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# MEASUREMENTS AND SIMULATIONS OF INTRABEAM SCATTERING EFFECTS AT NSLS-II

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*Abstract*

In this study, we present recent measurements of intrabeam scattering effects at NSLS-II and compare them with particle tracking simulations using ELEGANT. The evolution of bunch length, energy spread, and horizontal and vertical emittances is studied as a function of single-bunch current. Simulations incorporating intrabeam scattering and longitudinal impedance using a broadband resonator model—are used to interpret the measurement observations.


## INTRODUCTION

The National Synchrotron Light Source II (NSLS-II) is a 3 GeV third-generation light source delivering high-brightness photon beams for a wide range of user experiments. Table 1 summarizes key beam parameters for both the bare lattice and the operational configuration with all insertion devices (IDs).

Collective effects such as intrabeam scattering (IBS) and impedance-induced instabilities play a central role in determining the equilibrium beam quality in low-emittance storage rings [1]. In particular, the bare lattice—characterized by reduced radiation damping and shorter natural bunch length—exhibits stronger sensitivity to IBS and a lower microwave instability threshold. On the other hand, impedance-induced bunch lengthening increases with current and leads to reduced charge density, partially mitigating IBS effects. A proper interpretation of measured emittance growth therefore requires self-consistent modeling of both IBS and impedance effects.

In this study, we present systematic measurements of bunch length, energy spread, and transverse emittances as a function of single-bunch current for both the bare and operational NSLS-II lattices. The results are compared to simulations using ELEGANT [2], incorporating broadband longitudinal impedance and intrabeam scattering to interpret the observed trends.

## MEASUREMENTS AND SIMULATIONS

This section describes the experimental setup, simulation methods, and results used to study the interplay between intrabeam scattering and impedance effects in NSLS-II.

### Measurement Setup

Measurements of bunch length ($\sigma_z$), energy spread ($\sigma_\delta$), and transverse emittances ($\varepsilon_x$, $\varepsilon_y$) as a function of single-bunch current were performed using dedicated diagnostics

Table 1: NSLS-II Storage Ring Parameters for the Bare Lattice and Operational Lattice With All IDs

| Parameter | Symbol | Value | Unit |
|---|---|---|---|
| Circumference | $C$ | 792 | m |
| Beam energy | $E$ | 3 | GeV |
| Average current | $I_{\mathrm{av}}$ | 500 | mA |
| RF voltage | $V_{\mathrm{rf}}$ | 3.6 | MV |
| Harmonic number | $h$ | 1320 | |
| *Bare Lattice* | | | |
| Energy loss per turn | $U_0$ | 286.4 | keV |
| Natural energy spread | $\sigma_\delta$ | $5.1 \times 10^{-4}$ | |
| Bunch length | $\sigma_s$ | 8.2 | ps |
| Horizontal emittance | $\varepsilon_x$ | 2086 | pm |
| *Operational lattice* | | | |
| Energy loss per turn | $U_0$ | 799.3 | keV |
| Natural energy spread | $\sigma_\delta$ | $7.9 \times 10^{-4}$ | |
| Bunch length | $\sigma_s$ | 12.7 | ps |
| Horizontal emittance | $\varepsilon_x$ | 746 | pm |

at NSLS-II. Bunch length was measured using a streak camera system viewing visible synchrotron radiation from a bending magnet. The horizontal beam size was measured with the BM-A X-ray pinhole camera, located in a region of negligible dispersion ($\eta_x \approx 0$), allowing direct extraction of $\varepsilon_x$ using the known $\beta_x$ function. The vertical beam size and energy spread were obtained from the 3PW X-ray pinhole camera in Cell-22, which lies in a dispersive region ($\eta_x \approx 0.17$ m). Vertical emittance was determined from the vertical beam size using the nominal $\beta_y$ value, while $\sigma_\delta$ was extracted by combining horizontal beam size measurements from both BM-A and 3PW locations and solving $\sigma_x^2 = \beta_x \varepsilon_x + (\eta_x \sigma_\delta)^2$.

A single bunch was injected at approximately 1.5 mA and then slowly scraped down to lower currents using vertical collimators. Beam properties were recorded at each current level during this controlled decay to capture the full current dependence.

### Simulations Approach

Bunch length and energy spread were first modeled using a broadband resonator impedance, with parameters tuned to reproduce both the measured bunch length and the observed microwave instability threshold. For the bare lattice, the model achieving the best agreement used $R_s = 18$ kΩ, $f = 30$ GHz, and $Q = 1$. The resulting equilibrium longitudinal parameters were then used as input for IBS simulations.

