ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-MOPAB079

EXPERIENCE OF THE FIRST SIX YEARS OPERATIONS AND PLANS IN NSLS-II*

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Abstract

NSLS-II is a 3 GeV third-generation synchrotron light source at BNL. The storage ring was commissioned in 2014 and began its routine operations in the December of the same year. Since then, we have been continuously installing and commissioning new insertion devices, their front-ends, and beamlines. At this point, the facility hosts 28 operating beamlines from various radiation sources, including damping wiggler, IVU, EPU, 3PW, and bending magnets for infrared beamlines. Over the past six years, the storage ring performance continuously improved, including 500 mA with limited insertion devices close due to RF power limitation and routinely 400 mA top off operation, >95% operation reliability, maintenance of beam motion short- and long-term stability. In this paper, we report NSLS-II accelerator operations experience and plans for future facility developments.

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.

The storage ring was commissioned in 2014 and began its routine operations in the December of the same year [1-4]. Figure 1 shows the trend of beam current increment, ID beamline sources commissioning and operation reliability and operation hours. Over the past years, beam current and operation IDs sources have been steadily increased along with operation hours increasement.

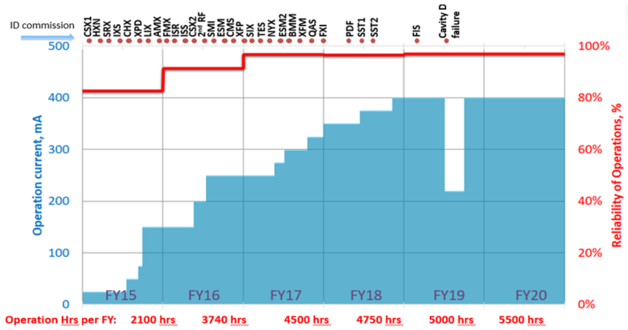

Figure 1: History of NSLS-II beam current, operation reliability, ID beamline sources and operation hours per year.

After the second superconducting RF cavity commissioning in 2016, which increased RF system power by ~ 300 kW, we started to raise operation current. In 2018, we routinely run at 400 mA and maintained it since then. However, in April 2019, the first RF cavity fluted beam tube indium seal showed vacuum leak and required to be removed from SR. At that time, operation beam current was forced to lower at 220 mA for 10 weeks operation. During the following long shutdown, we replaced the leak cavity with our third RF cavity, while it was under repair and will serve as the third RF system. In April 2021 (delayed by half year, due to Covid-19), a third RF system, including 300 kW solid state amplifier, cryomodule and cavity were installed and integrated into operation. Totally, three RF systems can deliver 700 kW power and is sufficient to support 500 mA operation. High current conditioning and optimization for stable operation is underway.

Currently, the operation beam lifetime is about 9 hours at 30 pm vertical emittance, with top off injection to maintain beam current stability within 0.5%. Third RF cavity helps to increase beam lifetime by raising total RF voltage. Along with beam current increase, we also steadily integrated new IDs sources into operation. Overall, there are 28 beamlines in routine operation to serve different research community. 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). New insertion devices, especially superconducting wiggler is starting to serve high energy X-ray beamline.

The operation time to serve user experiments gradually increase to 5000 hours, since 2019, similar as many mature operation facilities. In FY20, we served extra operation time to support Covid-19 related research, by comprising beam study and shutdown time.

Besides that, we also put efforts to improve machine performance, including reliability, beam stability, high current to 500 mA and diffraction limit 8 pm-rad vertical emittance.

OPERATION RELIABILITY

As a user facility to provide 24 hours, 7 days operation, reliability is a key parameter to reflect machine performance. To increase the reliability of operations, we have put a lot of efforts by improving many machine subsystems that were responsible for faults and related beam dumps. Overall, we achieved ~ 97% reliability with total beam dump number gradually decreased from

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95 (FY17) to 65 (FY20), while operation hours increase from 4500 to 5500 hours. The mean time between failure increases from 45 to 75 hours.

We encountered several significant events that reveal accelerator components vulnerabilities. Figure 2 showed subsystems caused downtime from subsystems over the past four years. The top contributions include power supplies, power dip, RF, Cryo Plant, Utilities. Big events are addressed here.

