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# ADVANCING TO 500 mA: HIGH-CURRENT RAMP-UP AND OPERATIONAL EXPERIENCE AT NSLS-II*

G.M. Wang†, F. Gao, Y. Hidaka, D. Padrazo, J. Rose, R. Todd,
T. Shaftan, V. Smaluk, T. Tanabe, Brookhaven National Laboratory, Upton, NY, USA

*Abstract*

Since the first light at 50 mA in 2014, NSLS-II has steadily increased beam current, reaching 500 mA in October 2019. Along the way, various challenges were addressed, including RF power consumption, wakefield effects, and unexpected component heating. Key improvements included enhanced temperature monitoring with 600 new sensors, optimized RF spring installation, and the installation of a superconducting wiggler in 2022 to reduce vacuum heating further. As a result, vacuum temperatures now remain below 70 °C at 500 mA. Extensive beam studies ensured stability for 29 beamlines, improving signal intensity, signal-to-noise ratio, and sample throughput. NSLS-II successfully operated at 500 mA in August 2023, with increasing high-current operational periods scheduled each year to enhance user experiments.

## 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.

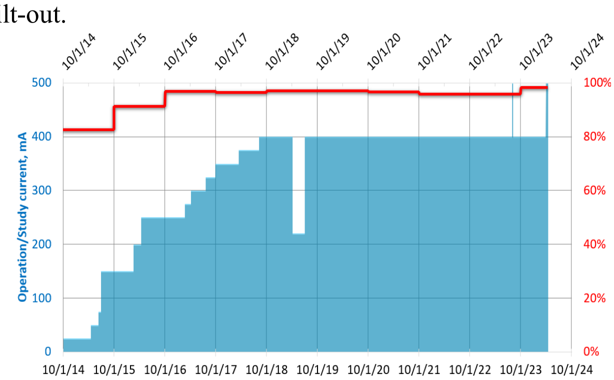


Figure 1: NSLS-II beam current and operation reliability.

Commissioned in 2014, NSLS-II began routine user operations in December of that year [1-4]. Since then, beam current, operating hours, and the number of insertion device (ID) beamlines have steadily increased. Figure 1 shows that following the commissioning of the second superconducting RF cavity in 2016, which added ~300 kW of RF power, the facility transitioned to routine 400 mA operations in 2018. Although a vacuum leak happened in the first RF cavity in 2019 that temporarily limited operations to 220 mA for 10 weeks, we quickly replaced the leak cavity with our third RF cavity during the following long shutdown. In April 2021, the third RF system, including 300 kW solid state amplifier, cryomodule and cavity, were fully installed and integrated into operation. This upgrade further increased the total RF power capacity and, together with the addition of a new high-power superconducting wiggler [5, 6], enabled the facility to 500 mA beam current studies and move toward routine high-current operation.

Currently, the storage ring supports beam stability with top-off injection at 500 mA and maintains a beam lifetime of approximately 9 hours at 30 pm vertical emittance. We support ~5000 operational hours per year, aligning with top-tier international light sources. The third RF cavity contributes to this lifetime by increasing the total RF voltage. The ring routinely operates with 29 beamlines serving diverse user communities, powered by a suite of insertion devices that include 6 EPUs, 6 damping wigglers, 10 in-vacuum undulators, 5 three-pole wigglers, a plain undulator, a superconducting wiggler and 2 bending magnets. The total energy loss per turn from IDs and dipoles is 960 keV.

Since we turned on the machine for the first time in 2014 with 50 mA current, we have steadily increased the current over time. In just five years, we reached a major milestone—500 mA beam current in October 2019—followed by extensive high-current studies to ensure stable and reliable performance with beamlines. Along the way, we overcome many significant challenges, including an increase in power consumption of the RF cavities, more intense wakefields, and the unexpected heating of some accelerator components. To address these challenges, several key improvements and upgrades were implemented, which are described in the following sections.

## USERS GAINS AND FEEDBACKS FROM 500 mA OPERATION

Beginning in August 2023, NSLS-II has operated at either 400 mA or 500 mA (over 60 days) to evaluate the long-term reliability of 500 mA operation and its impact on user experiments.

To assess the scientific impact of 500 mA operations, feedback was collected from beamline scientists and users following extended high-current runs. Figure 2 summarizes the overall user-reported gains and operational experience.

