Experimental characterization of X-ray transverse coherence in the presence of beam transport optics

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Abstract. A simple Boron fiber based interference scheme [1] and other similar schemes are currently routinely used for X-ray coherence estimation at 3rd generation synchrotron radiation sources. If such a scheme is applied after a perfect monochromator and without any focusing / transport optics in the optical path, the interpretation of the measured interference pattern is relatively straightforward and can be done in terms of the basic parameters of the source [2]. However, if the interference scheme is used after some focusing optics, e.g. close to the X-ray beam waist, the visibility of fringes can be significantly affected by the new shape of the focused beam phase-space. At the same time, optical element imperfections still have a negative impact on the transverse coherence. In such situations, which are frequently encountered in experiments at beamlines, the quantitative interpretation of a measured interference pattern is not straightforward. Here we show that this can nevertheless be done by using partially-coherent synchrotron radiation wavefront propagation simulations. The results obtained from measurements, performed at the 32-ID undulator beamline of the Advanced Photon Source, and wavefront propagation based simulations show, in particular, that new generation 1D Beryllium Compound Refractive Lenses [3, 4] do not reduce the X-ray transverse coherence in any significant manner.

1. Introduction
Modern optimized 3rd generation synchrotron radiation (SR) sources attain smaller and smaller electron beam emittances, gradually approaching diffraction limits for the soft and even for the hard X-ray spectral range. This results in a considerable increase of SR brightness, and motivates further improvement of the quality of optics transporting X-ray beams to samples in user experiments. Ideally, these optics should not introduce aberrations nor high spatial frequency “noise” to the transported radiation beams, which could result in degradation of wavefront quality and loss of useful flux at the sample position. The importance of diagnostics and characterization of X-ray optical elements for modern SR sources can therefore hardly be underestimated.

Traditionally, the quality of the optical elements is characterized by special instruments in dedicated laboratories [5] before installation and use of these elements on beamlines. In some cases, metrological measurements can be made on optical elements in situ, on dedicated X-ray beamlines, using special optical schemes [6], which usually differ from the experimental schemes in which the optical elements are finally used. Such special schemes are applied in order to increase the sensitivity of measured X-ray intensity distributions to the imperfections of the optical elements, and often also to simplify the interpretation of the measurements. On the other hand, the conditions (degree of coherence, wavefront quality and dimensions, etc.) at which such measurements are performed can differ from the conditions under which the optical elements will be used eventually. Consequently, it
may not be simple to conclude directly from such measurements whether the imperfections of a given optical element are tolerable under the conditions it will be used at the beamline.

From this point of view, an attractive perspective would be to attempt to characterize optical elements exactly under the conditions in which they are to be used at their intended beamlines, with minimal modifications to existing optical schemes. Such measurements may be relatively easy to perform. However, the interpretation of the results can be less straightforward, because the measured intensity distributions may depend on many different factors such as the effects of other beamline elements on the coherent wavefront. In this paper, we show that a direct interpretation is nevertheless possible by using partially-coherent SR wavefront propagation simulations [7]. This method is based on numerical calculation of the near-field frequency-domain electric fields emitted by individual electrons with different energies moving along different trajectories in an undulator (or in arbitrary magnetic field), and the simulation of propagation of these fields through optical elements of beamlines, using Fourier-optics algorithms. It therefore accurately takes into account all special features of single-electron synchrotron (undulator) radiation, expected electron beam emittance and energy spread, storage ring lattice functions, as well as parameters of X-ray optical elements. This provides advantages in terms of accuracy and level of details over other analytical and numerical calculation methods applied to partially-coherent synchrotron radiation [8 - 12].

2. Experimental setup

The experiments under discussion were performed at 32-ID beamline of the Advanced Photon Source (APS). The optical scheme, mimicking the layout of the Coherent Hard X-ray (CHX) beamline [13] – one of the first beamlines of the new low-emittance NSLS-II storage ring currently under construction at Brookhaven National Laboratory – is shown in figure 1. At \( z \approx 36 \) m from the center of the straight section, after a vertical-bounce Si(111) double-crystal monochromator, a set of 1D vertically-focusing Compound Refractive Lenses (CRL) [3, 4] is installed\(^1\). To minimize wavefront distortions, a mirror for the suppression of higher undulator harmonics is omitted and instead the Bragg angle of the second monochromator crystal is detuned to provide a nominal suppression of 1/50 for the 3rd harmonic. Further downstream, at \( z \approx 71 \) m, a 100 \( \mu \)m diameter Boron fiber with a 10 \( \mu \)m Tungsten core is oriented in the horizontal median plane. At \( z \approx 75 \) m an optically-coupled X-ray imaging CCD detector using a YAG screen is installed, providing an effective pixel size of 1.34×1.34 \( \mu \)m\(^2\).

