Effect of undulators on the lattice, emittance, and energy spread of NSLS-II

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Outline

- National Synchrotron Light Source II
- Compensation of Optics Distortion Caused by Wigglers and Undulators
- Undulator Effect on Beam Emittance and Energy Spread
- Beam-based Measurements
    - *Radiation Energy Loss*
    - *Emittance*
    - *Energy spread*
- Summary

Teamwork of

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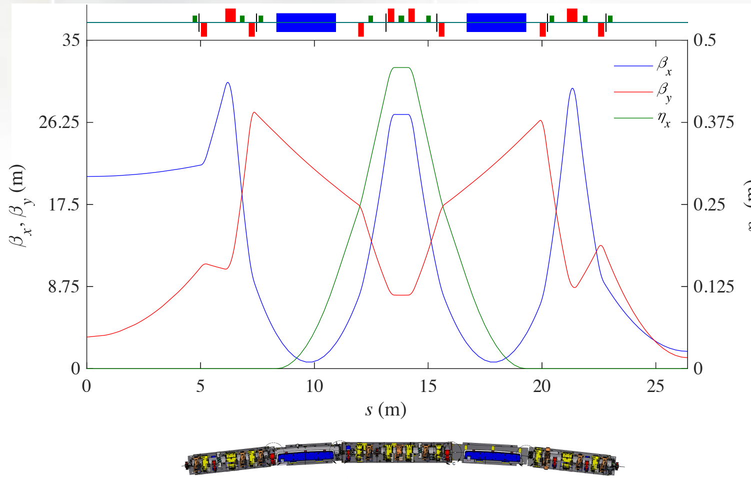
National Synchrotron Light Source II

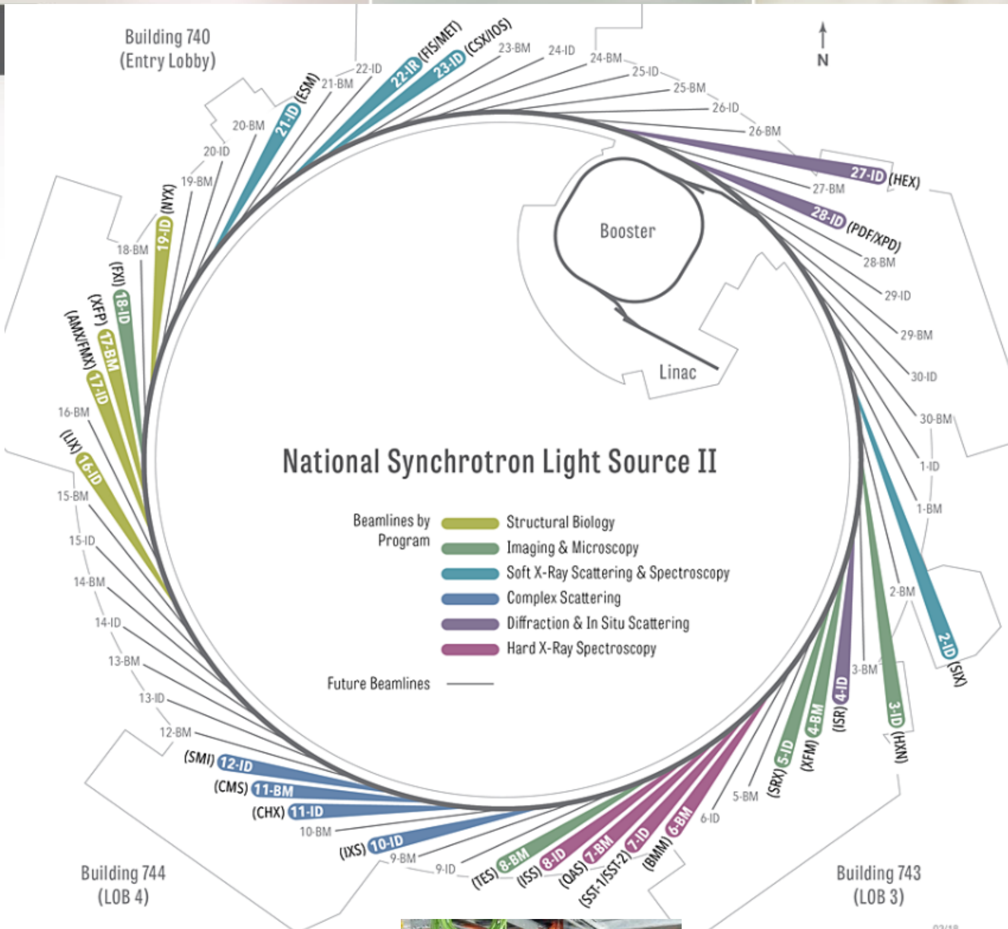
- 15 mirror-symmetric Double-Bend Achromat supercells
- Short (6 m) and long (9 m) straight sections
- 3 pairs of damping wigglers to decrease the beam emittance
- Commissioned in 2014 with the damping wigglers and 6 undulators installed as a part of the project
- Two lattice models were developed for the commissioning
  - without insertion devices (“bare”)
  - with damping wigglers (3DW);
  - effects of 6 installed undulators were small and not included in the lattice model;
  - the 3DW lattice is used for user operations since 2014



Parameter	Value
Energy	3 GeV
Circumference	792 m
Horizontal emittance (bare/3DW)	2.1 nm/0.95 nm
Betatron tunes, hor/ver	33.22/16.26
Natural chromaticity, hor/ver	−98/ − 41
Momentum compaction	3.6×10^{-4}
Energy loss per turn (bare/3DW)	286 keV/649 keV
Relative energy spread (bare/3DW)	$5.1 \times 10^{-4}/8.2 \times 10^{-4}$
Bunch length[a] (bare/3DW)	2.7 mm/4.3 mm

[a]Zero beam current, 3 MV RF voltage.

