New high-brilliance beamline BL-15A of the Photon Factory

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Abstract. Here we describe a new undulator beamline at the BL-15 site of the PF-ring. This new beamline has a short gap undulator which produces high brilliance X-rays ranging from 2.1 keV to 15 keV. The windowless beamline design promises softer X-ray experiments. The second source configuration and double surface bimorph mirror directs the highly focused or collimated radiation to two tandem stations. The upstream station is optimized for XAFS/XRF/XRD studies using a semi-micro focus beam. The downstream station features SAXS experiments using collimated soft or hard X-rays. A novel feature of the beamline is real-time energy synchronization with the undulator gap motion, which is critical for quick energy scanning. The beamline design has been finished and the construction work will start next spring. The construction will be completed during the summer shutdown of 2013, and the new BL-15A will be opened to users in the autumn operation of 2013.

1. Introduction

The Photon Factory accomplished the “Straight-Section Upgrade Project” during a six-month shutdown in the first half of FY2005 [1]. Four short straight sections had been newly produced at the PF ring for installation of short-gap undulators (SGU) to supply high-brilliance hard X-ray photons [2]. Out of the four sections, three have been already equipped with the SGU and are used for advanced studies: BL-1A and BL-17A for protein crystallography and BL-3A for condensed matter researches [3,4,5]. The last short straight section, BL-15A, is being built for small angle X-ray scattering (SAXS) and semi-micro focus beam characterization with the methods of X-ray absorption fine structure (XAFS), X-ray fluorescence (XRF) and X-ray diffraction (XRD).

The SAXS scientific programs enabled by the high brilliance beam derived from SGU#15 include structural studies of functional membranes, time-resolved X-ray scattering and large hierarchical structure analysis. All of these three programs require a high-brilliance light source; the required beam parameters are listed in table 1. In particular, grazing incidence SAXS (GI-SAXS) using vertically small-size softer beam ranging between 2.1-3.0 keV will help to control the depth of the membrane structure analysis and reduce the roughness defects of an imperfect membrane.

The beam requirements for XAFS/XRF/XRD studies are also listed in table 1. The semi-micro focus beam available in a wide range of photon energies allows analyzing the local structures of the elements and valence on inhomogeneous samples in the fields of environmental science and new
energy source science. The 2.1 keV X-rays provide access to absorption edges of phosphor and sulfur, which are very important targets for those fields.

The combination of SAXS and XAFS gives wide structural information from fine atomic structure to low and medium resolution. It can be beneficial to build these instruments as two stations on the same beamline. BL-15A is oriented toward joint advanced studies by the two techniques.

We have completed the beamline design of BL-15A and will start the construction just after the end of the PF-ring operation of FY2012. The first beam will be delivered in October 2013. After the commissioning of the beamline components and the experimental apparatus, we will start the user beamline operation. Here, we present the beamline design and the characteristics of BL-15A.

### Table 1. Requirements for XAFS/XRF/XRD and SAXS(GI-SAXS).

| Parameter                         | XAFS/XRF/XRD | SAXS(GI-SAXS) |
|-----------------------------------|--------------|---------------|
| Energy [keV]                      | 2.1-15       | 2.1-3, 7-13.5 |
| Beam size [mm]                    | 0.01-0.02    | 0.3 (H) x 0.01-0.1 (V) |
| Divergence [mrad]                 | -            | <0.3          |
| Photon flux [phs/s]               | -            | >10^10        |
| Energy resolution [\(\Delta E/E\)] | <2x10^-4     | <2x10^-3      |

- **Focusing system:**
  - Higher energy resolution: Optics, Collimated beam
  - Quick energy scanning: Others, Higher brilliance
  - Long camera stage

### 2. Beamline design

#### 2.1. Insertion device

The SGU#15 will be installed at the short straight section between B#14 and B#15. To cover the wide continuous energy range required by XAFS/XRF/XRD activities, the undulator has a periodic length of 17.6 mm and the number of periods, 27. The minimum gap is 4.0 mm, giving a \(K_{max}\) of 1.61. We will use the 1st-9th harmonics including the 2nd harmonic to cover the large energy gap between 1st and 3rd harmonics.

Synchronization between the ID gap and energy setting of a monochromator will be developed in the control system for quick energy scanning, by a configuration similar to the one proposed at NSLS-II [6]. Encoder reading of the updated ID gap is directly fed to the monochromator controller. The closed loop adjustments of the monochromator axes follow the gap in real time. For this synchronization, the RMS phase errors of the undulator magnetic field are adjusted below 2 degrees, and the field error of the first integral is suppressed to less than 5 G.cm during the gap change.

