RECENT DEVELOPMENT OF DIAGNOSTICS ON 3RD GENERATION LIGHT SOURCES

G. Rehm, Diamond Light Source, Oxfordshire, U.K.

Abstract

A Review of the most performing diagnostics on 3rd generation light sources will be given. Starting with the target performance specification of recent 3rd generation light sources, the demands for diagnostics will be highlighted. Topics include beam position monitors and their integration, emittance measurement by imaging of the stored beam or interference methods and diagnostic requirements for top-up operation. A survey of recent developments and the achieved performance at different accelerators will be presented.

INTRODUCTION AND SCOPE

Diagnostics have become an integral component of modern synchrotron light sources. Diagnostic systems have always been instrumental in monitoring the performance of any accelerator or storage ring, but with their increasing integration into feedback loops they are now even more important as they are often required to achieve the stated performance goals in the first place. The major headline figure which synchrotron light sources strive to improve continuously is brilliance, which can be increased either by more advanced insertion devices (creating more photons per electron), lowering the emittance or increasing the beam current. The latter appears to have found a technologically reasonable maximum in the region of 300–500 mA, probably set by the amounts of heat load and radiation dose (as higher stored current will cause higher loss rates) that appear manageable.

As a result, the main parameter which newer light sources have advanced on is lowering the emittance (see table 1). Until recently, the typical horizontal emittance for third generation light sources was about 5±2 nm rad. Two new projects, PETRA III[1] and NSLS-II[2] are aiming significantly lower at 1 nm rad, with the help of damping wigglers[3]. However, more relevant for diagnostics are the actual beam sizes which these emittances and optics create. After all, it is typically demanded for electron beam position monitors (EBPMs) to resolve to a fraction of beam size, and for transverse profiling systems to provide a resolution that allows the measurement of the beam dimensions with marginal error. But if beam size is important, then vertical beam size will create the tightest requirement, as this is typically at least one order of magnitude lower than the horizontal beam size.

Furthermore, while most light sources aim at an emittance coupling value of 1% in their design and for initial operation, modern linear optics correction routines and the availability of sufficient numbers of skew quadrupoles allow to reduce the emittance coupling down to 0.1% even for user operation, as demonstrated by the SLS[4, 5]. This has created the smallest vertical beam size (about 2 μm) at an ID source point in any light source so far, but this could be matched or surpassed at other light sources if they decide to operate at lower emittance coupling as well. However, the diffraction limit for the radiation emitted in an insertion device defines a minimum beam size that should reasonably be chosen in a light source, even if optics correction would allow better.

This review will strictly limit itself to diagnostics on 3rd generation light sources and focus on those aspects where major advances have recently been achieved or challenges have been met. These have been identified as EBPMs, transverse profiling for emittance measurement, and diagnostics specific to top-up operation, which is becoming increasingly more popular.

ELECTRON BEAM POSITION MONITORS

Definition of Resolution

As a rule of thumb, aiming at a resolution of the EBPMs of 10% of the beam size at a data rate and bandwidth suitable for fast orbit feedback is common practice. Typically a resolution specification of 200-500 nm within a bandwidth of 1-2 kHz would thus result from the beam dimensions in table 1. This rule is derived from the demands on source point stability and the reasoning that a feedback can only correct as well as its monitors can read. However, it has been shown that the amount of allowable source point motion strongly depends on the integration time of any detectors in use for beam line experiments[6]. This will decide whether the motion is perceived as smearing out of the beam (where the motion is significantly faster than the integration time), or an observable random motion of the beam (where it is slower than the integration time) that causes additional measurement noise. Low frequency noise and drift is thus of particular importance.

While measurement noise is typically expected to be ‘white’ so that the measurement error would decrease with the square root of the bandwidth, it has to be checked how far this holds for EBPMs. It follows, that the performance of an EBPM cannot be fully specified by a single ‘resolution’ figure, like 1μm resolution at 1 kHz bandwidth. Consequently, a terminology has evolved where ‘resolution’ typically denotes measurement uncertainty for frequencies integrated from 0.1 Hz or 1 Hz up to a specified bandwidth, ideally displayed as integrated spectrogram (see example in figure 1). On the other hand, ‘stability’ will denote those

Table 1: Summary of main parameters for light sources recently completed and in construction. $\beta_{x,y}$ are the smallest in any ID straight. Beam sizes are calculated as $\sigma_i = \sqrt{\epsilon_i \beta_i}$, not taking into account any contribution from dispersion/energy spread. SLS* denotes the recent operational conditions with slightly increased ϵ_x due to changed optics, but significantly reduced ϵ_y due to better coupling control. ESRF-U indicates the planned ESRF upgrade which aims at lowering ϵ_y besides many other changes.