NSLS II Insertion Devices

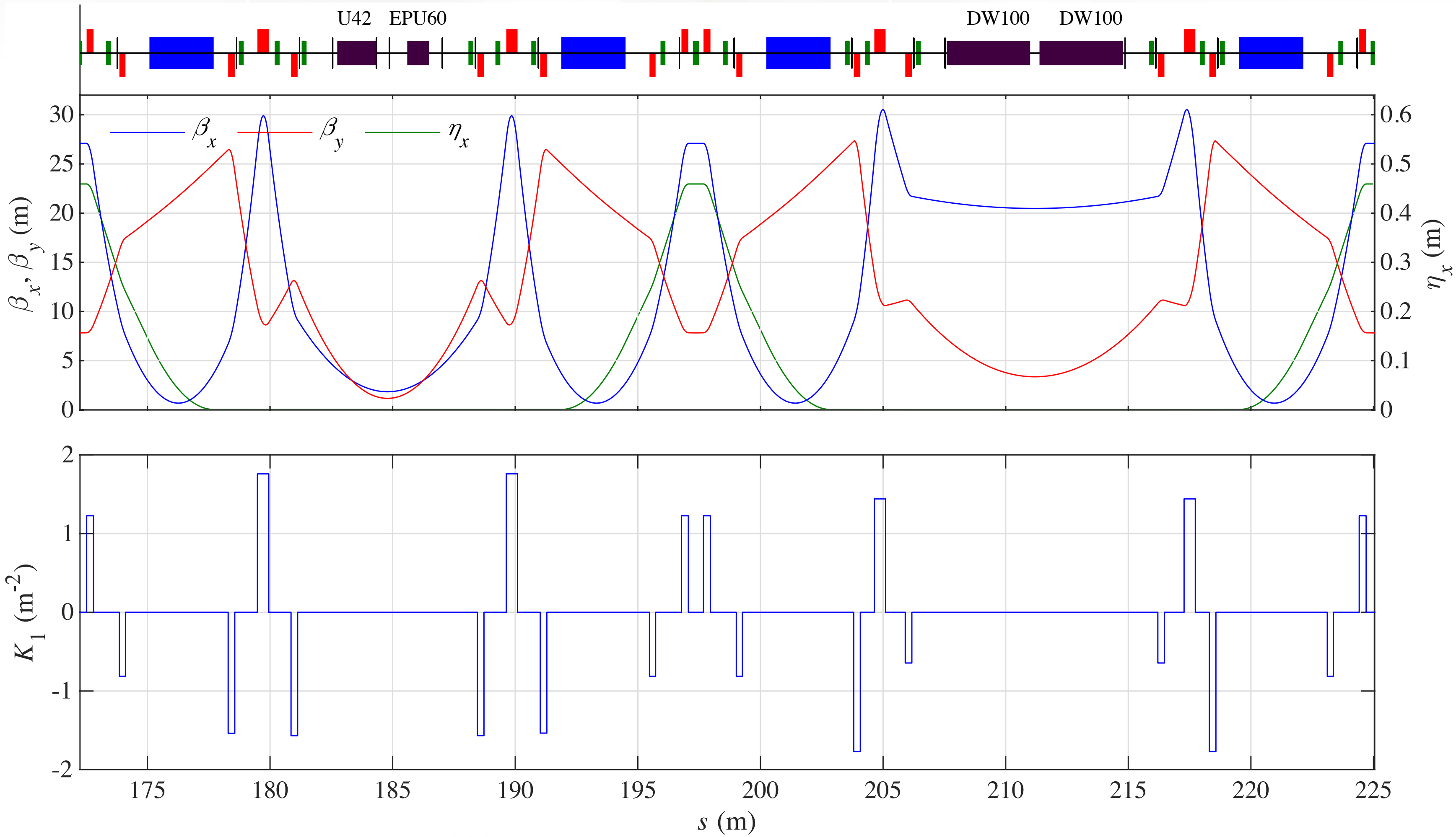


Cell	Beam-line	Year	Type	L (m)	λ_p (mm)	K^a	Gap (mm)
C08D	ISS	2015	DW100	2×3.4	100	16.5	15
C18D	FXI	2015	DW100	2×3.4	100	16.5	15
C28D	XPD	2015	DW100	2×3.4	100	16.5	15
C02C	SIX	2017	EPU57	3.5	57	4.4	16
C03C	HXN	2015	IVU20	3	20	1.83	5.2
C04U	ISR	2016	IVU23	2.8	23	2.05	6.2
C05D	SRX	2015	IVU21	1.5	21	1.79	6.4
C07U	SST1	2018	OVU42	1.6	42	3.27	11.5
C07D	SST2	2018	EPU60	0.89	60	5.7	11.5
C10C	IXS	2015	IVU22	3	22	1.56	7.4
C11C	CHX	2015	IVU20	3	20	1.83	5.2
C12D	SMI	2017	IVU23	2.8	23	2.05	6.2
C16C	LIX	2016	IVU23	2.8	23	2.2	5.7
C17U	FMX	2016	IVU21	1.5	21	1.79	6.4
C17D	AMX	2016	IVU21	1.5	21	1.79	6.4
C19U	NYX	2017	IVU18	1	18	1.55	5.6
C21U	ESM	2016	EPU57	1.4	57	4.4	16
C21D	ESM	2016	EPU105	2.7	105	11.2	16
C23U	CSX1	2015	EPU49	2	49	4.3	11.5
C23D	CSX2	2015	EPU49	2	49	4.3	11.5

[a]For EPUs, the maximum K parameter (linear mode) is shown.

Lattice Model

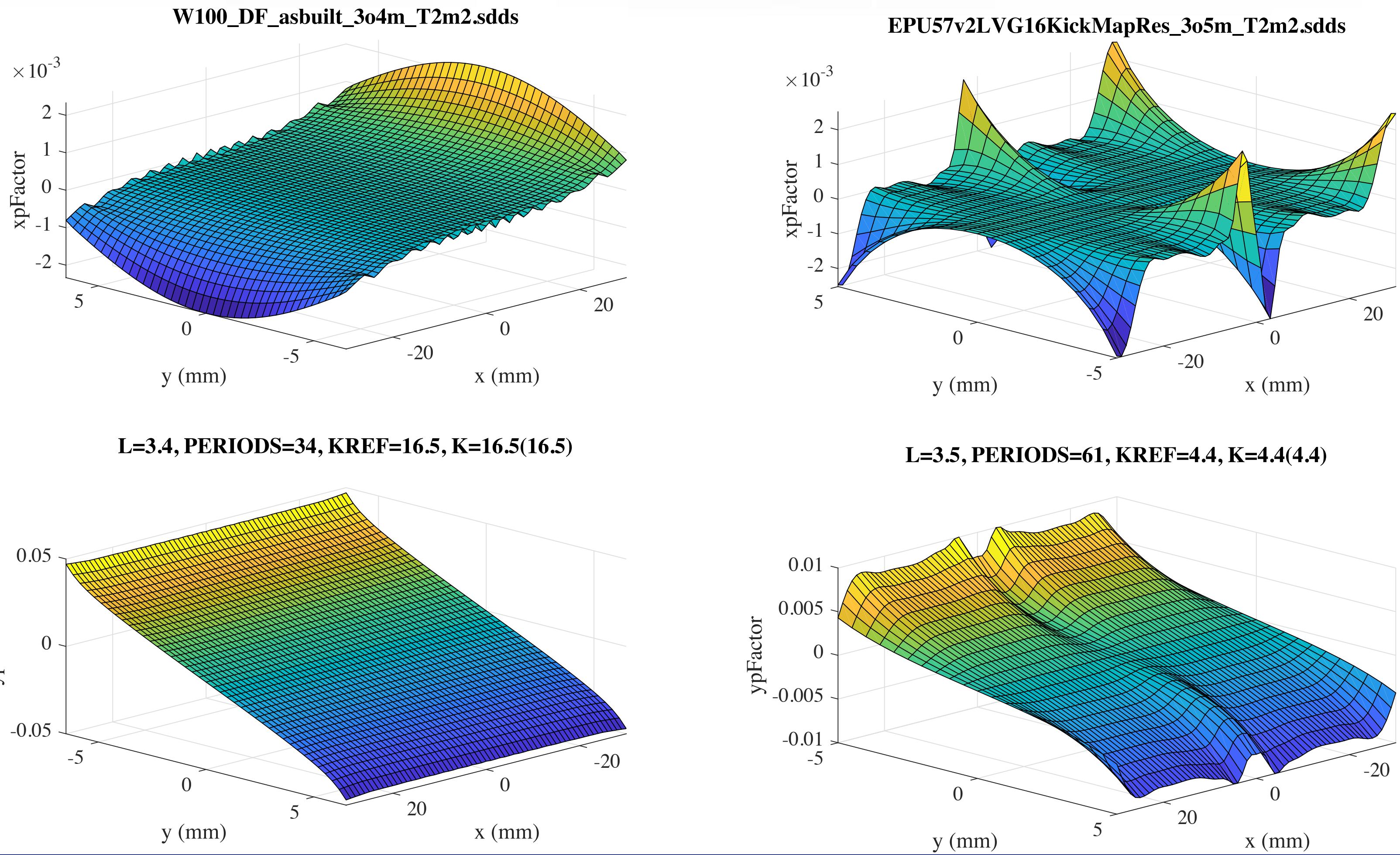
NSLS-II beta functions and dispersion (cells 7 and 8)