#### 2.2. Beamline optics and experimental stations

The main optics are a horizontal collimating mirror, a liquid nitrogen cooling double crystal monochromator, a vertical focusing mirror and a pair of asymmetrically horizontal focusing mirrors which employ a secondary source. These deliver a stable, semi-micro focus or collimated beam (figure 1). The monochromator crystals are Si(111), their lowest energy is limited to 2.1 keV. The two horizontal focusing mirrors are bimorph ones [7]. The secondary source aperture is controlled with a set of slits. Tuning the mirror surfaces and setting the size of the slits adjusts the size of the beam at the sample position. A vertical double mirror system is also installed in the last section in order to eliminate higher order reflections. The experimental hutch is separated into two tandem stations because of very different beam requirements of SAXS and XAFS/XRF/XRD experiments. The upstream and downstream stations are BL-15A1 for the XAFS/XRF activity and BL-15A2 for the SAXS activity, respectively. The 2nd horizontal focusing mirror has double mirror surfaces that provide highly focused and collimated X-ray beam for A1 and A2 stations, respectively (figure 2). The demagnification ratios for XAFS/XRF/XRD and SAXS are approximately 16.7:1 and 1:2 (or 1:1),
respectively. The front-end is retrofitted with several differential pumps for windowless operation. Windowless operation allows the beamline to utilize softer X-ray beam up to 2.1 keV.

The beamline is designed to have a very high stability and reproducibility for accurate and reliable measurements. This will be achieved by the following critical features, (1) secondary source arrangement, (2) main optics mounted on the stable floor frame and (3) all supporting stages with the first vibrational modes above 60 Hz which is simulated with normal mode analysis.

**Figure 1.** Plan view of BL-15A.

**Figure 2.** Schematic drawings of horizontal focusing system. (upper: XAFS/XRF/XRD, lower: SAXS)

The 2nd horizontal focusing mirror is mounted on the XAFS/XRF/XRD stage in the BL-15A1 station and focuses the beam 0.3 m downstream. The stage is equipped with a microscope, a cryo-cooler, ion chambers, fluorescence detectors and sample stage for semi-micro focus scanning study (figure 3a). At the BL-15A2 station, two diffractometers are installed in tandem for GI-SAXS/ASAXS and SAXS/WAXS studies, respectively (figure 3b). In GI-SAXS/ASAXS studies using softer X-rays, the sample stage and detector surface are set in the vacuum chamber on the GI-SAXS/ASAXS diffractometer. The SAXS/WAXS diffractometer has a long stage, with a maximum camera distance of 3.5 m. The vacuum path is lifted by motor stages, so that the path length can be changed easily.
3. Performances simulated by ray-tracing calculation

In order to check the beam performance, ray-tracing simulations were performed using the programs XOP and SHADOW [8,9]. Table 2 shows some results of these calculations at different focal points at different energies. Thanks to the high-brilliance light source, the windowless beamline design and the double surface bimorph mirror, sufficient beam performance for both techniques can be obtained in the entire energy range of interest. The photon flux of the 2nd harmonic range which is used only for XAFS study is almost the same as those in the adjacent range.

Table 2. Beam performance of BL-15A.

| Energy (eV) | 2101 | 2800 | 4406 | 7344 | 10281 | 13218 |
|------------|------|------|------|------|-------|-------|
| Harmonics  | 1st  | 2nd  | 3rd  | 5th  | 7th   | 9th   |
| K value    | 1.10 | 1.61 | 1.61 | 1.61 | 1.61  | 1.61  |

**Table 2. Beam performance of BL-15A.**

XAFS/XRF/XRD at 32.8 m [secondary source size: 0.1 mm (H) x 0.5 mm (V)]

- Beam Size (mm): 0.017 (H) x 0.009 (V)
- Photon Flux (ph/s): 1.3x10^{11}
- Divergence (mrad): 0.017 (H) x 0.009 (V)

SAXS at 42.75 m [secondary source size: 0.05 mm (H) x 3.0 mm (V)]

- Beam Size (mm): 0.339 (H) x 0.018 (V)
- Divergence (mrad): 0.058 (H) x 0.109 (V)
- Photon Flux (ph/s): 9.1x10^{10}

GI-SAXS at 36.75 m [secondary source size: 0.1 mm (H) x 3.0 mm (V)]

- Beam Size (mm): 0.275 (H) x 0.012 (V)
- Divergence (mrad): 0.157 (H) x 0.160 (V)
- Photon Flux (ph/s): 1.9x10^{11}

w/o terminal window

- Photon Flux (ph/s): 6.1x10^{11}
- Photon Flux calculated with a beryllium foil of 0.1 mm thickness as a terminal window.

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