

COMPARISON OF BEAM DIAGNOSTICS FOR 3RD AND 4TH GENERATION RING-BASED LIGHT SOURCES

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Abstract

Beam diagnostics for the fourth generation ring-based light sources (4GLSs) with a multi-bend achromat (MBA) lattice are discussed in comparison to the third generation light sources (3GLSs). While the MBA lattice enables small natural emittance of typically 100 pm rad, it has large non-linear effect that makes the machine operation difficult. In addition, stability requirements for the X-ray photon beam of the 4GLSs are stringent due to the small beam size and divergence. Therefore, novel diagnostic techniques are needed, such as highly accurate and stable beam position monitors, high resolution beam size monitors, and bunch-by-bunch feedback systems. We review beam diagnostic technologies implemented for 3GLSs and their application to the 4GLSs. To maximize the performance of the 4GLSs, R&D toward the photon-beam-oriented diagnostics is discussed.

INTRODUCTION

The third generation light sources (3GLSs) have been indispensable sources of brilliant X-rays for various science applications [1]. Several years ago, X-ray Free Electron Lasers (XFELs) became available [2,3], which was a significant breakthrough for photon science. The XFEL has excellent transverse coherence and extremely high peak brilliance. The success of the XFEL has stimulated 3GLSs to evolve the pursuit of higher brilliance and coherence.

The natural emittance of a 3GLS ranges from 1 to 10 nm rad and the average brilliance around 10^{20} photons/sec/mm²/mrad²/0.1%BW. Higher brilliance radiation can be obtained by reducing the natural emittance of the electron beam, if the emittance is larger than the diffraction limit [4]. Therefore, the goal of the emittance reduction for a ring-based light source is to achieve the diffraction limit. The diffraction limit for 10 keV X-rays, for example, is 10 pm rad, which is two orders of magnitude smaller than 3GLSs.

In order to approach the diffraction limit, a new type of lattice design, multi-bend achromat (MBA), has been established. The MBA is motivated by the emittance scaling formula [5]:

$$\epsilon_0 \propto \gamma^2 \theta^3,$$

where ϵ_0 is the natural emittance, γ is the Lorentz factor of the electron beam, and θ is the bending angle for each dipole magnet. In order to reduce θ , MBA uses more than 3 dipoles for each achromat cell. By using MBA, the natural emittance of around 100 pm rad can be achieved

and the brilliance can be increased to around 10^{22} photons/sec/mm²/mrad²/0.1%BW. In this article, we call the light source using the MBA lattice as a fourth generation light source (4GLS).

At this moment, there are two 4GLS facilities, MAX IV [6] and Sirius [7], under construction. Many other projects, such as ESRF Upgrade [8], SPring-8-II [9], APS Upgrade [10], Diamond-II [11], ALS Upgrade [12], PEP-X [13], BAPS [14] and TauUSR [15], have been proposed so far. The main parameters of these facilities are tabulated in Table 1.

In this article, the characteristics of 4GLSs and 3GLSs are compared, and requirements for beam diagnostics for the 4GLSs are discussed. Novel beam instrumentations developed for 3GLSs are briefly reviewed with prospects of 4GLSs. Finally, diagnostic challenges for 4GLSs are discussed.

Table 1: 4GLS Facility Examples. E is the beam energy in GeV, ϵ_0 is the natural emittance in pm rad and C is the circumference in meter.

Facility	E	ϵ_0	C	Lattice
MAX IV	3.0	330	528	7BA
Sirius	3.0	280	518	5BA
ESRF-U	6.0	147	844	7BA
SPring-8-II	6.0	149	1435	5BA
APS-U	6.0	150	1104	7BA
Diamond-II	3.0	276	561	DDBA
ALS-U	1.9	50	196	9BA
PEP-X	4.5	50	2199	7BA
BAPS	5.0	75	1263	7BA
TauUSR	9.0	3	6210	7BA

COMPARISON OF 4GLS AND 3GLS

Accelerator Beam Parameters

The MBA lattice used in a 4GLS has many technological challenges compared with a 3GLS (DB lattice). Typical beam parameters of the 4GLS and the 3GLS are summarized in Table 2.