Particle tracking simulations were performed using ELEGANT, employing element-by-element tracking with the

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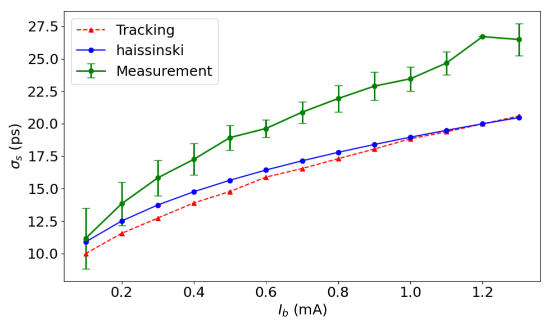
`IBSCATTER` element enabled. The simulation chain included synchrotron radiation damping, quantum excitation, longitudinal impedance, and IBS effects to compute the evolution of transverse emittances with current in a self-consistent manner.

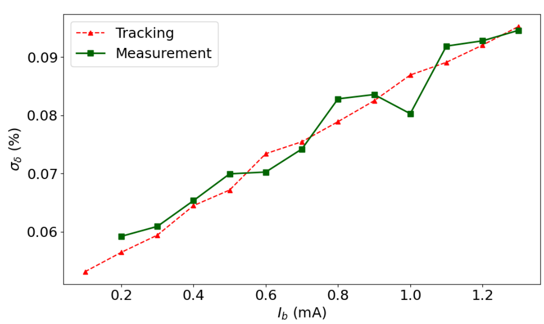
Additionally, a semi-analytical approach was used to cross-check the simulation results. Bunch lengthening due to longitudinal impedance was computed using the `haissinski` algorithm [3], while emittance growth from IBS was calculated using `ibsEmittance` [4]. The results of the two effects were iteratively applied to estimate self-consistent equilibrium values for $\sigma_z$, $\sigma_\delta$, and transverse emittances.

## *Results*

We now compare the measured beam parameters with simulation results for both the bare and operational lattice configurations of NSLS-II. A 4–5% beta-beating was considered in interpreting the measured zero-current emittance to account for small optics distortions and improve consistency with simulation.



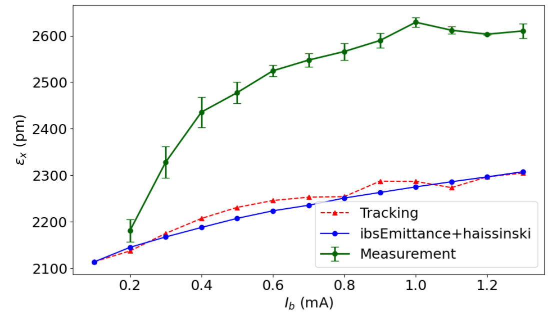

(a) Bunch length vs. single bunch current.



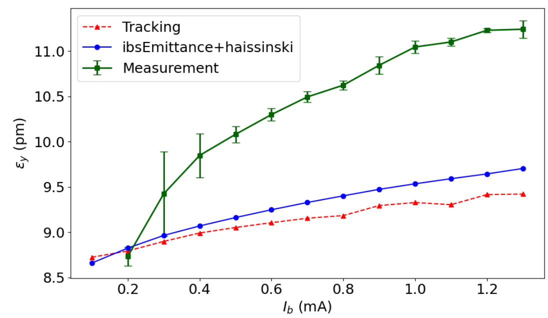

(b) Energy spread vs. single bunch current.

Figure 1: Measured and simulated bunch length and energy spread for the bare NSLS-II lattice at 3.6 MV RF voltage.

Figure 1 shows the measured and simulated bunch length and energy spread as a function of single-bunch current for the bare lattice at 3.6 MV RF. Both quantities increase rapidly with current, consistent with the previously reported low microwave instability threshold for this configuration [5]. Simulations using a single broadband resonator impedance reproduce the energy spread within approximately 5% across the measured current range, while the bunch length shows reasonable agreement with the overall trend but larger deviations at higher current.




(a) Horizontal emittance vs. current.




(b) Vertical emittance vs. current.

Figure 2: Measured and simulated horizontal and vertical emittance for the bare NSLS-II lattice.

Figure 2 compares the measured horizontal and vertical emittances with results from particle tracking and a semi-analytical IBS model. The horizontal emittance shows strong growth at low current due to intrabeam scattering and saturates at higher current. Simulations capture this behavior within 10% accuracy. The vertical emittance remains relatively constant, with variations on the order of 1–2 pm—near the resolution limit of the diagnostics. These small fluctuations may arise from weak vertical IBS or residual vertical coupling not fully included in the simulations.

Figure 3 presents the corresponding measurements and simulations for the operational lattice with all insertion devices. Two broadband impedance models were evaluated. The model with $R_s = 12$ kΩ, $f = 25$ GHz best reproduces both the bunch length evolution and the observed microwave instability threshold, and is adopted for further analysis. An alternative model with $R_s = 18$ kΩ, $f = 20$ GHz yields slightly better agreement with the measured energy spread and bunch length, but predicts a significantly lower instability threshold, inconsistent with observations.