Insertion Devices

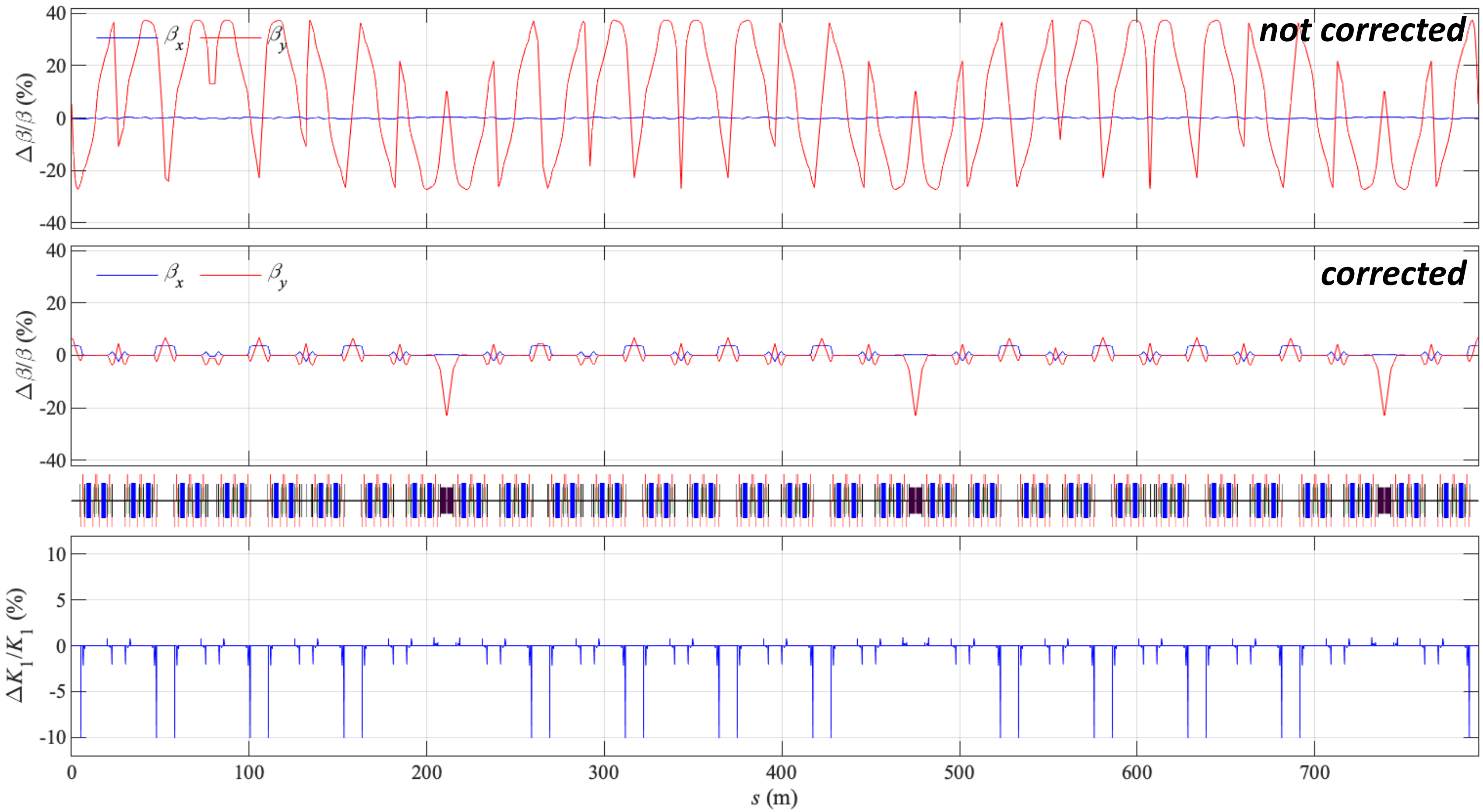
T. Tanabe, Y. Hidaka

- The wigglers and undulators are modeled as 2-dimensional kickmaps calculated by the RADIA Magnetostatics Computer Code [J. Synchrotron Radiat. 5, 481 (1998)]
- Implemented in ELEGANT lattice models as the KICKMAP elements [APS LS-287]



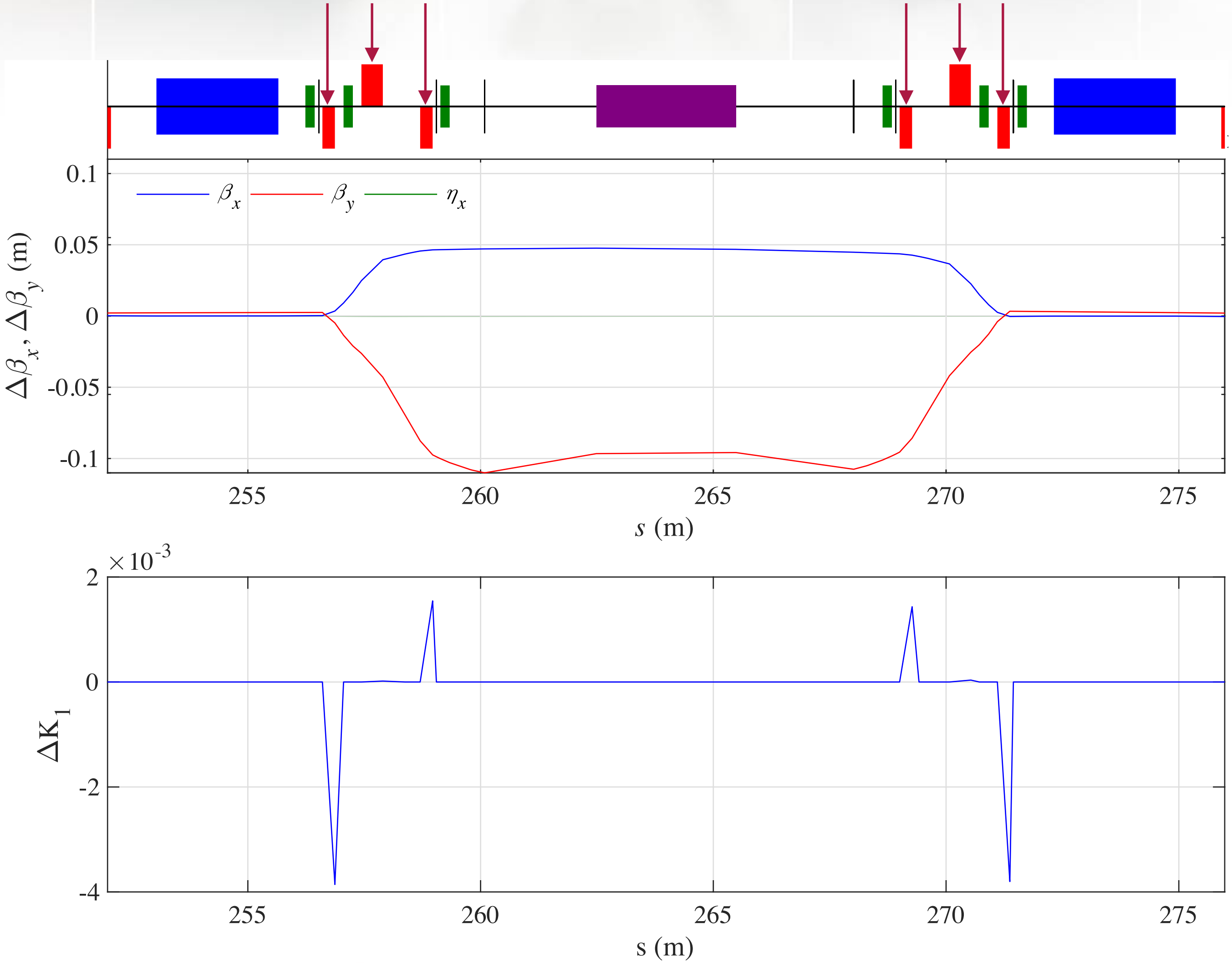
Effect of Damping Wigglers

- Original quadrupole settings from the bare lattice
- Distributed global compensation using all NSLS-II quadrupoles



