

BL05SS: Undulator Radiation and its Application to Beam Diagnostics

(1) Accelerator diagnostics beamline II (BL05SS)

BL05SS has an insertion device light source, two optics hutches, and an experiment hutch. The insertion device (ID05) is out-of-vacuum type and designed to be able to fit many kinds of experiments. The mounted pure-permanent magnet array, which is made of the ternary alloy Ne-Fe-B (NEOMAX-44H), is of planar Halbach type with the 51 periods of 76 mm long. When the magnet gap is a minimum value of 20 mm generating a peak field of 0.82 T, the deflection parameter K is a maximum value of 5.8, which leads to a multi-pole wiggler (MPW) radiation produced on the many higher-order harmonics that are useful for electron beam diagnostics. The MPW can emit the total radiation power of 10.4 kW when the electron beam current is 100 mA. By widening the magnet gap, ID05 as an undulator with small K can be also useful for the experiments requiring the higher spectral photon flux and the lower heat load to avoid the thermal drift of a frontend slit or the monochromator.

The layout of the X-ray transport channel of BL05SS is shown in Fig.1. The front end has a X-slit and a Y-slit to shape the white X-ray beam of the ID05. The optics hutch I has the graphite filters and the metal (aluminum) filters, which have moving mechanisms to adjust the intensities and the spectrum of white X-ray beam. The optics hutch II has a cryogenic double crystal monochromator, which covers the photon energy range of 4 to 38 keV by (111) reflection of silicon crystals. Beryllium windows installed in the experimental hutch allow us to handle the monochromatic X-ray beam in atmosphere. To develop techniques for the beam diagnostics based on observations of synchrotron radiations (SR), in the experimental hutch, we can measure energy spectra, angular spectral fluxes and temporal structures of undulator radiations from ID05.

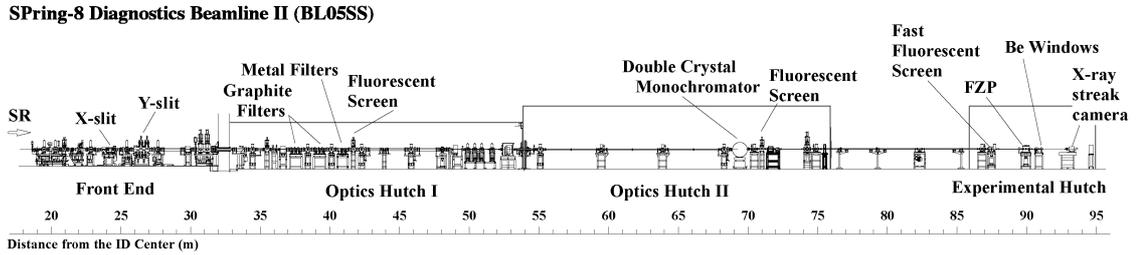


Figure 1: Schematic view of the SPring-8 diagnostics beamline II (BL05SS).

(2) Energy spectrum & Angular spectral flux of ID radiation

The energy spectrum produced by a filament electron beam in a given direction consists of a series of harmonic peaks, the frequency of which are multiples of the fundamental resonant frequency ω_1 . For a planar undulator, ω_1 is given by

$$\omega_1 = \frac{2c\gamma^2}{\lambda_u \left(1 + K^2/2 + \gamma^2\theta_x^2 + \gamma^2\theta_y^2\right)}, \quad \text{eq. (1)}$$

where λ_u , K , γ , c , and (θ_x, θ_y) are the period length, the deflection parameter, the electron beam energy divided by mc^2 , the light speed, and the angle between the electron and the observer, respectively. For a single electron and an observation point, the lobe of on-axis emission is zero for all even harmonics 2, 4, 6, while it reaches a maximum for the odd harmonics 1, 3, 5, the spectrum widths of which are equal to $1/nN$ where n is the harmonic number and N is the number of periods. For a given point of observation, all electrons of a thick beam do not have the same resonant frequency ω_1 . This can occur through the angular

divergence of the electron beam, which spreads both the horizontal and vertical angles of (θ_x, θ_y) . A spread of the transverse position of the electron beam also induces a spread of ω_1 because an observer located sufficiently close to the source point sees the radiation emitted by the various electrons under a different angle (θ_x, θ_y) . Equation (1) indicates that the spread in the angle θ_x and θ_y shifts the resonant frequency ω_1 to the lower energy side only. As a result, the electron beam emittance leads to the low energy tail of the spectrum through a slit. The energy spread of electron beam also has an effect on a spread of ω_1 . If the relative energy spread σ/γ of the electron beam is Gaussian, it introduces a Gaussian spread in the spectrum of each harmonic:

$$\frac{\sigma_\omega}{\omega} = 2 \frac{\sigma_\gamma}{\gamma} . \quad \text{eq. (2)}$$

To be summarized as follows, the peak of the harmonics observed on-axis of the electron beam always has a steep slope on the high energy side which is dominated by nN and by σ/γ , and has a reduced slope on the low energy side which is dominated by the emittance, beta function and observation aperture limited by the finite slit width.