	year	E [GeV]	I [mA]	C [m]	ϵ_x [nm rad]	ϵ_y [pm rad]	K [%]	β_x [m]	β_y [m]	σ_x [μm]	σ_y [μm]
SLS	2001	2.4	400	288	5	35	0.7	1.4	0.9	84	5.6
CLS	2005	2.9	500	171	20.5	92	0.45	9.5	2.6	441	15.5
ASP	2006	3	200	216	6.98	63	0.9	9	2.45	251	12.4
SLS*	2006	2.4	400	288	5.5	5.5	0.1	1.4	0.9	84	2.1
Soleil	2007	2.75	500	354	3.7	37	1	4	1.77	122	8.1
Diamond	2007	3	300	562	2.7	27	1	4.6	1.5	111	6.4
SSRF	2008	3.5	300	432	3.9	39	1	3.6	2.5	118	9.9
PETRA III	2009	6	100	2304	1	10	1	20	5	141	7.1
ALBA	2010	3	400	269	4.3	40	0.9	2	1.3	93	7.2
ESRF-U	2011	6	300	844	4	10	0.25	35.2	2.52	375	5.0
NSLS-II	2015	3	500	792	0.9	8	0.89	1.5	0.8	37	2.5

very slow fluctuations in readings which span timescales from seconds to days, and is specified as a peak to peak band.

Performance Evolution

In the past, many different EBPM processing electronics have been developed. For example Spring-8[8] and ESRF[9] developed analogue processing electronics which provided excellent performance at their time. The multiplexed electronics commercially manufactured by Bergoz [10] have found use in many light sources. And the SLS designed and built the first digital EBPM, which was subsequently integrated into one of the first truly global FOFB systems [7].

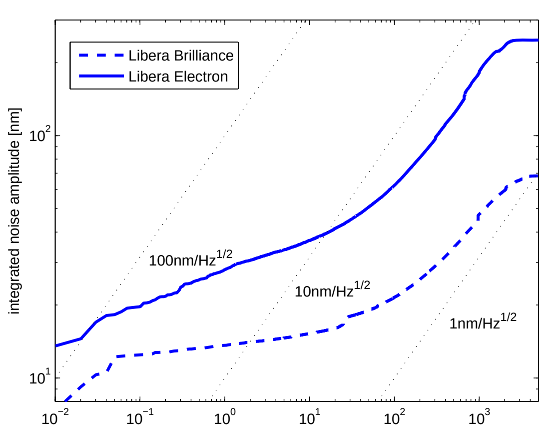

Figure 1: Example of integrated noise spectrum for two EBPMs, recorded in a lab setup. This illustrates that contributions from very low frequencies can be significant.

It might thus be surprising that more recently Instrumentation Technologies [11] managed to become the commercial supplier of EBPMs to equip 8 full lightsources within just 5 years. *Libera Electron* had been developed to meet the specifications of and in cooperation with Soleil [12] and Diamond [13]. It has subsequently been chosen to equip the ASP [14] and SSRF [15]. Elettra has recently upgraded its entire storage ring with *Libera Electron* and integrated them into a global fast orbit feedback[16], soon followed by similar systems at Diamond [17] and Soleil [12]. In the meantime, a follow-up product with further improved performance called *Libera Brilliance* has been chosen for ALBA [18], PETRA III [1] and an upgrade of NSRRC [19].

So far, this unusual concentration and reliance on one supplier has worked largely to the benefits of all customers, who have been able to share their experience and developments of software. However, as a result general R&D activity in the area of EBPM electronics has been scarce at light sources in the recent past. There have been some encouraging first results from new developments at the APS [20] and SLS [21], both aiming at a kind of 'universal' FPGA based ADC equipped system. The future might also show some interesting results from an R&D program recently started for the NSLS-II project [22].

An attempt to illustrate the evolution of EBPM performance in terms of the achieved resolution is made in figure 2. It shows that within a few years, the resolution has improved by nearly one order of magnitude. It also shows that the range of data rates at which position measurements are produced has broadened, and now regularly covers nearly 5 decades: from 'slow updates' at a few Hz, used for display and precision measurements, through 'fast data' for FOFB at some kHz to 'turn-by-turn' data at near MHz rate. The availability of the latter on all EBPMs in a storage ring has opened entirely new possibilities for studies of nonlinear beam dynamics [23].

In terms of longer term stability, available data in the literature is scarce. The SLS digital BPMs are reported to be stable to within ± 1 μm within a 24h period. Measurements at Diamond have shown ± 300 nm for *Libera Electron* and ± 100 nm for *Libera Brilliance* over a 24h period.

