# DEVELOPMENT OF TURN-BY-TURN DIAGNOSTIC SYSTEM USING UNDULATOR RADIATION

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*Abstract*

At the diagnostic beamline II (BL05SS) [1] of the SPring-8 storage ring, a turn-by-turn beam diagnostic system using undulator radiation has been developed to observe fast phenomena such as stored beam oscillations during the top-up injections, blowups of beam size and energy spread coming from the instabilities of a high current single bunch and so on. The fast diagnostic system observes a spatial profile of undulator radiation on a selected harmonic number. Especially, The profile widths of the higher harmonics than the 10th-order are sensitive to variation of the energy spread. The principle and experimental setup of the turn-by-turn diagnostic system, and examples of beam observations are reported.

## MAIN INSTRUMENTS OF BL05SS

BL05SS is a diagnostic beamline with an insertion device (ID05) which magnet array is of planar Halbach type with the 51 periods of 76 mm long. The maximum deflection parameter K is 5.8. Elaborate tuning of the magnetic field leads to the fundamental random phase error of 1.6 degree (r.m.s.) at the maximum K so that we can clearly distinguish individual higher order harmonics of the undulator radiation [2]. This is essential for the beam diagnostics, especially, energy spread measurement. To shape the radiation, a 4-jaw slit is installed in the frontend section at a distance of about 25 m from the source point. A double crystal monochromator using Si (111) is placed in the optics hutch at a distance of about 70 m from the source. The undulator radiation on a harmonic number selected by the monochromator goes into the experimental hutch where the turn-by-turn beam diagnostic system is installed at a distance of about 90 m from the source point (Fig. 1).

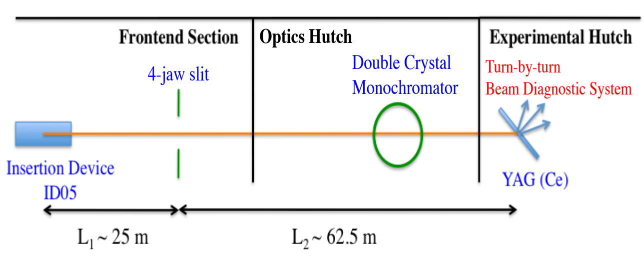


Figure 1: Turn-by-turn beam diagnostic system and the related main instruments of BL05SS

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## EXPERIMENTAL SETUP OF THE TURN-BY-TURN BEAM DIAGNOSTIC SYSTEM

The turn-by-turn beam diagnostic system is intended to observe fast motions of electron beam using spatial profiles of the monochromatic undulator radiation. This system consists of a fast fluorescence screen, imaging optics and a fast CCD camera with an image intensifier (Fig. 2). The fast fluorescence screen placed in vacuum is YAG (Ce) crystal with 0.1 mm thick and its decay time is several tens of nano seconds. An X-ray profile of undulator radiation with photon energy of about 10 keV is converted into a visible light profile on the YAG (Ce) screen. Converted center wavelength is 550 nm and its bandwidth is about 100 nm (FWHM). The imaging optics transforms the 2D-profile on the YAG (Ce) screen to two line profiles projected in the horizontal and vertical directions. Visible light is split into two light paths by a half mirror and one-dimensional focusing optics using cylindrical lenses is implemented in each light path. In the path-1, the strong vertical focusing makes a horizontal-projected line profile. The horizontal strong focusing in the path-2 makes a vertical-projected line profile. These two projected line profiles are simultaneously imaged on a photoelectric surface of the image intensifier (HAMAMATSU: C9548-02MP47). The material of the photoelectric surface is GaAsP. The image intensifier embeds dual micro channel plates (MCPs) and P47 phosphor screen with short decay time. The minimum width and the maximum repetition rate of the MCP gate are 10 ns and 210 kHz, respectively. The fast CCD camera (Roper Scientific: ProEM 512B) captures the intensified images of the two line profiles. The pixel number and size are 512(X)*512(Y) and 16 μm, respectively. This CCD camera has a special function referred to as the kinetics readout mode, which is very useful for the turn-by-turn measurements of the spatial profiles. By illuminating only a small portion of the CCD sensor, a series of sub-flames can be captured and vertically shifted in microseconds vastly increasing the time resolution. The fastest shift rate is 0.45 μs/pixel in each sub-frame. The sub-frame is triggered independently by an external signal synchronizing with the beam revolution signal or its frequency-dividing signal. The imaging optics and the camera position are adjusted to locate the illuminating area in a lower part of the CCD sensor. The smaller vertical size of the sub-frame enables profile measurements with higher repetition rate, which requires vertically strong focusing of the light on the narrow sub-frame.