This setup was implemented to measure partially-coherent X-ray interference patterns in the detector plane downstream of the Boron fiber with different numbers of individual lenses, and to quantify wavefront-preserving properties of the CRLs – an important topic for beamlines planning to use CRLs for transporting X-ray beams to final focusing optics or directly to a sample. In our measurements, the interference patterns were affected both by the source and the CRLs, including its focusing properties and imperfections. It was of our particular interest to measure and simulate the interference patterns in the vicinity of the X-ray beam waist created by the CRLs, since the samples will be illuminated in similar conditions at the CHX beamline. Instead of moving the fiber and detector relative to the X-ray beam waist, we decided to perform measurements with different numbers of lenses, thereby moving the longitudinal position of the waist with respect to the fiber and the detector.

\[ \text{Figure 1. Sketch (side view, not drawn to scale) of the optical scheme for the measurements performed at beamline 32-ID at APS.} \]

\(^1\) The 1D Be CRLs used in this work were obtained commercially from the University of Aachen.
3. Measurement and simulation results
The results of measurements of the interference patterns with different numbers of lenses at 8.5 keV photon energy, and the corresponding simulation results, obtained using the partially-coherent wavefront propagation method implemented in the SRW code [7], are presented in figure 2. As one can see from the image plots and from vertical cuts of the intensity distributions, the fringe contrast in the interference patterns gradually reduces with the installation of lenses in the optical path as the longitudinal position of the X-ray beam waist approaches the location of the fiber. When the X-ray beam waist is nearly at the position of the fiber (the case with 3 lenses), the fringes almost completely disappear. However, with further addition of the lenses, the waist moves upstream the fiber, and the interference fringes are restored – see the cases of 4 and 5 lenses in figure 2. This evolution of the measured interference patterns
is in qualitative agreement with the results of simulations (see third and fourth columns in figure 2). We note that the estimated transverse coherence length of the radiation at the location of the fiber at nominal electron beam size is only ~7 µm in the case of 3 lenses, whereas it is ~130 µm without lenses (as obtained from other partially-coherent wavefront propagation calculations performed for a virtual two-slit interference scheme with the slits located at the position of the fiber).

The cuts of the simulated intensity distributions vs. vertical position are presented for two different values of the vertical electron beam size – the nominal one predicted by accelerator physics ($\sigma_y \approx 15$ µm) and the one which better fits the measured interference patterns ($\sigma_y \approx 30$ µm). One can notice however, that this large source size value corresponds to a lower visibility of fringes near the waist as compared to the measurements (see cases of 2 and 4 lenses). This suggests that most likely, the measured visibility of fringes far from the CRL focus was somewhat affected by other optical elements, which were not included in the simulations, e.g. the monochromator (its effect could be particularly important taking into account that one of crystals was detuned at the time of the measurements to suppress high harmonics), Beryllium and kapton windows. Besides, the relatively long (up to 0.5 s) CCD exposure time that had to be used at these measurements could result in a reduction of the visibility of fringes due to averaging of effects from electron beam instabilities and optical element vibrations. Finally, the visibility of fringes in the measured interference patterns could be somewhat reduced due to limited apparent resolution of the detector. More detailed simulations and numerical analysis of experimental results are planned to be done. However, even without detailed analysis, simply by comparing visually the fringes in the measured and calculated (assuming perfect optics) interference patterns without and with 5 CRLs, one can conclude that the new generation of 1D CRLs, that were used in the experiments, do not affect the SR wavefront coherence in any considerable manner even in the vertical direction, where the source size is small.

4. Conclusion
Detailed partially-coherent SR wavefront propagation calculations can be very useful for various applications related to development and commissioning of beamlines in modern SR sources, including the in situ characterization of optical elements. In particular, such “reference” calculations, coupled with experimental measurements have shown that the addition of the new generation of CRLs into the beamline does not affect the beam coherence at the APS 32-ID beamline.

5. References
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