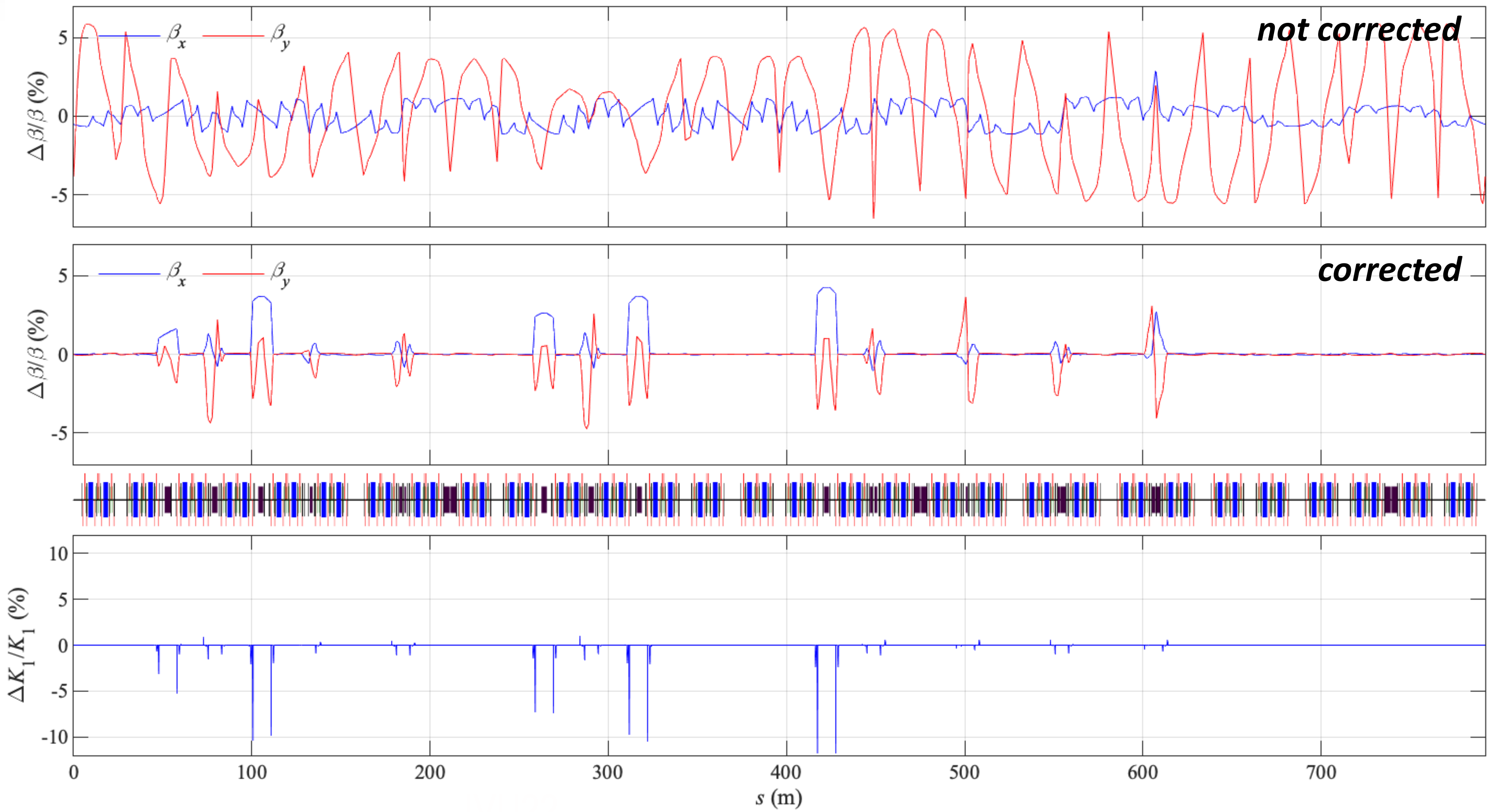
Local optics correction

Six quadrupoles powered independently



Effect of Undulators

- Original quadrupole settings from the 3DW lattice
- Local compensation using 6 quadrupoles near the straight section



Effect on Energy Loss, Emittance, and Energy Spread

Energy loss of an electron passing through a wiggler or undulator with the magnet length L, period λ_p, and strength parameter K
[H. Wiedemann, Particle Accelerator Physics II]

$$U_{\mathrm{ID}} = \frac{1}{3} r_e E_e \gamma^2 K^2 \left(\frac{2\pi}{\lambda_p}\right) L$$

The wigglers and undulators change the radiation integrals determining the emittance and energy spread:

$$\varepsilon_x = C_q \gamma^2 \frac{I_5}{I_2 - I_4} \qquad \frac{\sigma_E}{E} = \sqrt{C_q \frac{\gamma^2 I_3}{2I_2 + I_4}}$$

where $C_q = \frac{55}{32\sqrt{3}} \frac{\hbar c}{E_e} \approx 3.83 \cdot 10^{-13}\ \mathrm{m}$

For an ideal sinusoidal insertion device located in a zero-dispersion section, the radiation integrals can be calculated by the simple formulae
[S.Y.Lee, Accelerator Physics]

$$I_2 = \frac{L}{2\rho^2} \qquad I_3 = \frac{4L}{3\pi\rho^3} \qquad I_5 \approx \frac{\lambda_p^2}{15\pi^3\rho^5} \langle\beta_x\rangle L$$

where ρ is the peak bending radius of the ID field and $<\beta_x>$ is the horizontal beta function averaged along the device.

Beam-based measurements

Beam emittance, energy spread, and radiation energy loss

Three modes of the NSLS-II lattice:

1. Bare lattice (no wigglers and undulators);
2. Lattice with 3 pairs of damping wigglers only;
3. Lattice with the damping wigglers and 17 undulators.

