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OPERATION AND PERFORMANCE OF NSLS-II*

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Abstract

NSLS-II facility hosts 27 operating beamlines with 1 more under construction. The radiation sources vary, including damping wiggler, IVU, EPU, 3PW, and bending magnets. Over the past year, the storage ring performance continuously improved, including frequency feedback and photon local feedback. Machine reliability for now reached 97.4% for 4750 hrs operation with beam current upto 375 mA. Beam orbit short and long term stability has been significantly improved. Operation beam emittance was optimized with beamlines.

NSLS-II SR STATUS OVERVIEW

The National Synchrotron Light Source II (NSLS-II) is a 3 GeV, ultra-small emittance (H: 1 nm-rad and V: 8 pm-rad), high brightness third generation light source at Brookhaven National Laboratory. It is to deliver a broad range of light with the brightness of 10^{22} photons/s/mm^2/mrad^2/0.1%BW to 60-70 beam lines at full built-out.

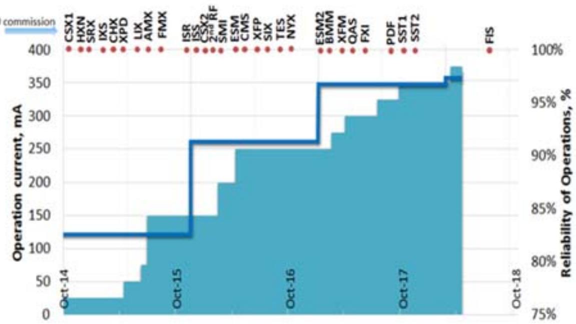

Figure 1: History of NSLS-II beam current, operation reliability and ID beamline sources.

The storage ring was commissioned in 2014 and began its routine operations in the December of the same year [1-3]. Figure 1 shows the trend of beam current increment, ID beamline sources commissioning and operation reliability. Over the past years, beam current and operation IDs sources have been steadily increased. After second RF cavity commissioning in 2016, RF system had sufficient power (310 kW each) for high beam intensity operation. Currently, machine runs at 375 mA (project goal 500 mA) with 2 minutes periodic top off injection to maintain current stability within ±0.5%. Meanwhile we have demonstrated 400 mA stable beam operation, which is the FY18 operation goal, with all insertion devices (IDs) gap closed during beam study. Further current increase along with more IDs in operation requires third RF system. The reliability of operation has been improved and maintained above 95%. The accumulative reliability is 97.4% upto now, about 2/3 of operation hrs (4750 hrs).

NSLS-II has established 28 beamlines, following into five projects: NSLS-II project beamlines (7 beamlines), Advanced Beamlines for Biological Investigations with X-rays (ABBIX, 3 beamlines), NSLS-II Experimental Tools (NEXT, 5 beamlines) project, Beamlines Developed by NSLS-II (BDN, 7 beamlines), and Partner Beamlines (6 beamlines). As shown in figure 1, installation of IDs, front-ends and beamlines happened during three shutdowns per year. 25 beamlines have been in routine operation, 2 beamlines are under commissioning and one is under construction. The radiation sources are various , including 6 elliptically polarizing undulators (EPU), 6 damping wigglers (DW), 10 in-vacuum undulators (IVU), 5 three pole wigglers, 1 plain undulator and 2 bending magnets to provide wide spectral range, from the far-infrared to the very hard x-ray region (>300 keV). They filled in 8 short straight sections and 8 long straight sections, more than half of available space (totally 15 short and 12 long straight sections). Six of them are canted beamlines to double the number of user experiments.

OPERATION STATISTICS

Table 1 showed NSLS-II yearly hrs distribution over the past years among operation, beam study, maintenance, shutdown, new ID/FE/beamlines related commissioning and refer two facilities, NSLS and APS. It also includes goal for operation current and reliability. Operation hrs quickly increases and will reach 5000 hrs next year, comparable with mature facility capability. The beam studies are for the machine performance improvements and new insertion device commissioning to pursue high operation reliability and high performance for both accelerator and beamlines. Over 20 beamlines have been commissioning and brought into operation. The number of users has increased over 1000 in FY17 and this trend will continue. We improved machine performance from various aspects, such as high current related heating and vacuum activity [4], beam short and long term stability, beam operation emittance optimization with beamlines, optimization of top off injection transition [5], compensation of ID caused coupling [6] etc. Maintenance usually happens every three weeks and lasts for 32 hrs, which turns out to be more efficient than one day maintenance. Since the injector related maintenance is relatively light, overnight period was also planned for injector study, such as 100 MeV linac injection for emergency situation [7] or linac stability study with machine learning [8].