The beam size of a 4GLS is approximately 20 μ m (H) x 5 μ m (V), which is determined by the horizontal (vertical) emittance of 100 (10) pm rad and the beta function of several meters. The beam orbit should be stable within 1/10 of the beam size in order to maintain the stable optical axis of a photon beamline. Thus, stringent orbit stability is required for the 4GLS.

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Table 2: Typical Accelerator Parameters of 4GLS and 3GLS

	4GLS	3GLS
Lattice	MBA	DB
Natural emittance	~ 100 pm rad	1 – 10 nm rad
Brilliance [photons/s/mm ² /mrad ² / 0.1%BW]	~10 ²²	~10 ²⁰
Beam size	~ 20 x 5 μm ²	~ 100 x 5 μm ²
Multipole B-field gradient	Strong	Moderate
Dynamic aperture	< 10 mm	> 10 mm
Chamber aperture	~ 30 x 20 mm ²	~ 70 x 40 mm ²
Misalignment Tolerance	~ 30 μm	~ 100 μm

The field gradients of multipole (quadrupole and sextupole) magnets in a MBA lattice are significantly larger than a DB lattice [4]. This feature causes smaller bore diameter (~30 mm), large non-linear effects on the beam dynamics, and the narrow dynamic aperture (< 10 mm) of the 4GLS. Consequently, the tolerances of the misalignment and the field error of multipole magnet are significantly more stringent than the 3GLS. In addition, almost same tolerance is applied to the misalignment of the beam position monitors (BPM), because the electron beam position is adjusted to the magnetic center by using the BPM data in the commissioning stage.

For the vacuum components of the 4GLS, the cross-section of the beam pipe is significantly smaller than the 3GLS because of the small bore diameter of multipole magnets. In addition, the small beam size enables narrower undulator gap, typically 5 mm. These narrow vacuum components produce large resistive wall impedance, which results in collective beam instabilities.

Photon Beamlines

One of the significant breakthroughs for the photon beamlines of a 4GLS is the capability of direct nano-focusing [9] (Fig. 1). The nano-focusing beamline of a 3GLS needs secondary source aperture (~ 10 x 10 μm²) to obtain small focal spot of 100 x 100 nm² [16]. In the 4GLS, the primary source radiation can be directly focused to 100 x 100 nm² thanks to the small emittance. However, the primary source fluctuation directly affects the focused photon brightness. Therefore, the pointing stability of the photon beam is quite important. The source position (angle) jitter is required to be less than 1/10 of beam size (divergence), corresponding to 2 x 0.5 μm (0.5 x 0.5 μrad). Thus, the stabilization of the optical axis is crucial for the 4GLS.

DIAGNOSTIC REQUIREMENTS FOR 4GLS

Beam Position Monitor

For the beam commissioning of a 4GLS, the BPM should have enough resolution of single-pass measurement to adjust the beam position to the design orbit. The demanded resolution is less than 100 μm rms for a 100 pC single bunch. In addition, BPM errors due to the misalignment and the electronics gain unbalance should be well below 100 μm. After the success of the beam storage, precise closed orbit distortion (COD) correction is needed. In this correction, the COD resolution better than a fraction of the beam size is required.

For the user operation of a 4GLS, the pointing stability of the synchrotron radiation is the most important issue. The stability target of the optical axis of each photon beamline should be as good as 1/10 of the beam size and the beam divergence, corresponding to 0.5 μm for the source position and 0.5 μrad for the angle. Therefore, the electron beam position should also be stabilized within 1/10 of the beam size. In addition, a reliable X-ray photon BPM (XBPM) should be developed for the optical axis measurement of the 4GLS.