**Enhanced Signal Intensity**: twenty-four beamlines reported noticeably stronger signal intensity under 500 mA

* Work supported by DOE under contract No. DE-SC0012704.
† gwang@bnl.gov

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conditions, providing greater sensitivity for low-signal measurements and improved detection limits.

**Improved Signal-to-Noise Ratio***:* seven beamlines observed a measurable improvement in signal-to-noise ratio, allowing for higher-quality data and reduced acquisition times.

**Increased sample process**: five beamlines indicated the ability to process a greater number of samples within the same measurement period, significantly boosting experimental efficiency.

Importantly, no beamlines reported concerns related to sample damage or optical instability due to the increased current, even in some beamlines, additional slit tuning was needed to mitigate heating, but manageable.

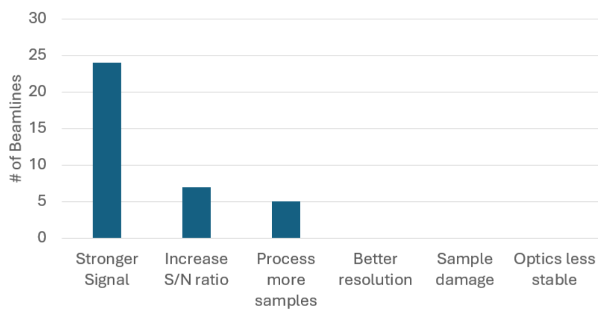


Figure 2: Feedback on Pros and Cons of 500 mA (compared to 400 mA).

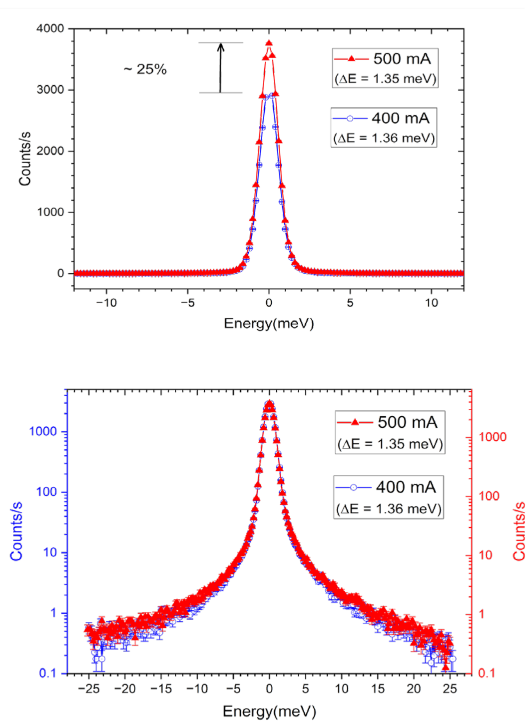


Figure 3: Beamline IXS performance comparation.

One representative beamline performance at 500 mA is the Inelastic X-ray Scattering (IXS) beamline. Figure 3 shows that under 500 mA conditions, the IXS team observed a ~25% increase in intensity across the entire energy range compared to 400 mA operation. Importantly, this increase in flux was achieved without degrading the energy resolution, which remained below 1.4 MeV. These results confirm that high-current operation can deliver meaningful scientific benefits without compromising measurement quality.

## VACUUM HEATING STUDIES AND IMPROVEMENT EFFORTS

Vacuum component heating has been one of the primary challenges encountered since the earliest stages of high-current studies at NSLS-II. Understanding and mitigating this heating requires adequate thermal diagnostics, including extensive deployment of temperature sensors across critical components. To properly evaluate impedance-induced heating effects, it is often necessary to maintain high current operation for at least five hours, allowing the system to reach thermal equilibrium and enabling meaningful assessment and validation of heating behavior.

