 Summary

In parallel with the support of user operations [40, 41, 42, 43, 44, 45], the NSLS-II Accelerator Physics group carries out a number of research and development works. The most significant accomplishments are summarized in this report. Besides, the physicists completed in 2016-2017 the following projects and activities: a review of beam-based techniques of impedance measurement [46]; development of a technique to measure synchronous phase shift from the RF beam loading [47]; study of collective effects caused by a long low-gap in-vacuum undulator [48]; development of advanced techniques for lattice simulation, measurement, optimization, and correction [49, 50, 51, 52, 53, 54]; study of collective effects for the APS-U project (MOU) [55].

The results of the accelerator physics studies completed in 2016-2017 are summarized in 13 articles published in peer-reviewed journals and in 38 reports presented at national and international conferences(SRI-2015, NAPAC-2016, IPAC-2016, IPAC-2017, IBIC-2017). Figure 1 shows the statistics of journal articles and conference reports published in the past 4 years.

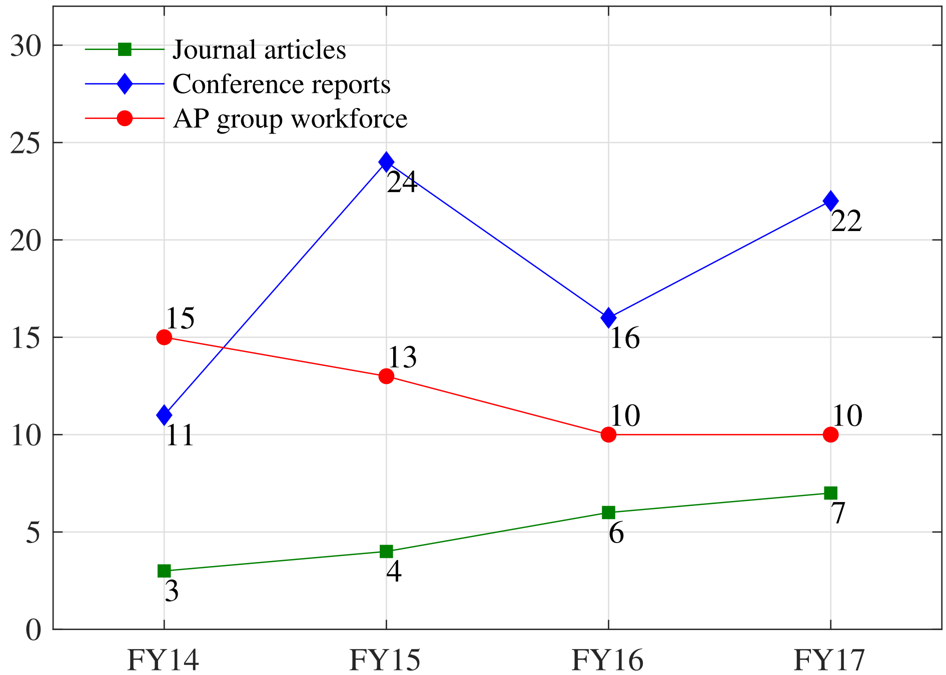

Figure 1: Number of journal articles and conference reports published by the NSLS-II Accelerator Physics group in FY14-FY17.

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