

NSLS-II ACCELERATOR COMMISSIONING AND TRANSITION TO OPERATIONS*

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Abstract

Over past year NSLS-II has completed accelerator commissioning and enabled operations of first project beam lines. Recently we further optimized the NSLS-II accelerators, increased the beam current to 400 mA without- and to 250 mA with Insertion Devices (IDs), commissioned top-off mode of operations and stabilized beam orbit to below 10% of the beam size in the source points. In this paper we report progress on the NSLS-II accelerator commissioning and operations and plans for future facility developments.

STATUS OF NSLS-II

NSLS-II, the new 3rd generation light source at BNL was constructed (2007-2014) to deliver a broad range of light with the brightness of 10^{22} photons/s/mm²/mrad²/0.1%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]. In 2015-2016 we have been continuously installing and commissioning new insertion devices, their front-ends and beamlines. At this point the facility hosts 14 operating beamlines with 5 more are approaching completion of construction.

Over past year we have been steadily increasing beam current. In April 2016 we reached routine operations with 250 mA with all ID gaps closed and all installed beam lines receiving photons. During beam studies we accumulated 400 mA with ID gaps open and monitored vacuum and temperature of the ring vacuum vessels.

One of the major accomplishments was installation and commissioning of the second RF cavity. For the past three months we were carrying on beam operations with two superconducting 500 MHz cavities, delivering power in excess of 100 kW to the circulating beam of 250 mA.

Active interlock (equipment protection system) has been tested and put into operations to maintain beam orbit within tight envelope of 0.5 mm and 0.25 mrad in the source points [2]. In September of 2015 we transitioned user operations from periodic refills once in 2 hours to the top-off mode, in which we maintain relative average current stability within 1%.

As NSLS-II beamlines were progressing towards their mature performance we have been focusing on improving beam orbit stability. Currently Fast Orbit Feedback maintains beam orbit within 10% of the beam size in the source points within the bandwidth of 100 Hz. Substantial progress has been achieved in increasing lattice (routinely 4%

beta-beat) and orbit (~10 μ m) reproducibility during machine restarts [3]. We also measured major performance parameters including emittance and lifetime and compared them with the machine models [4].

With three shutdowns per year NSLS-II adds several new IDs, front-ends and beamlines every shutdown, which requires frequent vacuum interventions and large scope of new hardware to commission during restarts.

BEAM LINE COMMISSIONING

Rapidly growing NSLS-II beam line community took off from the first six project beamlines that has been put into operations after machine commissioning in 2014-15. Year and half later we encounter the following beam lines (Table 1) that either have been recently commissioned or already operating (names in green) or getting ready for commissioning (names in orange).

Table 1: Current List of the NSLS-II Beam Lines

| Name | ID, length | SR cell # | Strength |
|---------|---------------|-----------|----------|
| CSX | EPU49, 2x3m | 23-ID | K=4.34 |
| XPD | DW100, 2x3.5m | 28-ID | 16.5 |
| HXN | IVU20, 3m | 3-ID | 1.83 |
| SRX | IVU21, 1.5m | 5-ID | 1.79 |
| IXS | IVU22, 2x3m | 10-ID | 1.52 |
| CHX | IVU20, 3m | 11-ID | 1.83 |
| LIX | IVU23 | 16-ID | 2.2 |
| AMX/FMX | IVU21 x2 | 17-ID | 1.79 |
| ISR | IVU23 | 4-ID | 2.05 |
| SMI | IVU23 | 12-ID | 2.05 |
| ISS | DW100 x2 | 8-ID | 16.5 |
| FXI | DW100 x2 | 18-ID | 16.5 |
| ESM | EPU57 | 21-ID | 11.2 |
| CMS | 3PW | 11-BM | B=1T |
| TES | BM | 8-BM | 0.4T |
| XFP | 3PW | 17-BM | 1T |

Some of the beam lines (such as CSX1, 2) are canted doubling the number of user experiments. NSLS-II IDs range from small gap 5.6 mm In-Vacuum undulators (IVU) to 100 mm period damping wigglers (DW), radiating out 16 kW at 250 mA of beam current per device (six DWs are installed).

Special efforts were dedicated to compare real spectral performances of undulators at hard X-ray beamlines to simulated ones in order to identify cases of underperforming IDs and to develop strategies for “restoring” their performance [5].