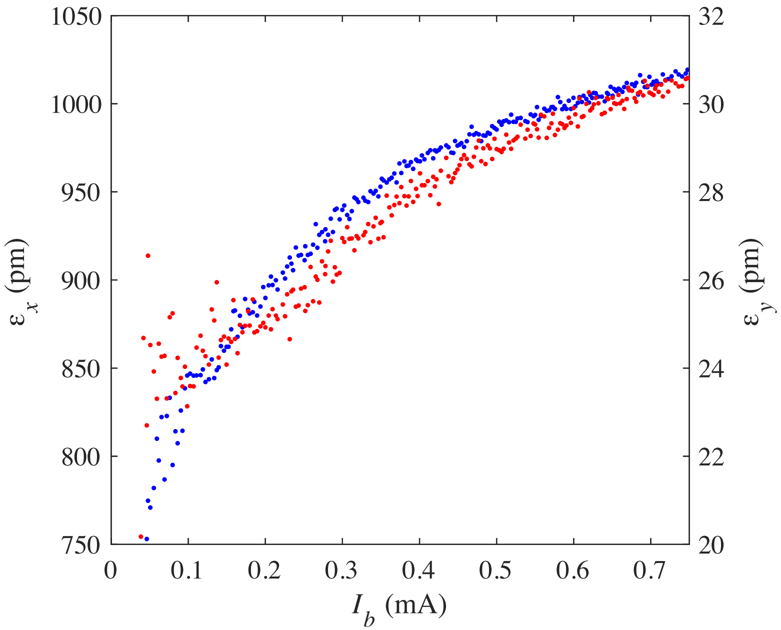
Diagnostic instruments:

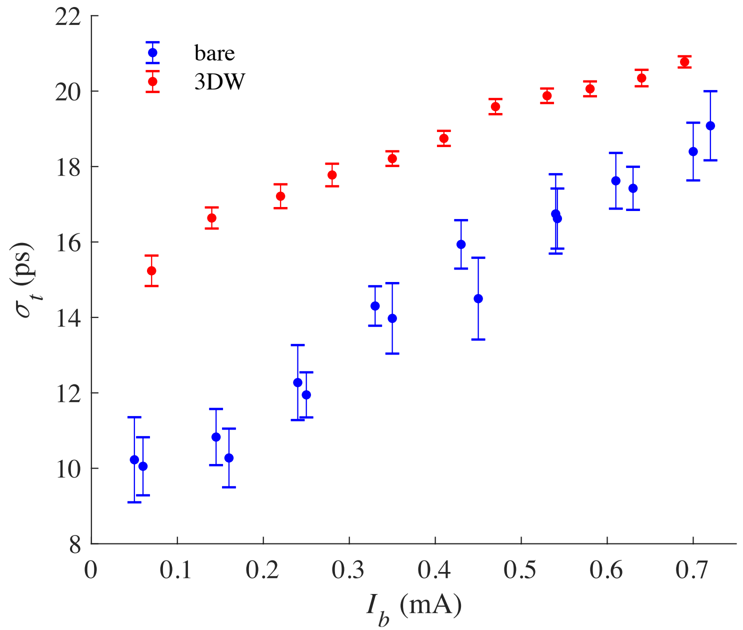
- X-ray pinhole camera installed in a non-dispersive location
  [IPAC-2018 WEPAF012]
  Emittance from transverse beam size.
- Synchrotron light monitor installed in a dispersive location
  [AIP Conf. Proc. 1741 (2016) 020014]
  Energy spread from transverse beam size.
- Streak camera
  [IBIC-2015 MOPB083]
  Bunch length and synchronous phase shift
- Coherent hard X-ray beamline
  [NSLS-II CHX]
  - Measurements at the photon energy of 13.1 keV,
  - 7th harmonic of the IVU20.
  - Emittances estimated from focused X-ray spot sizes;
  - Energy spread from spectral scans (without focusing).

Beam-based measurements

minimizing collective effects

- Collective effects, such as potential well distortion, intrabeam scattering and coherent instabilities affect the measured emittance, energy spread and bunch length.
- To minimize the collective effects, the measurements were done with a low beam intensity: total beam current of 10 mA in 1000 bunches (10 μA per bunch).





Radiation Energy Loss

The synchronous phase φ_s is determined by the radiation energy loss per turn U_0 and the accelerating RF voltage V_{RF}.

Each insertion device contributes an addition

$$U_{\mathrm{ID}} = \frac{1}{3} r_e E_e \gamma^2 K^2 \left(\frac{2\pi}{\lambda_p}\right) L$$

to the total energy loss resulting in the synchronous phase shift

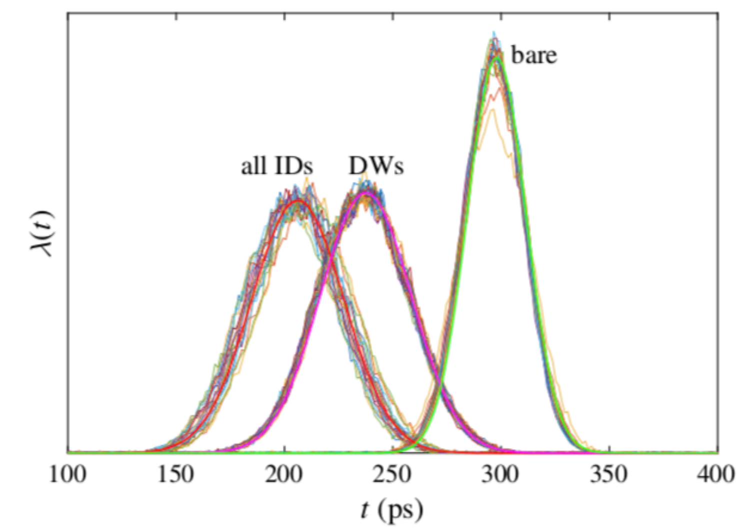
$$\Delta\varphi_s = \arcsin\frac{U_0}{V_{\mathrm{RF}}} - \arcsin\frac{U_0 + U_{\mathrm{ID}}}{V_{\mathrm{RF}}}$$

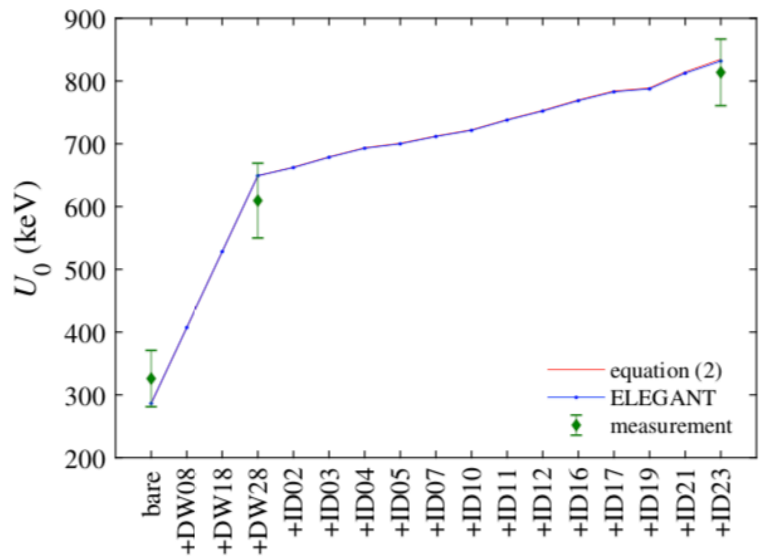
The phase shifts was experimentally determined by fitting the longitudinal bunch profiles measured using a streak camera.

The streak camera was preliminary warmed up and

the measurements were done in a minimum possible time interval to reduce the systematic error caused by the streak camera drift.

Since there is no absolute phase calibration, we can measure only the relative phase shift $\Delta\varphi_s = (t_{c2} - t_{c1})\omega_{\mathrm{RF}}$.