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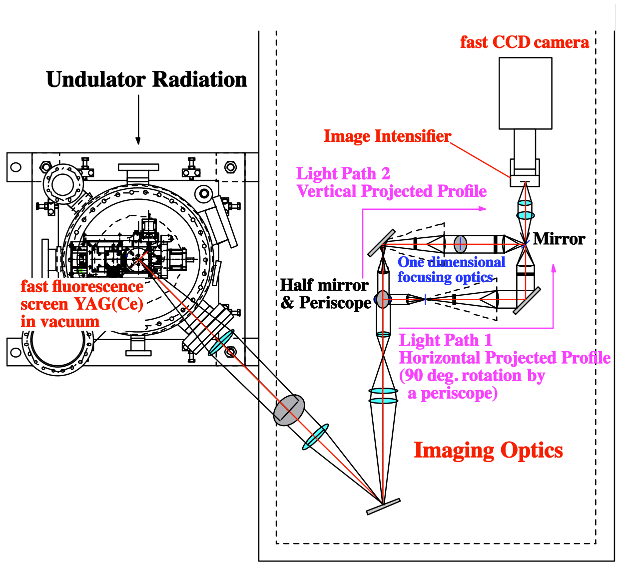


Figure 2: Experimental setup of the turn-by-turn beam diagnostic system which consists of a fast fluorescence screen YAG (Ce) in vacuum, an imaging optics on an optical table and a fast CCD camera with an image intensifier. Light spot of the path-1 in the imaging optics is rotated 90 degrees by a periscope with a half mirror.

## EXAMPLES OF BEAM MEASUREMENTS

### *Oscillations of Stored Beam Induced by Injection*

An off-axis beam injection to the SPring-8 storage ring needs a local horizontal bump in a closed orbit of the stored beam. The local orbit bump is excited by four pulse bump magnets which magnetic field patterns are half-sine with 8μs width. The excited orbit bump is not completely closed due to the difference of the field patterns and drift of excitation timings among four bump magnets. A residual kick by the field errors of the bump magnets induces a horizontal beam oscillation. In order not to disturb the user's experiments, the oscillation is suppressed as much as possible by a counter kick using a fast correction magnet [3] and tuning of the excitation timings of the four bump magnets. The residual oscillations after the tuning have been measured using the turn-by-turn beam diagnostic system. Angular oscillation measurement of the undulator radiation is shown here as one example. We observed the fundamental harmonic of 7.2 keV at the small deflection parameter K of 0.45 (magnet pole gap: 80 mm) through the 4-jaw slit with the horizontal and vertical wide angular apertures of 123 μrad and 45 μrad, respectively. Figure 3 shows a single shot image with the kinetics readout mode captured by synchronizing with a trigger signal to excite the bump magnets for the beam injection. Each sub-frame is triggered by a divide-by-five frequency-dividing signal of the revolution frequency. The MCP gate of the image intensifier is also triggered by the same signal as the sub-frame trigger of the CCD camera. The spatial profiles in the sub-frames are imaged with an exposure time of 200 ns controlled by the MCP gate width. The profiles shown in Fig. 3 are single shot images every 5 turns from the turn number -4 to 116, where the bump excitation timing (the injection timing) is defined as the turn number zero. So, an initial turn number -4 means 4 turns before the bump excitation. We can control the initial turn numbers to grab the profile by adjusting a delay and a width of the injection timing signal, which overrides a veto of trigger signals for the MCP gate and the CCD sub-frame. The initial turn number automatically changes in cyclic order of the five consecutive numbers. Here, the five means the frequency-dividing number of the gate signals. A series of single shot profiles every 5 turns with the initial turn numbers of -7, -6, -5, -4 and -3 were captured and sorted by the turn numbers to obtain the turn-by-turn profile data. The center positions of each horizontal profile fitted by a Gaussian function is converted to horizontal angles from the view of the source point, which are shown in Fig. 4(a) as a horizontal angular oscillation. Figure 4(b) shows the FFT analysis of the angular oscillation data. A single sharp peak corresponds to the fractional horizontal betatron tune of 0.15. The phase of the observed oscillation and its FFT peak intensity will be a useful tool for feedback control to the excitation timing of the injection bump and its correction magnets to reduce the beam oscillations induced by the injection.