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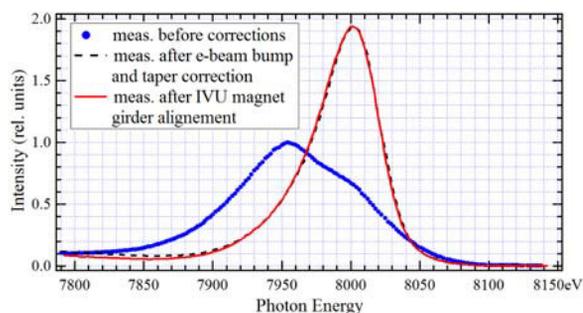


Figure 1: IVU21 spectral flux per unit surface at 5th harmonic measured at SRX beamline before and after applying two types of corrections.

Figure 1 illustrates results of such studies carried-out at SRX beamline. In this case, simulations suggested that a possible reason for lower spectral flux initially measured at that beamline could be a presence of some “taper” or/and misalignment of magnet arrays with respect to electron beam trajectory within the IVU. This was confirmed during studies when different orbit “bumps” were applied, followed by spectral measurements at the beamline. Then the IVU controls were modified to allow for independent steering of magnet arrays, and a restoration of the IVU spectral performance, resulting in the increase of the spectral flux per unit surface by a factor of ~2, was demonstrated in regular operations. Final corrections resulted in a change of the IVU vertical “elevation” by ~300 μm and the gap “taper” by ~35 μm.

INJECTOR AND TOP-OFF

Top-off mode of operations was tested and turned to routine operations in Oct 2015. Multibunch (20-100 bunches) injections take place every 2 minutes delivering about 5 nC into storage ring buckets while maintaining beam current at 250 mA inside the deadband of 1% and bunch-to-bunch charge variation below 15% [6, 7].

The NSLS-II injector is operating continuously either for initial fills (1 Hz) and taking 8 minutes to accumulate 250 mA or for top-off, entering “sleeping” mode after every injection. In this mode booster power supplies are set to zero output current except for the dipole circuits that idle at 50 A injection porch level.

Several improvement projects are on the way including rework of quadrupole power supplies and kicker pulsers to increase reliability of their operations. Another notable project that we recently begun is preparation of commissioning linac / booster operations at 100 MeV to increase redundancy of the linac klystrons and reduce voltages on booster injection elements.

SECOND RF CAVITY

NSLS-II storage ring RF system uses two 500 MHz single-cell superconducting RF cavities and two klystron transmitters capable of delivering power of 310 kW each. The second cavity was installed in the winter shutdown and commissioned to the voltage of 1.6 MV (Fig. 2).



Figure 2: RF cavities C and D in the storage ring tunnel.

During the second cavity commissioning several multipacting zones have been detected between 600 and 800 kV. A few of conditioning techniques is being applied including partial warm-up and CW/pulsed RF cavity treatment.

Motivated by fast progress in understanding properties of NSLS-II RF feedbacks we tested a new tool for machine studies called “RF jump”, which is an essence a longitudinal pinger that drives beam off-energy within a fraction of synchrotron oscillation. The RF jump helped to assess the energy acceptance and enable experiments on modulation of beam energy near 1/2 resonance stopband.

HIGH CURRENT OPERATIONS

As the NSLS-II design calls for the current of 500 mA we are making steady progress in increasing beam intensity. During the last run we studied accumulation and top-off of 400 mA (Fig. 3)

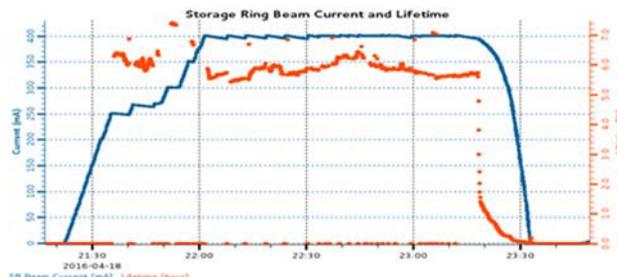


Figure 3: Injecting and topping off 400 mA.

While the average vacuum pressure in the ring chambers was acceptable at 4E-8 torr we observed and studied rapid increase of the kicker ceramic chamber temperature, which was sensitive to the bunch length. Upon removing the chamber Ti coating revealed local damage.