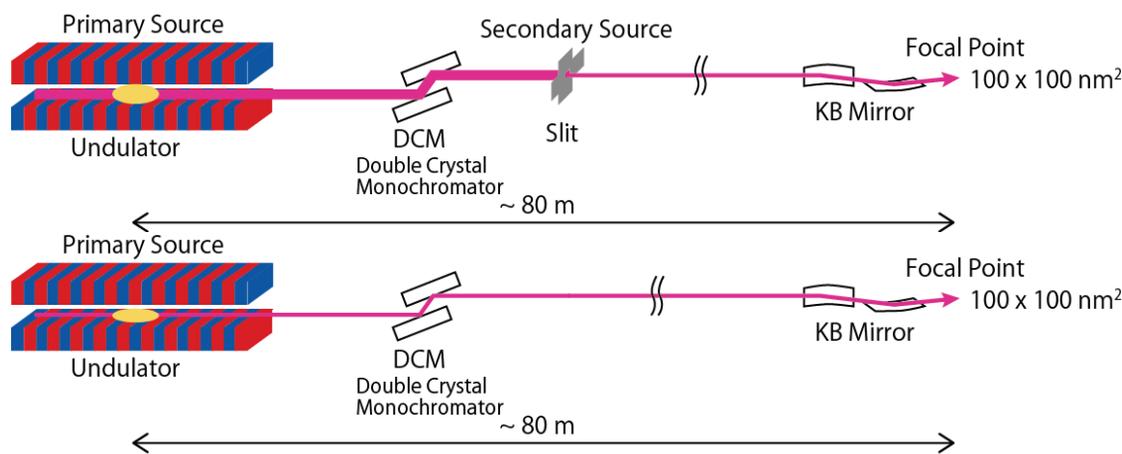


Figure 1: Schematic views of nano-focus beamlines. The upper figure shows the nano-focus beamline with secondary source aperture in 3GLS, and the lower figure shows the direct nano-focus beamline in 4GLS.

A fast orbit feedback (FOFB) is effective to eliminate the beam position fluctuation. Since the bandwidth of the fluctuation is several 100 Hz, the FOFB is required to have sufficient bandwidth. For a slow drift, the orbit stability of 1 μm level is demanded for a user operation period (~ 1 week or longer).

Beam Size Measurement

Since the beam size of a 4GLS is as small as $20 \times 5 \mu\text{m}^2$, the beam size monitor should have the resolution better than 5 μm . The high resolution beam size monitor is important to estimate the beam emittance, XY coupling etc.

Mitigation of Collective Beam Instabilities

Narrow vacuum components of a 4GLS cause large resistive wall impedance, which induces collective beam instabilities. The scaling formula of the transverse resistive wall impedance for a round pipe is [5]

$$Z_T(\omega) \propto \frac{1}{b^3 \sqrt{\omega}},$$

where b is the pipe radius. The growth rate of the instability is

$$\frac{1}{\tau} \propto \int \beta Z_T ds,$$

where β is beta function. Since the chamber radius of a 4GLS is approximately half of that of a 3GLS and the beta function is also about half, the growth rates of a 3GLS and a 4GLS have an approximate relationship,

$$\frac{1}{\tau_{4GLS}} \sim \frac{4}{\tau_{3GLS}},$$

according to the above formulae. This means that the 4GLS has roughly 4 times larger growth rate than the 3GLS. The coupled-bunch instability (CBI) threshold current is estimated to be less than 100 mA. For the transverse mode coupling instability (TMCI), so called single-bunch instability, the threshold bunch-current can be typically less than 1 mA/bunch. Thus, the 4GLS cannot avoid collective beam instabilities coming from the resistive wall impedance. To mitigate the instability, a bunch-by-bunch feedback (BBF) system is necessary for the 4GLS.

Real-time Tune Measurement

Since an undulator has a focusing effect, the betatron tune is shifted by an undulator gap change. The tune shift of a 4GLS may cause unacceptable degradations of beam lifetime and injection efficiency due to the large non-linear effect of the MBA lattice. Therefore, the betatron tune should be continuously monitored during the user operation period and the tune shift should be fed back to quadrupole magnets in order to keep the constant betatron

tune. The resolution of the real-time tune monitor should be less than 0.001.

DIAGNOSTIC INSTRUMENTS FOR 4GLS

The success of a 3GLS has been closely linked to the innovation of beam diagnostic technologies motivated by the “electron-beam-oriented diagnostics”, based on the idea that the photon beam performance is guaranteed by the electron beam quality. Many cutting-edge diagnostic instruments have been developed for the 3GLS. Some of these technologies, described below, meet the requirements for a 4GLS.