The energy spectrum is obtained by measuring the spectral photon flux using an ionization chamber set up in atmosphere, while changing the energy of monochromatic X-ray by scanning Bragg angle of the Si(111) double-crystal monochromator. A rectangular tantalum slit is placed in front of the ionization chamber to measure the on-axis photon flux of ID05. The aperture of the slit was $4.2 \mu\text{rad} \times 4.2 \mu\text{rad}$. The nominal equilibrium emittance and relative energy spread of 8 GeV stored electron beam are $2.4 \text{ nm}\cdot\text{rad}$ and 1.1×10^{-3} , respectively. A typical example of the energy spectrum of the fundamental harmonic measured at the magnet gap of 80 mm, which gives the deflection parameter K of 0.45, is shown in Fig.2. The tail of the low energy side comes from the horizontal emittance. The effect of the slit aperture is negligibly small. The slope on the high-energy side is dominated by $1/nN \sim 0.02$. The energy spread has a negligible effect on it. When the magnet gap is the minimum value of 20 mm, the deflection parameter K of 5.8 leads to the fundamental harmonic of 0.45 keV. As a consequence, many higher-order harmonics are observed in the photon energy range of 4 to 30 keV (Fig. 3). For the harmonics higher than the 19th, the energy spread has the non-negligible effect on the slope of the high-energy side.

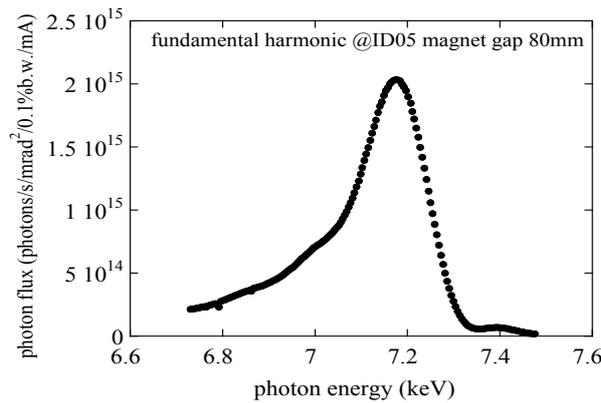


Figure 2: Measured on-axis energy spectrum of the fundamental harmonic when the magnet gap is 80 mm. The deflection parameter K is 0.45.

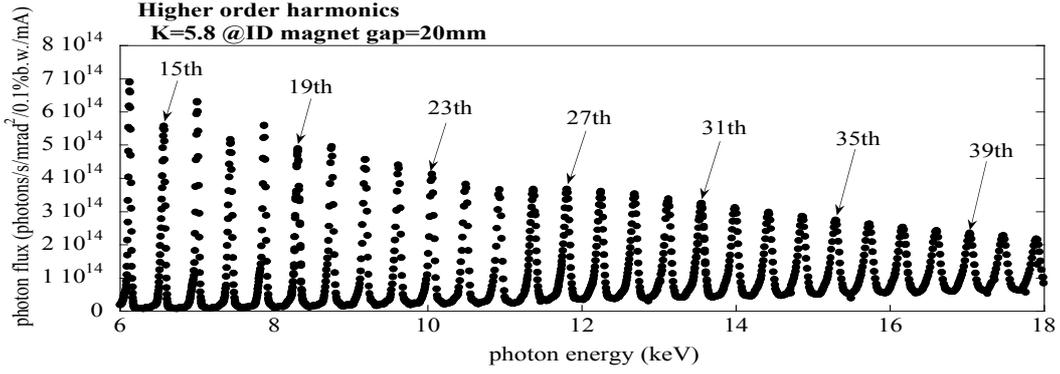


Figure 3: On-axis energy spectrum measured at the minimum magnet gap of 20 mm, which gives the deflection parameter K of 5.8. We can see many higher-order harmonics.

Angular spectral photon flux can be also observed using an X-ray CCD camera. Fig. 4 shows an example of the angular spectral flux observed at the photon energy of 8.3 keV, which corresponds to the peak of the 19th harmonic for the magnet gap of 20 mm. The center spot is the spatial profile of the 19th harmonic. The outer rings correspond to the off-axis radiations of the 20th and 21st harmonics. The horizontal width of the center spot is determined by the horizontal angular divergence of electron beam, while the vertical width is dominated by the energy spread of electron beam and the intrinsic angular divergence $(\lambda/2L)^{1/2}$ of undulator radiation, where λ and L are the wavelength of the radiation and the total length of ID, respectively. The vertical angular divergence of electron beam has a negligible effect due to small emittance coupling ratio.

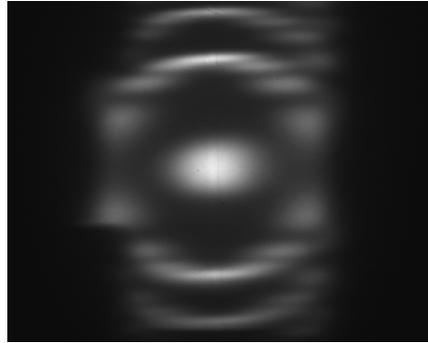


Figure 4: Observed angular spectral flux at the photon energy of 8.3 keV corresponding to the peak of the 19th harmonic for the minimum magnet gap of 20 mm. The center spot is the 19th harmonic radiation, and two outer rings correspond to the off-axis radiations of the 20th and 21st harmonics.