BEAM STABILITY

Small beam emittances of 1.7 nm-rad (x) and 60 pm-rad (y) call for reasonably tight requirements on the orbit stability. During NSLS-II design orbit stability of 10% of the beam size has been selected and approved by the local beam line community.

Fast Orbit Feedback (FOFB) was commissioned and suppressed low frequency range of orbit noise from sub-Hz to 100 Hz (Fig. 4). The major source noises are identified as booster-induced transients in ~1 Hz range, 60 Hz and harmonics, ~100s of Hz driven by IGBT switching in

switch-mode power supplies and synchrotron peak at 2.4kHz.

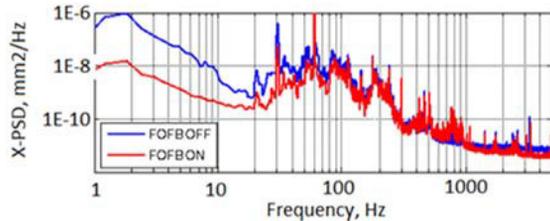


Figure 4: RF BPM spectrum with and without FOFB.

The integrated (within 100 Hz) orbit stability is routinely measured as 1.6 μm (x) and 0.3 μm (y) in the low beta straight sections.

Maintaining close dialog with NSLS-II beam lines on the subject of beam stability we investigate sources of orbit drift as observed by RF BPMs in the ring and X-BPMs in front-ends and beam lines. (Fig. 5).

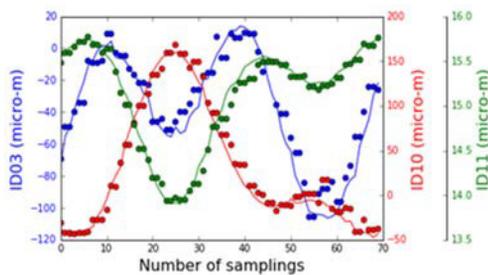


Figure 5: Simultaneous measurements of RF- (dots) and X-BPM signals for 3 most sensitive NSLS-II beam lines via two-corrector orbit modulation.

Future improvements of FOFB include maximizing its bandwidth and further reducing integrated spectral intensity in pursuit of better beam stability.

ACCELERATOR PHYSICS

Studies focused on optimization of the storage ring linear lattice continue. Recently performance of several algorithms based on turn-by-turn BPM data analysis have been compared experimentally: weighted correction of betatron phase and amplitude, ICA, MIA, and driving-terms-based linear optics characterization [8]. A LOCO algorithm based on closed orbit measurement has been used as a reference. Minimal beta-beat of about 2% has been achieved.

Lattice with chromaticity of $+7/+7$ has been developed and tested during beam studies [9] (Fig. 6). Injection efficiency was measured near 100% and lifetime for 10mA/100 buckets was about 13 hours. This lattice is a promising candidate for the regular beam operations and expected to optimize gain of Bunch-by-Bunch feedback and reduce sensitivity to beam instabilities.

Dependence of betatron tune shifts on average current has been observed and studied. The effect's model was developed whereas multiple bunches were described by a set of coupled Vlasov equations for the evolution of the phase density associated with every bunch. It was determined that the observed tune shift was explained by the effect of

the dipole and quadrupole impedance cause by ID chambers in the low-frequency regime [10].

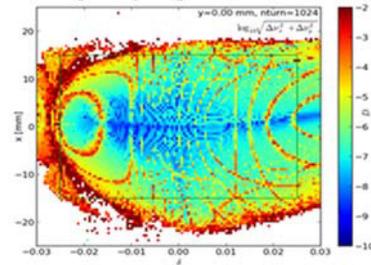


Figure 6: Off-energy FMA for the lattice with $\xi_{x,y}=+7/+7$.

By means of special processing of BPM ADC signals the resolution of NSLS-II BPMs for single- and few-bunch fills was recently improved by an order of magnitude to about 1 micron rms turn-by-turn (TBT) [11]. In addition, this provides individual TBT signals for up to 8 bunches stored in the ring. This is valuable for many studies of collective effects and single particle dynamics as it enables simultaneous measurements of bunches with different charges (or betatron amplitudes), thus eliminating harmful effects of machine drifts.

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