BPM Electronics

For the BPM electronics, a multiplexing method was used in the early stage of the 3GLS (Fig. 2a). In this method, many BPM signals are sequentially read with one ADC by using RF switch. This method has an advantage of small gain error of the electronics. However, the data throughput rate of this method is around 100 Hz, which is not suitable for a fast orbit feedback (FOFB). Therefore, the signal from each electrode is read by an individual ADC in recent BPM electronics (Fig. 2b). This BPM electronics was developed, for example, in APS [17], SLS [18], etc. This kind of electronics is also commercially available, such as Libera Brilliance+ from Instrumentation Technologies [19]. These new electronics has data throughput rate of 10 kHz level, which is sufficient for a FOFB.

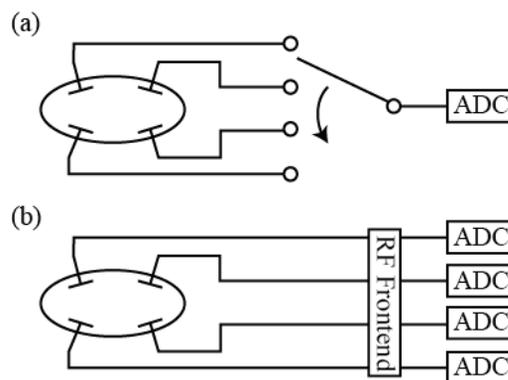


Figure 2: Schematic diagrams of BPM electronics. (a) Conventional multiplexing method. (b) Recent BPM electronics.

Fast Orbit Feedback (FOFB)

The fast fluctuation of a beam orbit up to several 100 Hz can be eliminated by a fast orbit feedback (FOFB) system. The FOFB system collects the BPM data along whole storage ring and controls the currents of corrector magnets. Recently, many 3GLSs are equipped with FOFBs, such as ESRF [20], APS [21], SLS [22], SOLEIL [23], Diamond [24], PETRA III [25], etc. The feedback bandwidth is approximately 100 Hz and the data rate from the BPM is typically 10 kHz. The feedback bandwidth is mainly limited by the response speed of a corrector

magnet and eddy current of a vacuum chamber. Some facilities designed a fast corrector magnet and a vacuum chamber with small eddy current, and achieved system bandwidth of more than 1 kHz [23]. Each FOFB system reduces the fast orbit fluctuation down to less than 1 μm . These FOFB systems are applicable to the 4GLS.

Beam Size Monitor

The beam size monitor is an indispensable device for emittance and XY coupling measurements etc. Since the beam size of the 4GLS is typically $20 \times 5 \mu\text{m}^2$, the beam size monitor is required to have the resolution better than 5 μm . For the 3GLS, based on the visible and X-ray synchrotron radiation.

For visible light monitors, optical interferometers are used at many facilities, such as KEK-ATF [26], SPring-8 [27], SLS [28], etc.

For X-ray monitors, many methods to measure the beam size have been implemented, such as a pinhole camera [29], a zone plate monitor [30], a vertical undulator method [31], and an X-ray Fresnel diffractometry [32]. Because of the diffraction due to the long wavelength, visible light monitors require large acceptance angle ($\sim 10 \text{ mrad}$) to achieve μm resolution. Therefore, a visible light monitor is not feasible for the 4GLS. X-rays have sufficiently short wavelength to resolve μm beam size and X-ray monitors are feasible for the beam size measurement of the 4GLS.

The X-ray pinhole camera does not need any monochromator, while the other X-ray monitors require monochromatic X-rays. Therefore, the pinhole camera is one of the simplest methods. A schematic view of the pinhole camera is shown in Fig. 3. The resolution of the pinhole camera is limited by Fresnel diffraction of the pinhole. To obtain less than 5 μm resolution, a photon energy of $\sim 50 \text{ keV}$ and a pinhole size of $\sim 20 \mu\text{m}$ are typical parameters for the pinhole camera [29].

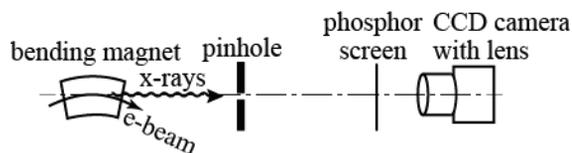


Figure 3: Schematic view of an X-ray pinhole camera.