(3) Application: Emittance diagnostic technique using single-slit X-ray Fresnel diffraction

A new emittance diagnostics technique based on X-ray Fresnel Diffractometry (XFD) [1] has been developed for measuring micron-order electron beam size at a source point of an insertion device (ID). The XFD uses monochromatic X-ray Fresnel diffraction by a single slit with optimized width to create a double-lobed diffraction pattern as shown in Fig. 5. The principle is based on the correlation between the depth of a median dip in the double-lobed pattern and source size at the ID, namely the valley of the dip shallows with increase of the source size. An

example of the vertical source size measurement by the XFD at the beam diagnostics beamline II (BL05SS) with ID05 is shown. The undulator radiation of 7.2 keV was diffracted by a front-end 4-jaw slit with the optimized vertical width of 150 μm and horizontal width of 200 μm . The slit is located at distance $L=26.8$ m from the source point. The Fresnel diffraction pattern was observed by using a high-resolution X-ray imaging system (HAMAMATSU) which consists of a P43 fluorescent screen, an imaging optics with lenses and a CCD camera. The imaging system is placed at distance $R=65.4$ m from the slit. Figure 6 shows the observed double-lobed diffraction images for some different vertical emittances. The double-lobed structures are clearly observed in the vertical direction, though in the horizontal direction, the diffraction patterns are smeared out due to large horizontal emittance. The degradation of contrast of the double-lobed patterns indicates growth of the vertical electron beam size at the ID05 source point due to increase of the XY betatron coupling. The smallest among the beam sizes evaluated from the double-lobed patterns is 8.1 μm (r.m.s.) for the 2D image in Fig. 6(a) with the highest contrast. A light source size at the ID smaller than 10 μm is successfully resolved by the XFD.

[1] M. Masaki et al., "X-ray Fresnel diffractometry for ultralow Emittance diagnostics of next generation synchrotron light sources", Phys. Rev. ST-AB **18**, 042802 (2015).

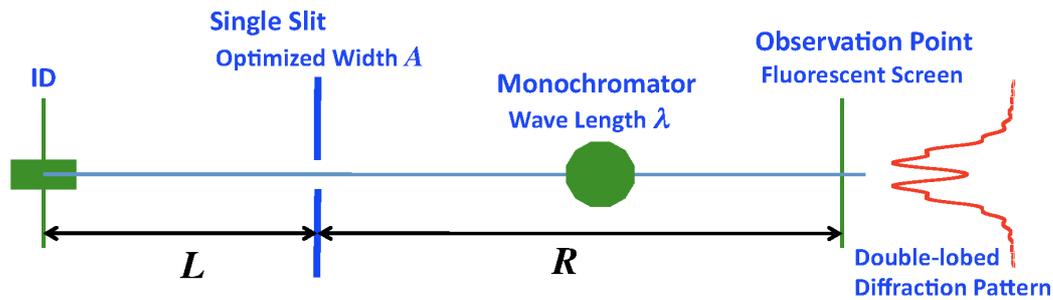


Figure 5: Layout of ID source size measurement using the XFD.

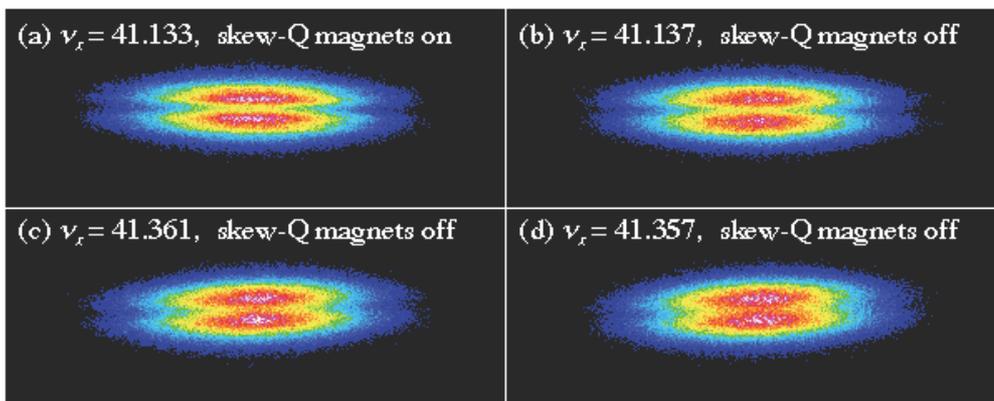


Figure 6: Double-lobed diffraction images observed at four different vertical emittances, changing operation points by moving horizontal betatron tunes ν_x , turning on/off skew quadrupole magnets for XY betatron coupling correction.