As a user facility, high reliability is NSLS-II first goal. We have put big efforts to maintain and improve machine

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Table 1: Injected Beam and Stored Beam Relative Position at the Exit of Septum

	NSLS-II				NSLS X-ray	APS
	FY16	FY17	FY18	FY19	FY12	FY16
Operations (hours)	3718	4500	4750	5000	5150	5000
Studies (hours)	1713	872	850	850	721	632
Maintenance and interlock certification (hours)	594	440	440	440	376	872
Shutdown (hours)	2825	2224	2200	2200	2513	2256
ID, FE, BL Commissioning (hours)		724	520	270		
Reliability Goal	90	95	95	95	95	
Operating Current: Start/End (mA)	200/250	250/300	300/400	400/500	300	100

reliability, including 1) optimization of machine recovery sequence and tools to minimize machine down time, ~0.8 hrs in average, vary depending on beam dump sources from 20 mins to a few hrs, 2) weekly review beam dump and machine down time, analyse each beam dump sequence from post mortem data [9] and develop subsequent corrective actions, 3) integrate important parameters into alarm system, analyse subsystem performance trend and develop an effective preventive maintenance program to improve subsystem reliability, 4) periodic inspection and replacement during maintenance and shutdown for Electricity, Utilities, Mechanical, Vacuum and Insertion Device.

Figure 2 showed FY18 subsystems caused downtime and number of dump. The top first contribution down time is from utility, which is due to water flow blocked in skid caused magnet overheating and requires tunnel access, backflush flow restrictor etc and took ~5 hrs. To correct this issue, actions include closely monitor water quality, adding temperature sensor in magnet and routine inspect magnet heat distribution, replacement of small water flow restrictor and work sequence coordination to minimize holding time. Other long down time has 1) snow storm caused power dip, 5.6 hrs, 2) global control network failure, ~3.5 hrs, 3) ID BPM fail, which requires re-validate and activate beamline, ~2.8 hrs. In the number of dumps chart, the dominant contribution is from RF system, which usually takes about half hr to recover for operation. Since Nov. 2017, Cavity D had issue to run at nominal value and voltage dropped from 1500 kV to 875 kV to keep stable beam operation. The reason is still under investigation.

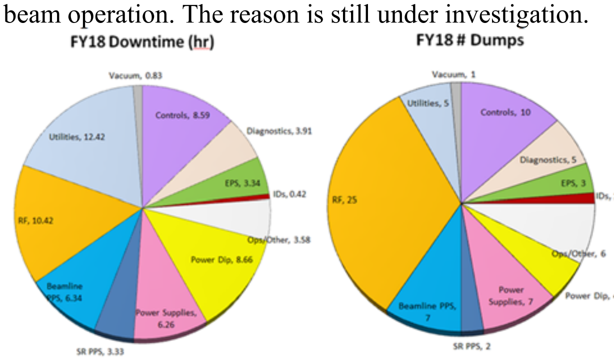

Figure 2: Subsystems caused downtime distribution and number of dump in FY18.

SHORT AND LONG TERM BEAM STABILITY

As NSLS-II beamlines were progressing towards their mature performance, we have been focusing on improving beam orbit stability. Currently Fast Orbit Feedback (FOFB) maintains beam orbit within 10% of the beam size in the source points within the bandwidth of 100 Hz [10]. Further improvements to accommodate operation demanding include 1) individual ID angle/offset adjustment with local bump feedforward method [11] to coherently work with FOFB, 2) orbit recovery using FOFB after beam dump to improve orbit reproducibility, 3) shifting fast correctors strength to DC correctors to avoid fast corrector saturation [12], 4) adding ID BPMs in FOFB to improve ID sources long term stability.

However, some beamlines have large long term drift due to environment (local vehicle tunnel) and electron BPMs in SR does not reflect real beam motion source and cannot correlate well with beamline target position. Photon local feedback (PLFB), based on xBPM and ID correctors, was proposed to stabilize photon position. Usually, xBPM is 10s meters away from ID source, so this improves photon source angle stability resolution by a factor of 10, comparing with the method of maintaining ID electron BPMs stability from FOFB. PLFB does not involve any mechanical devices control and can correct high frequency motion. It is a general method and can be applied to all existing and new beamlines. Currently, four beamlines have adopted this method and long term drift at the front end xBPM is maintained within 1 μm level, which is ~60 nrad angle stability, much beyond electron BPM resolution.

With the new experience from bending magnet (BM) beamlines operation, we learned that their sample data collection can last over 10s hours and long term stability is critical to get high quality imaging. Bending magnet and three pole wiggler photon sources are located at high dispersion region. SR circumference daily change can cause BM photon source drift ~50 um, which cannot be corrected with FOFB. RF frequency feedback was developed to compensate daily energy drift caused dispersion region position change. Figure 3 showed one BM beamline (TES) sample image improvement with RF frequency feedback system.

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We also implemented an online function to collect 10 seconds BPM data per minute at10 kHz sampling rate and analyze them in time and frequency domain, which provides insights of orbit stability, locations of noise sources, performance of feedback systems etc.

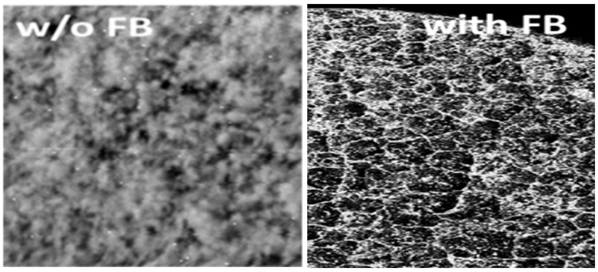

Figure 3: Bending magnet beamline (TES) sample (a microtextured composite) improvement with RF frequency feedback system.