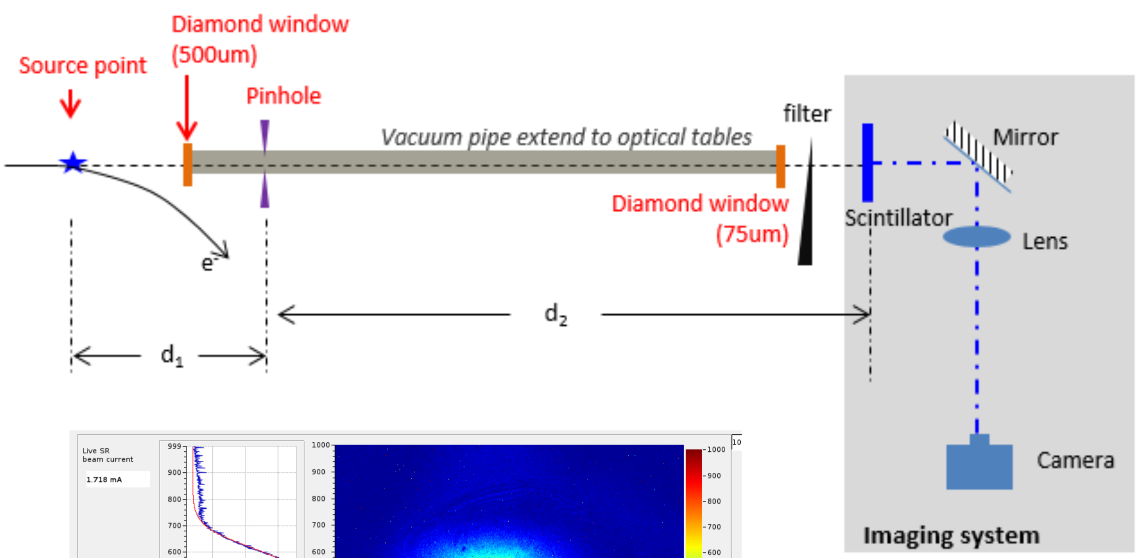


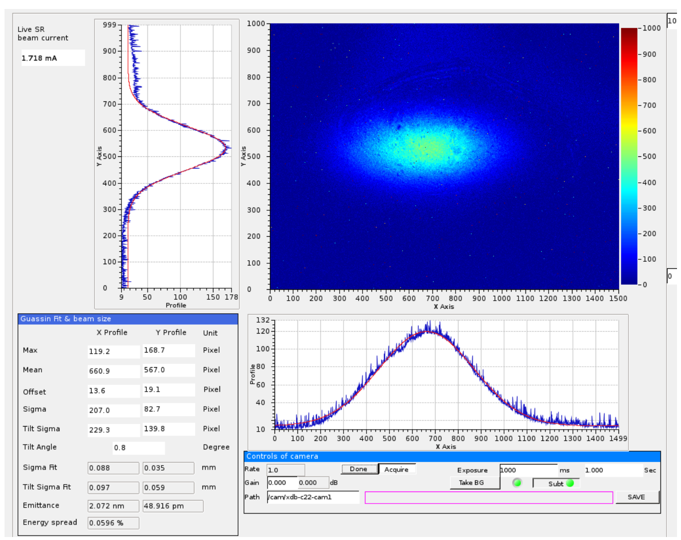


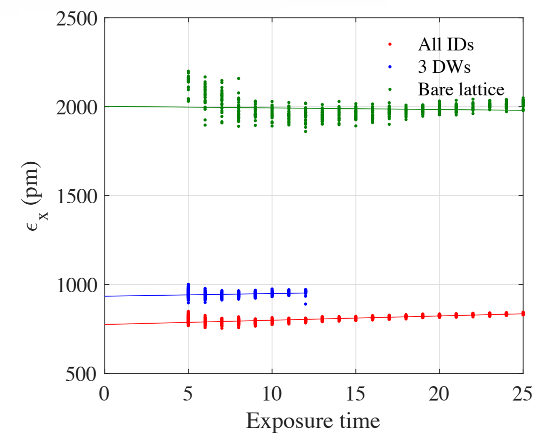
Emittance measurement

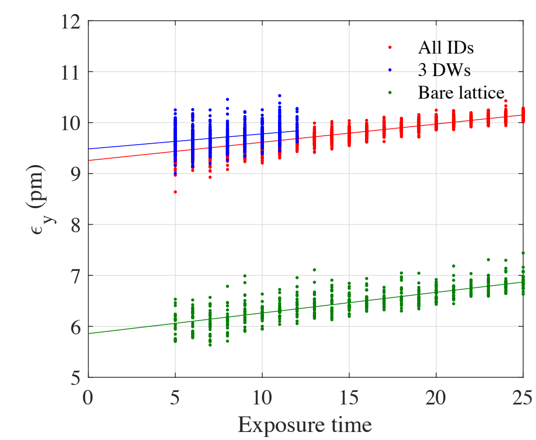
X-ray pinhole

- Emittance is measured by an X-ray pinhole camera in the diagnostic beamline (BM, cell 22).
- To eliminate the systematic errors, the camera settings were accurately adjusted before the measurement.









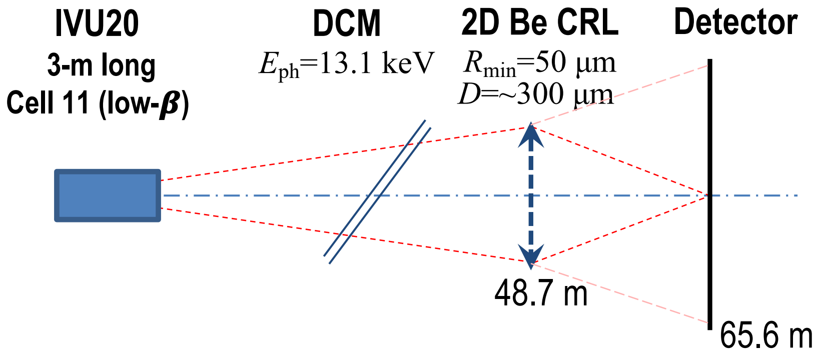
$$\sigma_x^2 = \beta_x \varepsilon_x + \left(\eta_x \frac{\sigma_E}{E}\right)^2$$

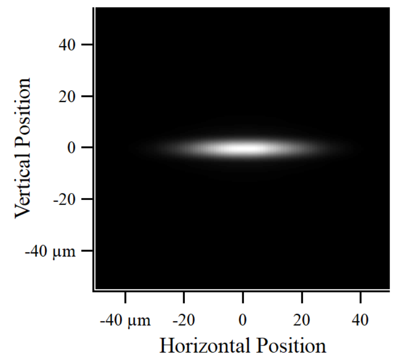
Emittance measurement

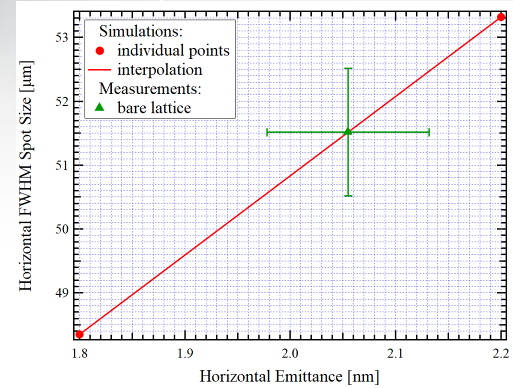
CHX beamline

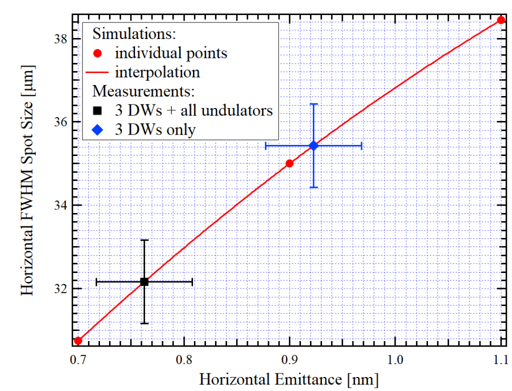
O. Chubar, L. Wiegart, P. Illinski

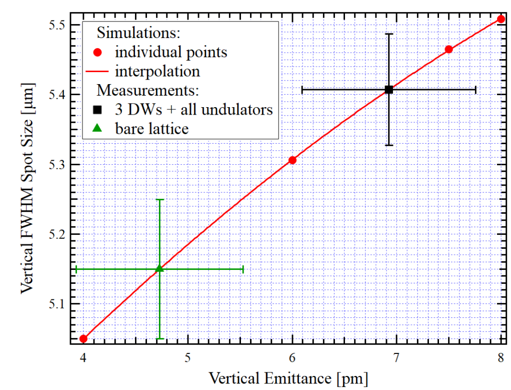
- Emittances estimated from FWHM spot sizes of X-ray beam focused by 2D Be Compound Refractive Lens and measured by the high-accuracy "fluorescent knife-edge” detector.