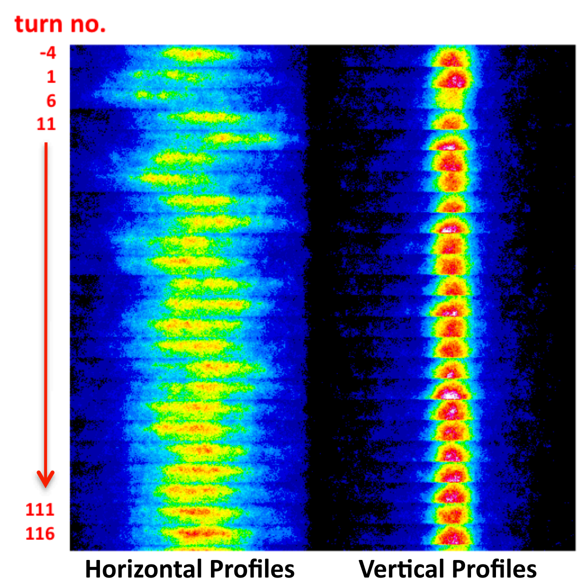


Figure 3: An example of a single shot image with the kinetics readout mode captured by synchronizing with the beam injection timing. An electron bunch residual-kicked at the rising edge of the half-sine excitation pattern of the bump magnet was gated by the image intensifier. The left side numbers are turn numbers where the bump excitation timing is labeled as zero turn. The top profile is captured before the injection.



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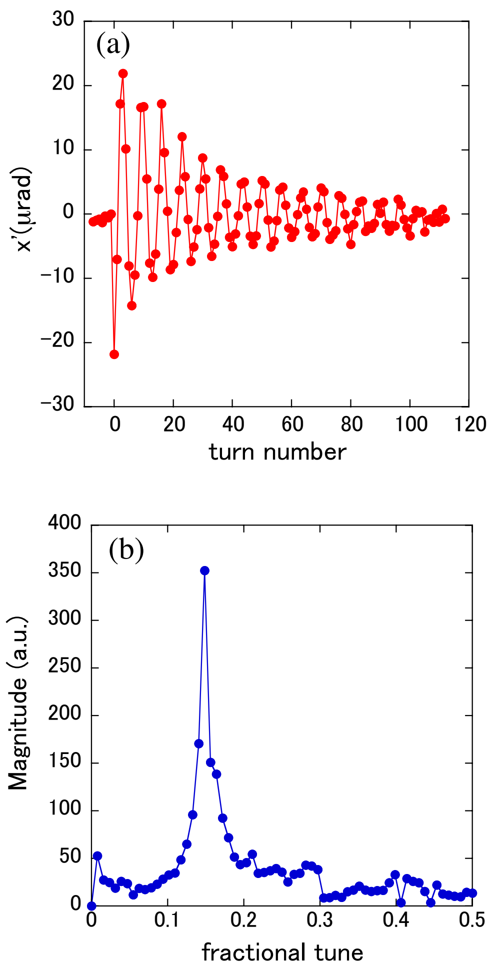


Figure 4: (a) Horizontal angular oscillation of the undulator radiation obtained from the turn-by-turn profile measurements synchronizing with the injection timing. (b) FFT analysis of the angular oscillation data. A main peak indicates the fractional horizontal betatron tune.

### *Energy Spread Measurement*

ID05 becomes a multi-pole wiggler with the large K value, when the magnet pole gap is narrow. Spectral fluxes and their angular divergences of the higher harmonic radiations from the multi-pole wiggler are sensitive to variation of the energy spread of electron beam. This property of the higher harmonics has an advantage for the energy spread diagnostic. The horizontal width on the YAG (Ce) screen of the photon beam profile on the higher harmonic is dominated by horizontal electron beam emittance, while the vertical width is dominated by the energy spread and intrinsic angular divergence of the photon beam itself [2], because vertical electron beam emittance has a negligible effect owing to the small emittance-coupling ratio. Thus, the fast energy spread measurement is possible by observing the vertical profile of the photon beam. Furthermore, observation of a 2D-profile on the higher harmonic enables us to measure the horizontal emittance and energy spread simultaneously.

As an example of the energy spread measurement, its bunch current dependence is shown here, during test operation with beam energy of 7 GeV. We observed the monochromatic 15th harmonic radiation of 11.36 keV at the large deflection parameter K of 3.74 (magnet pole gap: 30.44 mm). The horizontal slit aperture in the frontend was narrow size of 0.2 mm to reduce heat load on the double crystal monochromator. This narrow aperture has another effect that the horizontal beam distribution at the source point is projected on the YAG (Ce) screen, based on the principle of a pinhole camera. The vertical aperture of the slit was 1.2 mm wide not to intercept the 15th harmonic radiation. A relation between the energy spread and the vertical width of the monochromatic 15th harmonic radiation observed on the CCD camera was calibrated experimentally. We measured the vertical widths of the radiation from multi-bunch beam with small bunch current as a function of the center energy of electron beam while changing the RF frequency. The maximum beam energy shift was 0.18%. Figure 5 shows a calibration curve extracted on the basis of this beam energy dependence of the measured vertical width. The small bunch current allows us to assume that the vertical width measured at the original RF frequency corresponds to the natural energy spread 0.0957 % in theory at the beam energy of 7.0 GeV.