Ceramic chambers [7] are critical components used in the NSLS-II storage ring kickers and pingers for beam injection and dynamics studies. These chambers require a uniform titanium coating of approximately 2 μm thickness with ±10% uniformity across the entire surface to ensure proper electrical performance. Uneven localized heating or rapid temperature fluctuations pose a significant risk of damage to these structures. To address this, an air-cooling system was installed alongside an infrared (IR) camera system for real-time monitoring of heat distribution. Additionally, an in-house coating system was developed using DC magnetron sputtering, coupled with a thickness monitoring setup to ensure coating quality. These improvements have successfully enhanced the thermal performance of the ceramic chambers, reducing their operational temperature to approximately 40 °C at 400 mA beam current. In addition to these practical improvements, both theoretical and experimental studies were conducted to better understand impedance and beam-induced heating effects in titanium-coated ceramic chambers [8, 9]. Using field-matching theory and numerical simulations, the impedance was characterized and shown to result in power dissipation primarily within the titanium layer. Beam-based measurements were in good agreement with simulations, with deviations within 2–8%, confirming the accuracy of the model. These results contribute valuable insights into the thermal behavior of coated ceramic chambers and inform more reliable designs for future accelerator applications.

The NSLS-II storage ring contains 770 RF contact springs, which are critical for ensuring electrical continuity across vacuum flanges. Improper installation of these springs was found to cause electromagnetic mode trapping, leading to localized heating in excess of 80 °C. Initially, temperature monitoring was limited to a small number of locations, but subsequent in-situ thermal surveys revealed that the majority of overheated flanges were located in straight sections. To address this, a total of 600 low-cost 1-wire temperature sensors were installed at flange locations to improve diagnostics. In parallel, a new RF spring

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installation procedure was developed to ensure better electrical contact and reduce heating risk. 39 RF springs have been replaced as part of this ongoing mitigation effort, resulting in improved thermal stability across the storage ring.

In November 2022, a superconducting wiggler was installed to further reduce vacuum heating by lengthening the electron bunches. As a result, all vacuum temperature sensors now read below 70 °C at 500 mA high current.

As part of additional R&D efforts, internal temperature measurements were performed on RF-shielded bellows with intentional vertical offset under 500 mA conditions [10]. Results showed good agreement with GdfidL simulations and confirmed acceptable heating performance. In parallel, shims were tested in the C01 straight section to improve RF spring contact. Simulations estimated approximately 0.5 W of power dissipation per tab, and experimental results confirmed no adverse heating, supporting their use for improved electrical contact.

## RF SYSTEM

The RF system experienced an increased demand for transmitter power at 500 mA compared to 400 mA. To meet this requirement, a third RF transmitter and an additional cavity were added. This third transmitter utilizes solid-state amplifiers (SSAs) and is the world's first continuous-wave 310 kW transmitter operating at 500 MHz. In 2025, a second solid-state transmitter replaced a klystron transmitter. The addition of the SSAs significantly reduced the RF phase noise imprinted on the beam motion due to their inherently low-noise design. Integrated beam motion went from 4-5 microns to ~1.5 microns in dispersive straights. To ensure reliable performance, inter-cavity phases were carefully adjusted to balance the forward power distribution among the transmitters. The digital RF control system has proved to be very flexible and the beam stability has been maintained throughout the range of operating beam currents from commissioning in 2014 to the 500 mA operations by simply adjusting the proportional and integral loop constants from the control system interface. Prior to March 2023, the RF system had suffered from intermittent dropouts as we commissioned to 500mA, while running flawlessly at 400 mA or below. The system would intermittently trip off the beam during the ramp-up from 450 mA to 500 mA, occurring about two-thirds of the time, with no clear cause. Adjustments to the kp and ki settings of the LLRFs, as well as the load angle of the cavities, were made to address the instability, but these measures proved insufficient. In 2023, it was discovered that a newer version of a "primitive" multiplier block in the digital controller, introduced during a prior upgrade, had not been functioning correctly. Once the primitive was reverted to a simpler, earlier multiplier version, the beam dropout issue was resolved. Apart from this error introduced during a programming upgrade prior to 2023 the system commissioned in 2014 has worked without modifications to meet the 500 mA operations.

## SUMMARY AND OUTLOOK

Since August 2023, NSLS-II has operated at 500 mA to support user experiments, enabled by targeted thermal management improvements. These include in-house ceramic coating development, installation of 600 temperature sensors, and resolution of RF spring installation issues. R&D on flange and bellows alignment also informed impedance-related heating control. All vacuum temperatures remained below 70 °C during high-current runs.

To enable sustained 500 mA, 8 pm [11] reliable operation, a fourth RF system and a third harmonic cavity are required. Third harmonic cavity is under development. 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.

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