Optical design of the NSLS-II metrology beamline

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Abstract. The article describes the optical design of the NSLS-II test beamline, dedicated to at-wavelength metrology, in situ surface figuring, crystal optics, radiometry, detectors and instrumentation testing. A key aspect of the beamline design is configuration flexibility, providing as wide as possible range of photon energy, beam size, and divergence, including the optimum trading of SR flux to a required degree of coherence. For this application we propose to use the chromatic properties of compound refractive lens (for hard x-ray) or zone plate (for soft x-ray) to provide band-pass energy filtering and variable spatial coherence. Using such a scheme, it is possible to efficiently vary the transverse coherence from 10 \( \mu \text{m} \) to 10 mm at ~1\% monochromaticity. The flux extracted permits real-time phase imaging and at-wavelength metrology, even at the bending magnet beamline.

1. Introduction
The next generation of SR machines has electron emittance below \( \lambda/4\pi \) for radiation well into the hard x-ray regime and the beamlines shall preserve source ultra-high brightness. As a result, the x-ray optics fabrication and metrology remain a pressing issue, even though there are a variety of optics (i.e., reflective mirrors, refractive compound lenses, diffractive zone plates, multilayer optics, and crystal) approaching diffraction-limited performance [1]. For instance, the figure and finish requirements of x-ray mirrors (~1 nm RMS over ~250 mm long optical surface) are beyond the fabrication and metrology capability of most suppliers. NSLS-II proposes to combine the ultimate precision of at-wavelength metrology with in situ fabrication of SR reflective optics to make final mirror corrections directly on site. Ion beam erosion [2], a process known for its local and deterministic profiling of substrate surface at nm accuracy while preserving surface roughness, is consistent with simultaneous x-ray metrology. As the wavefront distortions at different spatial frequencies result in a different impact on the system’s optical performance, at-wavelength metrology shall be capable of measuring the distribution of figure errors over 1 mm (hard x-ray) to 10 mm (soft x-ray) pupil size to 0.1 \( \mu \text{m} \) frequency [3]. It also needs to be versatile, as mirror performance in its initial (not-well-aligned) state may have a wave-front departure exceeding tens of \( \lambda \). We will use a sequence of metrology tests with increasing accuracy and sensitivity, ranging from Foucault to Hartmann array curvature to x-ray shearing interferometry, to provide complete characterization of the optical system.

Such capabilities are naturally core to the comprehensive scope envisioned for the NSLS-II test beamline, which will serve as a hub for advanced prototype instrumentation, calibration of specific beamline systems before they can be deployed, and as a radiometric standard to measure the quantum efficiency, uniformity, linearity, and time response of detectors. Beamline scope extends to crystal testing and includes topography and measurements of spatially resolved diffraction, reflectivity, and scattering. While the principle of the design and the beamline components for many such activities are well known [4], the coherent properties of bending magnet (BM) beamlines at ultra-bright SR sources are less explored. Following we provide a description of NSLS-II metrology beamline with analysis mostly limited to its coherent properties. Their efficient use will not only benefit at-wavelength metrology, but have an important extension to x-ray imaging which requires coherence, such as phase
imaging, coherent scattering, and x-ray interferometry [5]. As different techniques require different degrees of light coherence, the optical beamline design challenge consists of optimum trading of beam flux for a required degree of coherence.

2. Principles of the Beamline Design

The NSLS-II test beamline uses a three pole wiggler (TPW) placed upstream of the downstream bending magnet (BM) as a source. It has an extended energy coverage from 250 eV (predominantly bending magnet radiation) to 25 keV x-rays (out of the main pole of TPW) using combination of monochromators, mirrors and x-ray lenses. The beamline layout provides the possibility to remove upstream optical components, and segmentation of the beamline into several white-beam-compatible hutches allows for multiple dedicated setups to be developed over time in parallel. It also remains flexible with several components playing complimentary roles.

![Optical scheme (a) and conceptual layout (b) of NSLS-II metrology beamline.](image)

The novel arrangement shown in figure 1 for at-wavelength metrology is optimized for two energies: ~1 keV (for testing soft x-ray components, as Si mirror before coating) and ~6 keV (for shallow grazing hard x-ray mirrors), although other radiation will be available once the beamline operation becomes mature. With the proper choice of an extraction angle it is possible to combine the lower-energy peak originating from a side pole with the high-energy lobe produced by the main pole of the TPW. 2D x-ray lenses (compound refractive lens [CRL] for hard x-rays, and Fourier zone plate [ZP] for soft x-rays) inserted into the beam are used to focus the light onto an entrance slit. To reduce the total length of the beamline and increase the angular acceptance, the focusing lens is located behind the ratchet wall (at approximately 20 m from the source), with the entrance slit just after the ratchet wall. The power load of 1W/mm$^2$ is moderate, although efficient cooling is required. A pair of CRLs with $R_{apex} \sim 0.15$ mm or a ZP with outermost zone $\sim 1$ μm (assuming 5 mm diameter) provide adequate focus distance. Because of refractive/zone plate lens chromaticity, a combination of a lens and a slit serves as an energy filter. A second set of refocusing optics after the entrance slit (~30 m) is used to adjust the virtual source-to-test optics distance with limited wave-front perturbation.

At-wavelength metrology and ion beam figuring will use a custom design (~3 m long, modular design) HV chamber with an independently suspended optical breadboard inside. Special optics, such as gratings for shearing interferometry or Hartmann array, can be place either upstream or in precise scanner downstream. A CCD-based imaging system with spatial resolution approaching ~ one micron and a large (~2mm) field of view will be placed downstream. A second, in-vacuum CCD, mounted on a rotational arm, will be used for 2-axis vertically dispersive reflectometry. Such a set-up can also be the basis for a development of novel techniques programs using phase or coherent diffractive imaging.