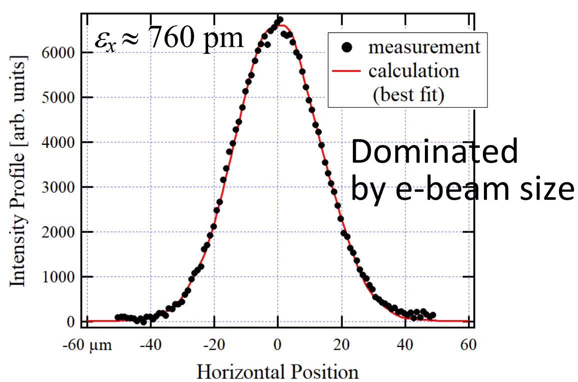


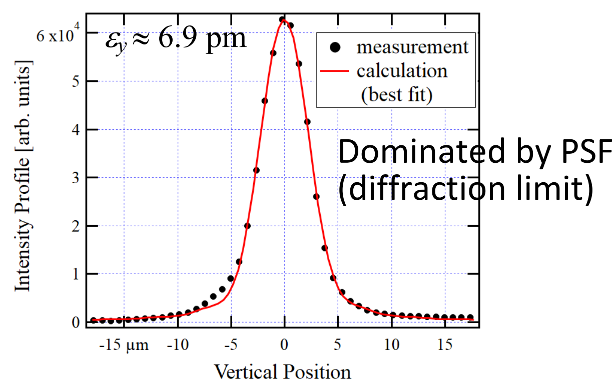






- Data processing: forward-simulations with [SRW code]() in combination with a fitting procedure.





Emittance

- The damping wigglers have the most effect on the emittance reduction, more than a factor of two.
- The effect of all 17 undulators is an additive 15%.

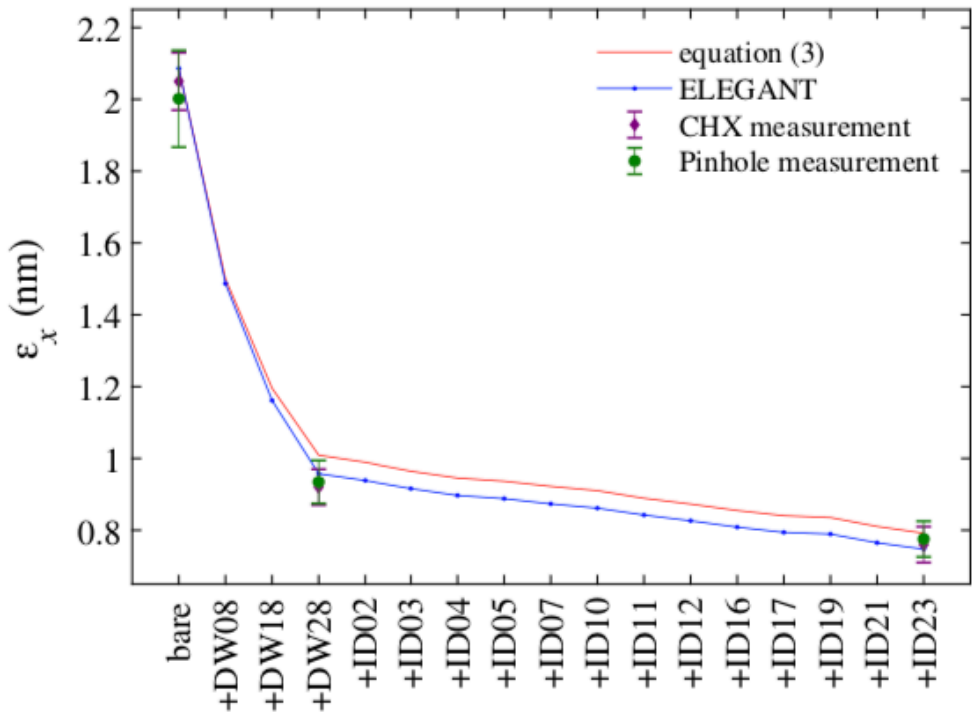
The equilibrium emittance is reached when quantum excitation is equal to radiation damping.

$$\varepsilon_x = C_q \gamma^2 \frac{I_5}{I_2 - I_4}$$

$$I_5 = \int \frac{\beta_x \eta_x'^2 + 2\alpha_x \eta_x \eta_x' + \gamma_x \eta_x^2}{|\rho|^3} ds$$

$$I_4 = \int \frac{\eta_x}{\rho^3}(1 + 2\rho^2 K_1) ds$$

$$I_2 = \int \frac{1}{\rho^2} ds$$



At NSLS-II, all IDs are installed in the dispersion-free straight sections.

The ID contributions to I_5 and I_4 are negligible compared to I_2.

By having twice the beam energy loss from the wigglers, the radiation damping is doubled, and the quantum excitation is not changed.

Hence, the equilibrium emittance should be reduced by half.

Energy Spread Measurement

Since the beam current was only 10 μA per bunch, we can neglect collective effects and estimate the beam energy spread σ_E/E using the zero-current bunch length formula

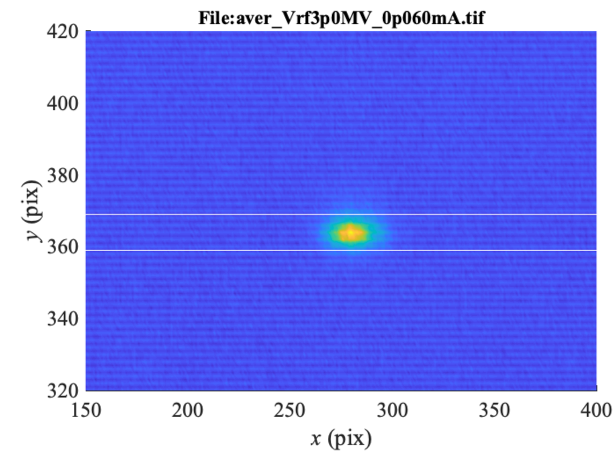
$$\sigma_t = \frac{\sigma_E/E}{\omega_0}\sqrt{\frac{2\pi\alpha\, E/e}{h_{RF}V_{RF}\cos\varphi_s}}$$