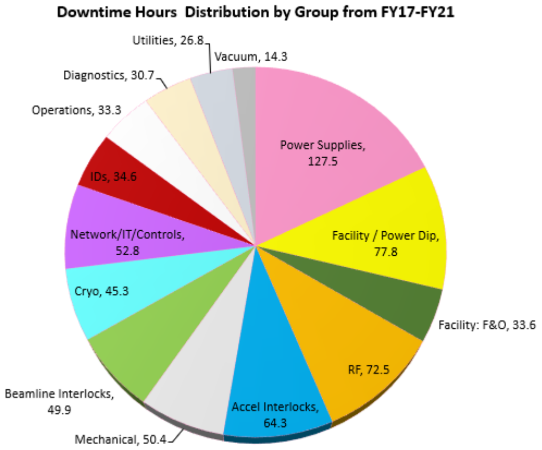


Figure 2: Subsystems caused downtime from FY17-FY21.

In 2018, one main dipole in Booster ring failure took 50 hours to troubleshoot and repair a connector pin oxidation problem. After that, we installed diagnostics system to monitor dipole performance.

For the RF system, after the 2nd new cavity integrated into operation in FY16, we experienced 111 beam trips and 87 hours downtime due to vacuum issue and field instability. The vacuum seal leak was fixed with in situ repair. In FY19, we lost the first operation RF cavity due to vacuum seal failure from necessary cavities warm-up. Luckily, it happened during shutdown, without hurting operation reliability, but affected operation current, from 400 mA to 220 mA. Cavity warm-up was tangled with cryo-plant issue. In 2017, there was a burst disc event due to cryo plant emergency stop. This caused cryo-plant contamination and required frequently cold box warm-up and pump & purge. Since then, we experienced 16 times warm-up and each one typically takes about 2.5 days. Besides planned time during maintenance day or shutdown, we lost 35 hours operation and >200 hours beam studies. Ideally, a redundancy of cryo-plant is needed based on other machine experience, such as Pohang light source, lost 3 months due to a turbine failure with no redundancy. We continuously upgrade cryo-plant to improve its performance, including 1) install an additional buffer tank to add helium storage capacity and increase time available for keeping cavities cold during cryo-plant maintenance, 2) add helium purifier system, 3) cryo-plant control test stand and 4) replaced pressure relief valves on cavities to increase its reliability.

For the utilities, deionized water (DIW) to cool magnets showed deficiencies in the control of Dissolved Oxygen (DO) and resistivity, thus caused copper to form oxides and block small passageways, resulting in magnet ground faults and magnet overheating from waterflow restriction. Individual block cleanup required ~ 5 hours to flush magnet.

We modified the make-up water system to improve water quality, optimize DI water quality level based on test stand study result, systematically flushed magnets during facility shutdowns and replaced mechanical restrictions. We succeeded in de-risking the DIW system and the rate of leakage currents and trends measured by flowmeters are now substantially reduced.

FAST ORBIT FEEDBACK BANDWIDTH IMPROVEMENT

Beam stability is another important parameter to affect beamline performance. NSLS-II fast orbit feedback [5] includes 90 fast correctors and ~200 BPMs running at 10 kHz sampling rate. FOFB running alone can suppress fast beam motion well within 10% of beam size. However, it is not sufficient to maintain long term drift. Over the past years, we have put efforts to improve beam long term stability and reproductivity, including 1) individual ID angle/offset adjustment with local bump feedforward method [6] 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 [7], 4) adding ID BPMs in FOFB to improve ID sources long term stability and 5) Photon local feedback (PLFB), based on xBPM and SR correctors to improve beam angular stability by a factor of 10, comparing with SR BPMs feedback system, by taking advantage of xBPM long distance (~ 20 m) from ID source. Overall, we can maintain long term stability in ID section within 1 μm and bending magnet sources within 10% of beam size.

We also put efforts to improve FOFB bandwidth and gain [8]. The bandwidth is limited by FOFB loop latency. We characterized feedback system stage-to-stage latency. This is a very effective way to diagnose the issue and provide insights to improve the system. Two major improvements were done, including removal of 100 μs delay in the BPM firmware and increasing of cell controller (CC) sampling rate from 5 kHz to 10 kHz. The overall latency and improvements are shown in Fig. 3. After upgrading BPM and CC firmware, the bandwidth was improved from 250 Hz to 400 Hz in horizontal plane and 250 Hz to 300 Hz in vertical plane. The difference between could be from magnet and chamber configuration. The gain also increased by almost 10 dB in both planes. The beam integrated motion reduced by 30%. Typical ID source position and angular integrated motion (1-500 Hz) is 0.6% in horizonal plane and 7% in vertical plane [9].