Using longitudinal parameters from the selected impedance model, we performed particle tracking simulations including IBS. The horizontal emittance shows good agreement with measurements, confirming the consistency of the modeling framework. The vertical emittance again remains nearly flat, and small discrepancies with simulation

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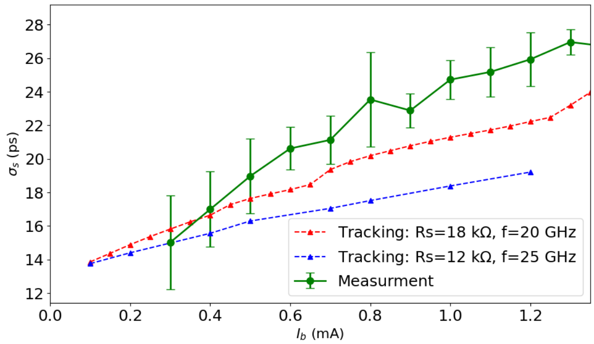
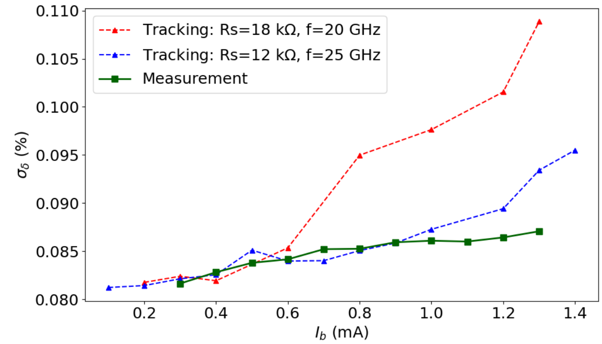
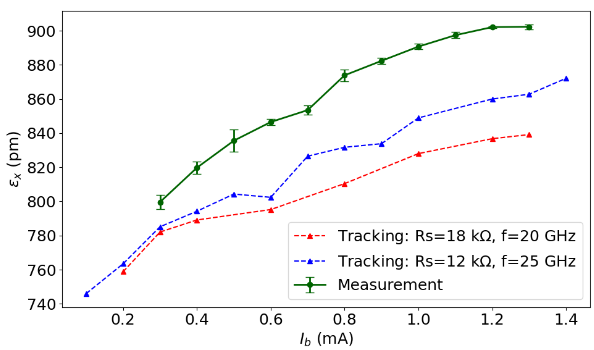


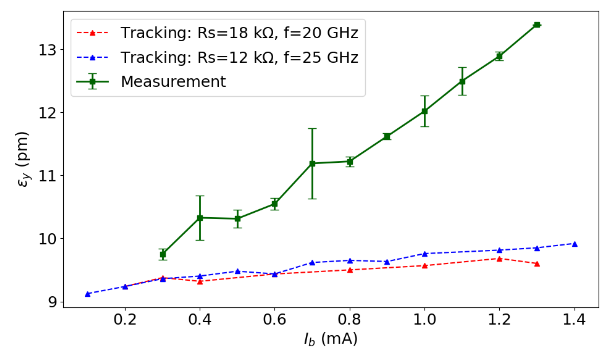

(a) Bunch length vs. current.




(b) Energy spread vs. current.




(c) Horizontal emittance vs. current.




(d) Vertical emittance vs. current.

Figure 3: Measured and simulated bunch length, energy spread, horizontal and vertical emittances for the NSLS-II operational lattice with insertion devices.

are attributed to either weak vertical IBS or measurement limitations.

At very low currents (< 0.4 mA), diagnostic resolution limits and may overestimate emittance growth. Future measurements with improved calibration and slow vertical scraping are planned to reduce these errors, enabling better simulation benchmarking and low-emittance mode optimization. Modest discrepancies between measurement and simulation will be further investigated to determine whether they stem from measurement errors, theoretical assumptions, or unmodeled beam dynamics.

## CONCLUSION

We presented measurements and simulations of bunch length, energy spread, and transverse emittances as a function of single-bunch current for the bare and operational lattices at NSLS-II. A self-consistent framework combining intrabeam scattering and impedance-induced bunch lengthening was used to interpret the data. Simulations reproduce the main trends, including emittance growth and the onset of microwave instability, with differences between lattice configurations captured through impedance adjustments. Remaining discrepancies at low current, especially in the vertical plane, will be addressed through improved diagnostics and optics calibration. These efforts will refine IBS and impedance models and support future low-emittance storage ring designs.

## ACKNOWLEDGMENT

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