To facilitate additional testing, the beamline also features an upstream roll-in double crystal monochromator (DCM, with Si $<111>$ crystals as main option, but possibility to install multilayer mirrors), downstream diffractometer, large optical table with auxiliary equipment, and a high resolution detector. Other detectors, e.g., energy-dispersive or fast cameras, will be available. A variable curvature bending mirror system can be installed in the test chamber to provide user-specified
illumination or sweeping of the beam, if desired. An integrated motor and detector control system is of the greatest importance. It would not only enable remote operation, but provides easy, configurable access to video servers, analog and digital I/O, counters, frequency generators, or external timing signals if ultra-fast time-resolved measurements are demanded.

**Figure 2.** TPW 1keV illumination profile as seen on a screen 21 m downstream (a) and (b) intensity distribution as measured along the central horizontal line at different wavelengths. (c) TPW mutual coherence function at the location of the first lens. (d) Focus spot for 1 keV radiation extracted by the ~5 mm diameter lens (ZP) and schematic location of the Young’s slits to estimate the wave-front coherent property. (e) Normalized angular distribution of fringes for slit separation of 7 (~FWHM of the spot size, offset by -0.3 for clarity) and 4 μm. (f) Beamline flux through the entrance slit at different energy, assuming focusing condition for 6.5 keV radiation and Be-based CRL.

### 3. Analysis of the Beamline Coherent Property

The NSLS-II bending magnets have a relatively low (2.4 keV) critical energy. To boost the energy, the NSLS-II features three-pole wiggler with a central pole field of 1.14 T. Figure 2 shows the illumination profile at the location of the lenses, calculated using the wave-field emitted by electrons propagated through the TPW magnetic structure [6]. Contrary to expectations, the resulting illumination is not a simple combination of “bending magnet”-like emission originating from the bending magnet, side, and main poles of the TPW. The lower energy portion is dominated by a two-lobe structure, primarily as a result of side-to-main pole interference. Only for the energy above 10keV does the TPW emittance property converge to the classical bending magnet radiation picture. Electron beam source (RMS) of ~128 μm (h)*13 μm (v) corresponds to the coherent length of ~30 μm (h)*300 μm (v) for E ~1 keV at the location of the lens. To calculate the degree of transverse coherence of the radiation wave-front, a fringes visibility produced by a pair of slits (as in 2-slit Young’s interference) is calculated as a function of the slits’ separation. The numerical analysis validates the estimates (Fig. 2c). Still, TPW radiation remains far from one of a Gaussian-spread incoherent source, as a finite fringes visibility remains even at a focal spot (Fig. 2e). The focus (~30 μm [h]*3 μm [v], RMS) has a small blurring due to multiple source contributions (Fig. 2d).

For energy away from the focusing condition, the entrance slit blocks the light and serves as an energy filter [7]. The spectral resolution of in-line monochromator consisting of a lens and a diaphragm is about twice the ratio of lens-to-diaphragm diameters, although the exact number depends on lens details (such as ZP central stop size or CRL effective transmittance). In the case of a Be parabolic lens tuned to 6.5 keV, the spectral resolution ΔE is calculated to be 60 eV, although the long energy tail presence is evident (Fig. 2f). The temporal resolution is still sufficient for most interferometric schemes, and even lower energy monochromaticity will be possible by increasing the vertical slit size or by masking the optics. For hard x-rays, the focal condition can be further adjusted by inserting additional lenses into the beam. Estimates suggest that such chromatic translocator will extend the beam operation to other energies (4.2, 7.3, 8.4, 9.5 keV), assuming the same lenslet. The fine energy adjustment will be facilitated by a longitudinal translation of the slit to satisfy the virtual distance condition for the optics being tested.
High energy suppression needs further analysis coupled to the mechanical design of the beamline, as high energy can be reduced by zero order stop, lens offset and roll-in filters. In combination with capability to adjust critical angle of (DCM) mirror pair, it should be possible to reduce high order contribution below $10^{-4}$.

As wave-front perturbations come from both the test optics and the refocusing lens (ZP or CRL), the transmissive optics is chosen as the most ideal approach—one with negligible low-frequency phase error. The long focal distance of the lens relaxes the technological challenges, and we expect practical devices to preserve the wave-front [8]. Because some at-wavelength metrology schemes need 2D, a provision for independent horizontal and vertical focusing will be included. On-axis optics do not change the beam direction, providing easy alignment and operation. Flux estimates vary due to the efficient trading of flux to the transverse or longitudinal coherence, and is estimated to be $\sim 10^9$ ph/s/mm² or comparable to the $10^{11}$ ph/s/mm² flux reported for the 1 km-long SPring-8 ID beamline [9], which will permit real-time measurements.

4. Summary
The NSLS-II test beamline combines BM/TPW source (0.25-25 keV) with flexible beamline layout to support a wide variety of test methods and capabilities to develop novel instruments. The combination of transmissive x-ray lens and slit serve as in-line, band-pass monochromator with moderate temporal and adjustable transverse coherence to perform at-wavelength wave-front analysis. It has a broad spectral range and provides a simple and versatile platform for x-ray optics testing or for the development of experimental techniques which requires coherence, such as phase imaging, coherent scattering, and x-ray interferometry. The optics can be removed and upstream roll-in DCM in combination with variable curvature mirror facilitates flexible settings for crystal and detector testing. It is expected that configurational flexibility to choose energy, band width, phase acceptance (transverse coherence), beam size and divergence become a basis for successful development of novel optics and SR instrumentation.

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