DIFFRACTION LIMIT VERTICAL BEAM EMITTANCE STUDY

Beam vertical emittance is designed to be at 8 pm, diffraction limit. Usually, vertical emittance in operation is larger so that beam lifetime is relatively longer, thus less frequent top off injection to relieve injector demanding. Last year, we scheduled dedicated study with beamlines to understand the optimal working point.

The beam vertical emittance is due by vertical dispersion and betatron coupling. We use 15 dispersive skew quads and 15 non-dispersive skew quads to control vertical emittance. At low current, we correct vertical dispersion first, then correct coupling driven term with BPM turn by turn data. There is a pin-hole camera to monitor beam emittance down to 5.5 pm. With beam current increase, we further optimized bunch by bunch feedback gain to maintain beam emittance below 8 pm.

Figure 4 showed one result from beamline with 8 pm and 30 pm vertical emittance. At lower emittance, both peak intensity and peak width showed improvement. But the measured peak intensity showed 25% increase, while ideal model should be 45%, which reveals the limitation from beamline optics distortion and cannot benefit from diffraction limit emittance. On the other hand, lower the emittance by a factor of 4 increases relative beam motion by a factor of 2, as the absolute beam motion is independent of beam emittance.

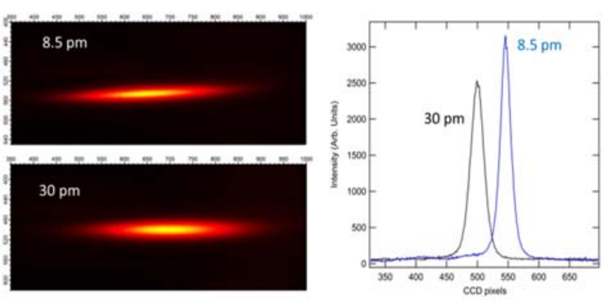

Figure 4: Impact of vertical beam emittance on HXN beam line imaging and intensity.

We also scheduled a period operation of 8 pm emittance with 19 beamlines. The feedbacks of vertical emittance are that 1) 3 beamlines (coherent/small focusing beamlines), prefers 8 pm, 2) 1 beamline prefers 16 pm, to comprise beam stability and their optics limitation and 3) the rest of majority beamlines prefer 30 pm to have less frequent top off injection.

HIGH CURRENT BEAM STUDY

NSLS-II beam current design goal is 500 mA. In Feb. 2016, we firstly accumulated 400 mA and observed ceramics chambers heating to 100 °C along with vacuum activities. Further inspection showed one chamber discoloration and internal coating damage. Later activities to solve ceramic chamber heating issue include adding local cooling fan, monitoring heating distribution with IR camera and installation of more temperature sensors, which reveals heating sources located at the flange joint positon. After that, we carefully positioned RF springs in joint flanges and bellows and temperatures in all ceramic chamber location are below 40 °C with cooling fan at 400 mA. Another development project is the in-house coating ceramic chamber, which was installed in Jan. 2018 and verified with beam successfully.

There are about 800 RF springs around SR, but temperature sensors may not cover every location. With the experience of potential RF spring installation issue [3], we scheduled a systematic heating survey, right after high current study. It showed that the bellows at the downstream of ID straight section are apt to be hotter than other locations. This agrees with installation situation that this location is hard to access than others. We also installed IR camera to monitor each suspicious location and totally replaced 9 RF springs. Figure 5 showed one example of C16 area vacuum activity and heating distribution due to RF spring distortion.

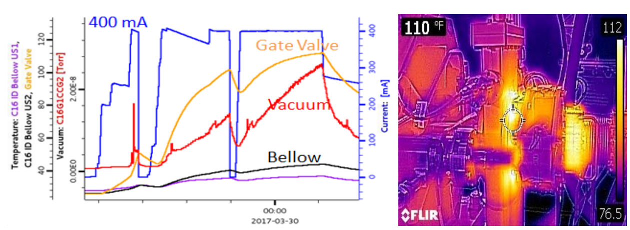

Figure 5: C16 area vacuum activity (left) and heating source distribution with IR camera (right).

SUMMARY AND OUTLOOK

NSLS-II storage ring is in routine top off operation at 375 mA with machine operation reliability >95%. We have demonstrated 400 mA stable ops. Further beam intensity increase requires 3rd RF cavity. We improved long term beam stability with RF frequency feedback and PLFB while maintain short beam stability <10% of beam size. There are rapidly growing of NSLS-II beam line community (28 BLs by FY18) and users (over 1000/year). We work closely with beamlines on operation emittance to benefit both beamlines and accelerator.

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In FY19, ops hour will increase to 5000 hrs. 3rd RF system was in the development plan and will be installed and commissioning in mid-2020. Operation current further increase to goal 500 mA will be thereafter. New beamline, High Energy X-ray Diffraction (HEX) from superconducting wiggler source, was funded by New York State and will be installed after 2020.

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