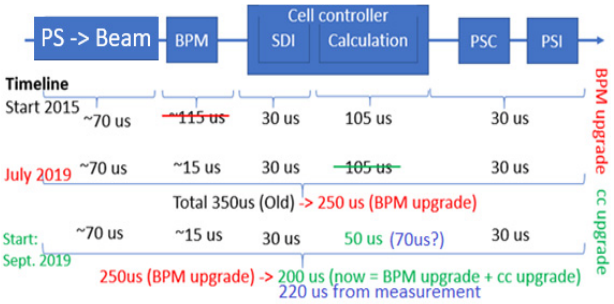
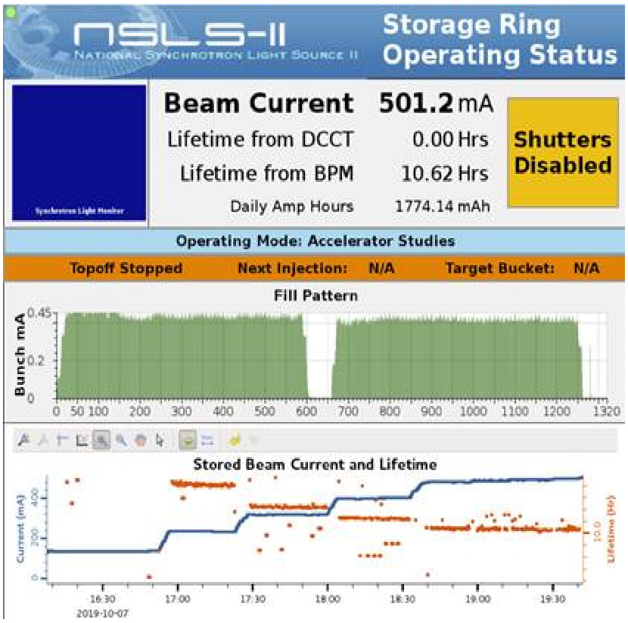


Figure 3: FOFB stage-to-stage latency and improvements.

PATH TO HIGH BEAM CURRENT

NSLS-II operating current continue increase with designed goal at 500 mA. In FY18, we achieved 400 mA routine operation current and maintained it since then, which is limited by RF power. In the beam study, we focused on the impedance caused heating on the vacuum components, especially the ceramic chambers, and flanges connected through RF springs.

Ceramic chambers are used for four fast kickers for beam injection and pingers for beam dynamics studies. The required coating is 2 μm in thickness over the entire inner surface (half meter long) with ± 10% uniformity. However, with the non-uniform Titanium (Ti) coating from initial purchase, we observed heating to 100 °C since the first high current study in 2016 [10]. Since then, we replaced damaged kicker chamber, installed air cooling system, replaced RF springs between flanges and bellows. We also developed in-house coating technique, using DC magnetron sputtering along with integrated thickness monitor and successfully coated five new ceramic chambers. Three of them are in operation with temperature improved <40 °C at 400 mA.



Beam Current 501.2 mA
Lifetime from DCCT 0.00 Hrs
Lifetime from BPM 10.62 Hrs
Daily Amp Hours 1774.14 mAh
Shutters Disabled
Operating Mode: Accelerator Studies
Topoff Stopped
Next Injection: N/A
Target Bucket: N/A

Figure 4: Demonstration of 500 mA.

Another component that caused local heating is RF springs. There are 770 RF springs in SR, but only limited locations were instrumented with temperature sensors. To pinpoint hot spots, we installed over 800 1-wire thermometers as the diagnostic system for high current study to monitor every flange's temperature. This is very helpful to pinpoint hotspots. Overall, 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 developed new RF spring design with denser and more flexible conductor coverage. Totally, more than 40 RF springs were replaced. In Oct. 2019, we successfully demonstrated 500 mA with only 3 pair of damping wiggers in operation, as shown in Fig. 4. RF power were close to the normal operation range, 230 kW.

SUMMARY AND OUTLOOK

We have been constantly improving and developing NSLS-II to increase operation reliability, beam stability and increase the beam intensity over the past six years. We have demonstrated 500 mA stable beam during study. Storage ring is in routine top off operation at 400 mA with machine operation reliability >95%. Further beam current increase is on the way with third RF system conditioning and optimization. Efforts were made to improve subsystem's reliability, including cryo-plant, DI water system etc. We improved beam stability by 30%, by increasing fast feedback system bandwidth and gain,

To reach 500 mA, 8 pm-rad [11] reliable operation, third harmonic cavity is under development and planed for installation and operation in later 2022. This will increase bunch length by a factor of 2, thus increase beam lifetime, aid in reducing impact from collective effects and reduce vacuum chamber overheating.

ACKNOWLEDGMENT

I would like to thank my high-skilled colleagues for their dedication and efforts to reach the high-performance beam quality in NSLS-II.

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