Bunch-by-Bunch Feedback (BBF)

The resistive wall impedance of a 4GLS is significantly larger than a 3GLS because of narrower vacuum chambers and narrower undulator gaps. Therefore, a bunch-by-bunch feedback (BBF) system to mitigate collective beam instabilities is indispensable for the 4GLS. Recently, most of the 3GLSs, such as ESRF [33], APS [34], SPring-8 [35], Elettra [36], SLS [36], SOLEIL [37], etc., have developed BBF systems for large bunch-current operation etc. These BBF systems are applicable to 4GLSs with proper modifications.

Real-time Tune Monitor

The conventional excitation method for tune measurement spoils the transverse beam stability. Therefore, it cannot be used as the real-time tune monitor for the user operation of a 4GLS.

Using a BBF system is one of the promising ideas for the real-time tune monitor. A small dedicated bunch is excluded from the feedback loop, and is transversely perturbed by the feedback kicker for tune observation. The tune value can be continuously measured from the spectrum of the betatron oscillation of the dedicated bunch. The real-time tune monitors are available in some of the 3GLSs, such as Elettra [38], SLS [39], SPring-8 [40], TLS [41], and PETRA III [42]. For example, TLS performed a tune feedback test [41]. The real-time tune data from the BBF system was fed back to some quadrupole magnets and the tune value was confirmed to be maintained at a certain operating point. This tune feedback system is useful for the 4GLS.

DIAGNOSTIC CHALLENGES FOR 4GLS

As described in the previous section, the state-of-the-art diagnostic techniques have been developed for the 3GLS motivated by “electron-beam-oriented diagnostic”, based on the idea that the photon beam performance is guaranteed by the electron beam quality. The cutting-edge diagnostic instruments implemented for 3GLSs are applicable to 4GLSs.

For the 4GLS, “photon-beam-oriented diagnostics” is crucial to maximize the photon beam performance at the user experimental stations in the beamlines. One of the breakthroughs expected for the 4GLS is the direct nanofocusing (Fig. 1), which requires tight stability of the optical axis of the photon beam. Therefore, the stability of the electron beam is crucial.

While the position readout of the BPM can be locked to the targeted value by using a state-of-the-art beam orbit feedback system, the possible slow displacement of BPM heads and the drift of readout electronics gain give rise to the drift of the beam orbit and the optical axis. One of the major challenges of beam instrumentation for the 4GLS is to stabilize the photon beam and to maximize the photon brightness on the experimental sample. The goal of the long-term stability performance is less than 1 μm for the source position and less than 1 μrad for the optical axis orientation.

Sources of the slow drift of the BPM are ground motion, the thermal expansion of the girder and vacuum chamber, the gain variation of the electronics, etc. Therefore, temperatures of these components should be regulated precisely. Monitoring the displacement of the BPM head can help the stability improvement. These R&D efforts are required for the 4GLS.

The development of a reliable X-ray photon BPM (XBPM) is also important. If the XBPM can be included for the orbit feedback loop, the optical axis can be directly stabilized and the tolerance of the electron BPM can be relaxed. In addition to the feedback, the feed-forward

control to compensate the optical axis variation due to undulator gap change can be realized by using a reliable XBPM. Although XBPMs are already used in photon beamlines [43-45] of 3GLSs, they still have disadvantages to be settled for the orbit feedback, such as undulator gap dependence. Breakthrough in the XBPM technology is required to realize the accurate and fast non-destructive detection of the radiation central cone.

SUMMARY

To pursue further brilliance and coherence of a ring-based light source, 4GLSs with MBA lattice have been under development. The cutting-edge diagnostic instruments developed for 3GLSs are applicable to meet requirements of the 4GLS, such as digital BPM electronics, a fast orbit feedback, a high-resolution beam size monitor, a bunch-by-bunch feedback, and a real-time tune monitor. The innovations of diagnostic technologies for the 3GLS have been motivated by the “electron-beam-oriented diagnostics”. For the 4GLS, “photon-beam-oriented diagnostics” is crucial to maximize the photon beam performance at the user experimental station in the beamline. One of the major challenges is to stabilize the optical axis of the photon beam. To achieve this, technological breakthroughs are needed for the stable BPM and the reliable XBPM.

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