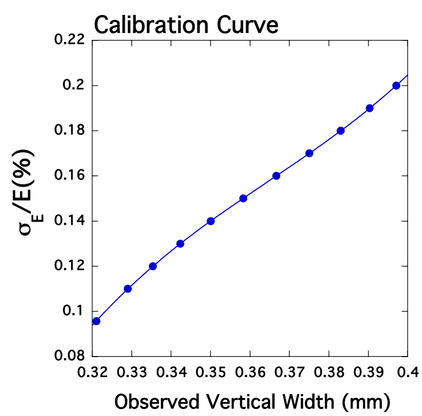


Figure 5: Calibration curve based on the experimental beam energy dependence of the vertical width observed on the CCD camera of the monochromatic 15th harmonic radiation at the beam energy of 7 GeV. Solid line is a fitted curve by a third degree polynomial function.

The gated single shot images of a single bunch were captured with the kinetics readout mode. The gate width was 200 ns, which was controlled by the image intensifier. Examples of the single shot images observed at the bunch current of 2.9 mA and 13 mA are shown in Fig. 6. We can see that the vertical profiles at 13 mA broaden, compared with that at 2.9 mA. Each single shot image includes 24 sub-frames and one vertical profile per sub-frame is registered. Since 100 shots were taken at each bunch current, an average width of the 2400 vertical profiles was converted into the energy spread using the calibration curve shown in Fig. 5. A preliminary result of measured energy spread depending on a single bunch



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current is shown in Fig. 7. In this measurement, the energy spread increased even at small single bunch current of 2 mA. At the bunch current of 13 mA, that reached about double the original value. We plan to cross-check this result by beam size measurement at a bending magnet source point with the horizontal dispersion.

The SPring-8 storage ring has a plan of the user time operation with a single bunch current larger than 10 mA. Generally, the energy spread tends to increase with the bunch current due to the wake fields and the induced microwave instabilities. This means that a spectral flux density from an undulator is not proportional to the single bunch current and may be saturated. This is an issue that has the potential to impact the performance of a light source. Therefore, the fast energy spread measurements will be important for performance estimations of the light from a single bunch beam with large bunch current which has short lifetime.

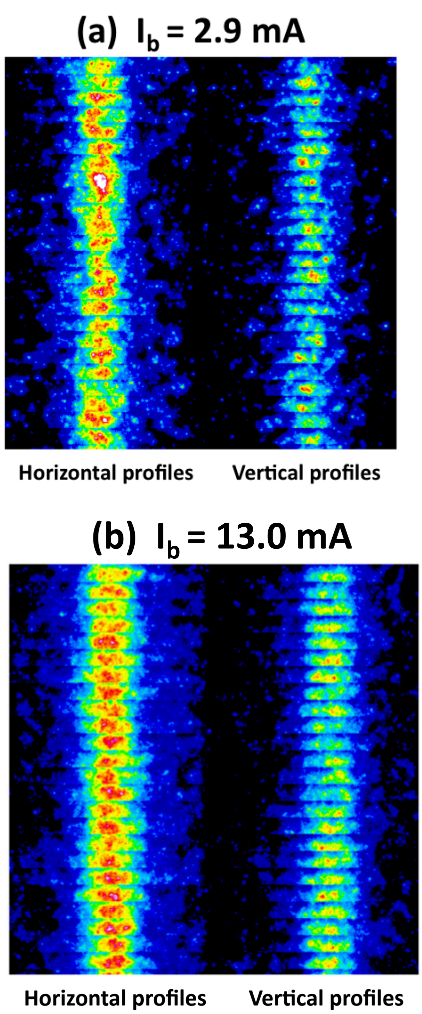


Figure 6: Examples of single shot images with the kinetics readout mode captured at single bunch current of 2.9 mA (a) and 13 mA (b). The gate width controlled by the image intensifier is 200 ns. The widths of the vertical profiles (right-hand side) at 13 mA broaden in comparison with that at 2.9 mA.

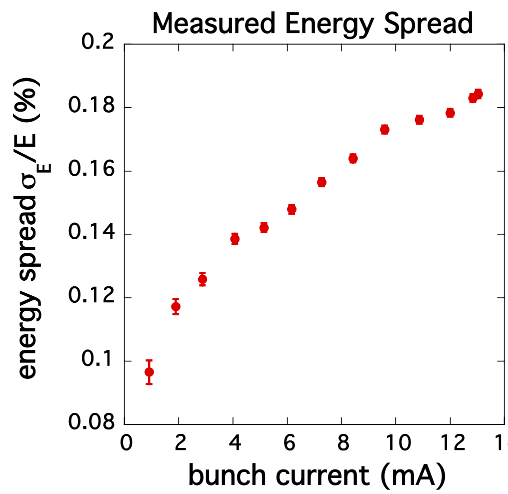


Figure 7: Preliminary result of single bunch current dependence of the energy spread measured in the test operation at 7 GeV.

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