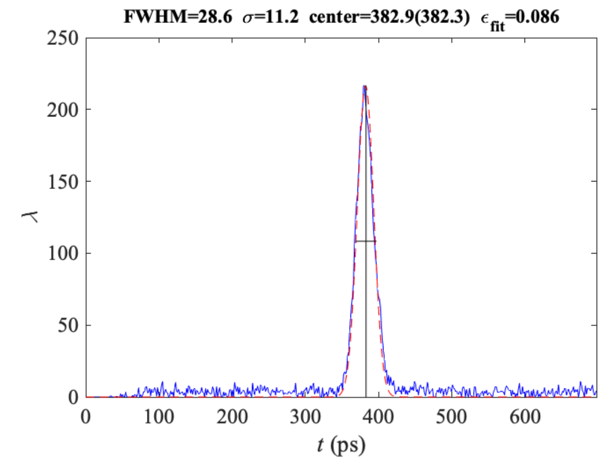
where h_{RF} is the RF harmonic number,

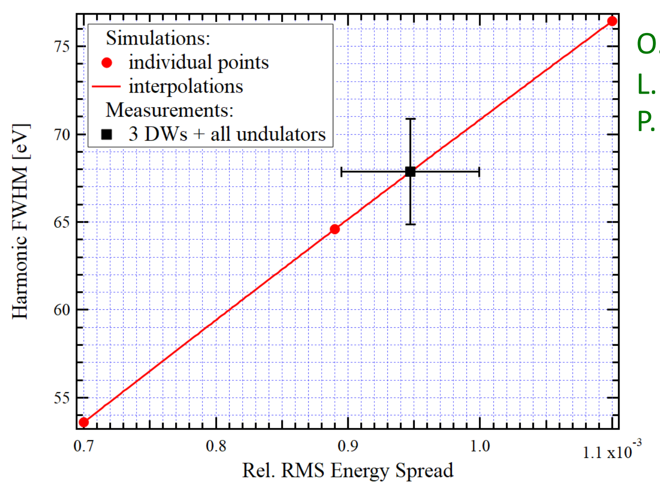
α is the momentum compaction factor.

The bunch length σ_t was measured by a streak camera.

The energy spread was also determined from the spectral scan of 7th harmonic of the IVU20 undulator radiation vs photon energy measured in projection geometry (without the x-ray beam focusing) and from SRW simulations.







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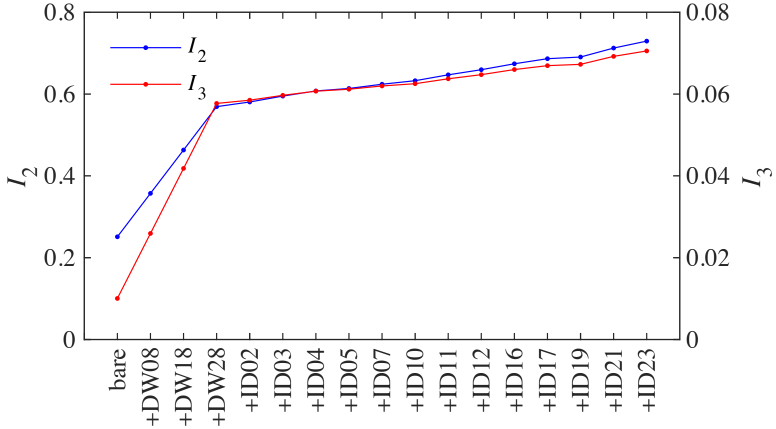
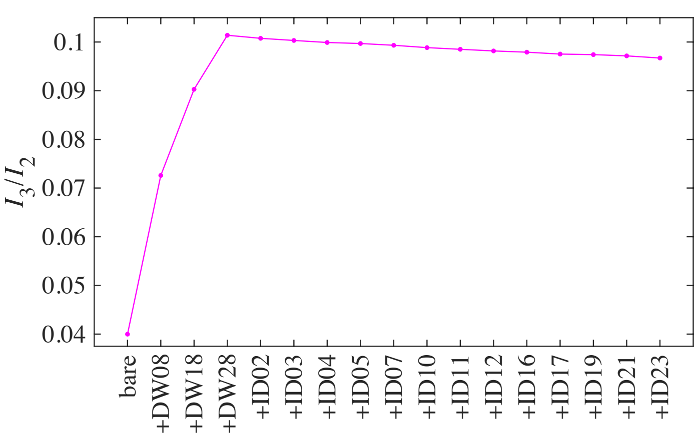
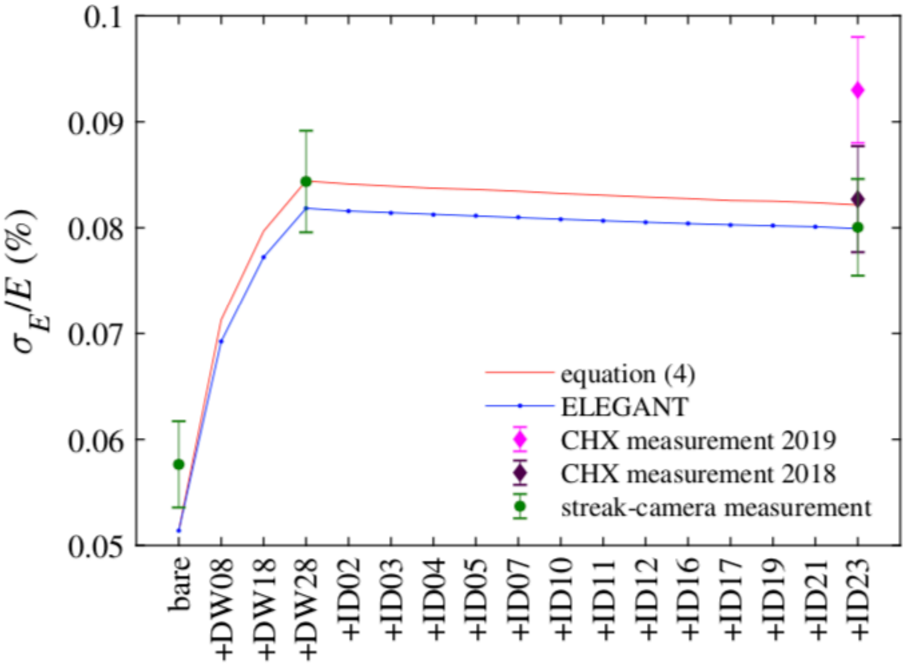
Energy Spread

- The damping wigglers increase the energy spread by a factor of 1.7.
- The effect of all 17 undulators results in a small decrease of the energy spread.

$$\frac{\sigma_E}{E} = \sqrt{C_q \frac{\gamma^2 I_3}{2I_2 + I_4}} \quad I_4 = 0 \text{ if } \eta_x = 0 \qquad I_2 = \int \frac{1}{\rho^2} ds \qquad I_3 = \int \frac{1}{|\rho|^3} ds \qquad I_4 = \int \frac{\eta_x}{\rho^3}(1 + 2\rho^2 K_1) ds$$







The discrepancy between the 2018 and 2019 CHX measurements can be explained by a misalignment of the IVU.

Summary

- NSLS-II is in user operations since 2014. As a part of the project, 3 pairs of damping wigglers and 6 undulators were installed from the beginning.
- Up to now, 20 light-generating insertion devices are in operation:
  3×2 damping wigglers and 17 undulators of various types.
- The lattice distortion caused by the damping wigglers is compensated globally.
- The lattice distortion caused by each undulator is compensated locally using 6 quadrupole magnets located nearby.
- The lattice model of the NSLS-II ring with all the insertion devices was developed and tested with the beam.
- Beam-based measurements of the beam emittance, energy spread, and radiation energy loss were carried out using NSLS-II optical diagnostics and CHX beamline.
- The measured emittance is 2.05 nm for the bare lattice (no wigglers and undulators), 0.92 nm for the lattice with 3 damping wigglers, and 0.76 nm for the lattice with all IDs.
- The measured values of the emittance, radiation energy loss, and energy spread show a good agreement with analytical formulae and numerical simulations.

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Thank you for your attention!

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