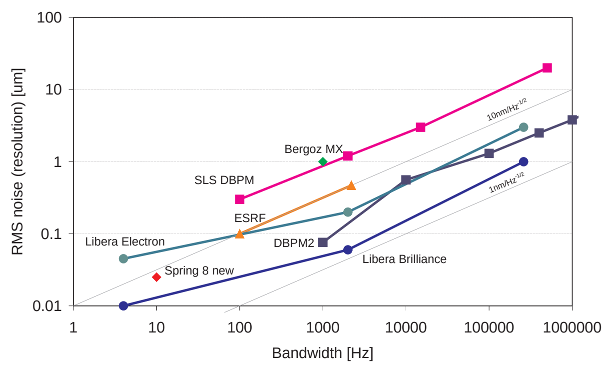

Figure 2: Comparison of resolution reported for EBPMs at various data rates. Data is a collection from publications and measurements at Diamond, all referring to lab measurements.

EMITTANCE MEASUREMENT

Measurement of emittance in a storage ring typically requires some kind of transverse profiling and subsequent calculation of the emittance from the measured beam dimensions and Twiss parameters assumed to be known. In a light source, synchrotron radiation lends itself as a method for transverse imaging as it facilitates a non destructive and quick measurement of the beam profile. An excellent overview of the various techniques has recently been produced [24], so that here only most recent results using these techniques and a survey of their popularity shall be presented.

As discussed before, the very small vertical emittances in the order of a few pm rad which can be achieved with good coupling correction will lead to very small beam sizes. These are clearly the challenge to measure, even if they are typically about a factor of 3 larger than the vertical beam sizes displayed in table 1, as most light sources choose to measure the beam profile at a bending magnet source point where β_y is often about 10 times larger than at the ID source point. Even so, beam sizes below 10 μm need to be resolved. Direct imaging with visible or UV light is clearly no longer possible as the required resolution is far below the self diffraction limit at these wavelengths.

Consequently, imaging the beam using the X-ray part of the bending magnet spectrum is a natural alternative. The most popular method is a pinhole camera, which has recently been implemented at Soleil[25], Diamond[26], ASP[27] and SLS[28]. Pinhole systems using hard X-rays can be set up in air and entirely inside the machine tunnel, which makes them a very reliable and compact system. Recent calculations taking into account the spectral distribution of the source (bending magnet radiation with some filtering through metal sheets applied) and applying numerical methods to precisely evaluate the diffraction, have shown that with the correct choice of pinhole size and magnification (i.e. distances source to pinhole and pinhole to screen) a resolution of better than 5μm can be achieved [25, 26, 29].

This compares very favourably to other imaging techniques that use focussing elements. Diffractive optics like Fresnel Zone Plates (FZP) have been demonstrated at Spring-8 [30] and SLS [31]. Compared to the pinhole camera, these setups are more akin to 'real' beamlines, requiring a beam transport all in vacuum (as FZP are currently only available for soft X-rays) as well as a front end and shielded hutch. Despite the much larger experimental effort, FZP on light sources have so far only produced performance comparable to other methods. However, a setup with two FZP has demonstrated below 1μ resolution on the KEK-ATF [32]. Compound refractive lenses [33] have been tested in an imaging application at the ESRF[34], but are not in regular use. PETRA III[1] is planning a setup where a pinhole can be exchanged with a compound refractive lens.

There are also some highly performing alternatives to imaging the beam: At the SLS[28] a method first applied at MAX-II[35] is in use, where analysing the profile of the vertically polarised radiation in the visible has produced better resolution than the pinhole in use there. Another recent development has been a direct projection method which is at widespread use at the ESRF[36]. It uses a compact system to image the vertical fan of extremely hard X-rays (>150 keV) directly behind the dipole crotch absorber. However, for this system to perform, it needs to be placed as closely as possible to the source point and needs sufficiently hard radiation, as otherwise the measured profile

Table 2: Comparison of vertical beam sizes σ_y and emittances ϵ_y measured using various systems. Σ_0 denotes the ultimate resolution and $\sigma_y' = \sqrt{\sigma_y^2 - \Sigma_0^2}$ the de-convoluted beam size, which was subsequently used in the emittance calculation

	type	Σ_0	σ_y	σ_y'	ϵ_y
		[μm]	[μm]	[μm]	[pm rad]
Spring-8	FZP	4.1	14.6	14	7
Diamond	Pinh. 1	3.9	7.8	6.8	2.2
Diamond	Pinh. 2	3.5	7.7	6.9	2.1
Soleil	Pinhole	5	19.8	19	4.7
ESRF	Project.	34	38.5	18	10
SLS	V. polar.	-	7.5	7.5	3.9
SLS	Pinhole	9	13.5	10	-

will be dominated by the vertical opening angle of the radiation and not the beam size. If these conditions are met, the vertical beam profile can easily be monitored in a multitude of locations around the ring due to the compactness and low cost of this system. This is a unique feature that enables verification of the coupling correction in many places simultaneously.

Finally, PETRA III also proposes to test vertical profile measurement using a laser wire [1] system, employing a system resembling the one tested at KEK-ATF [37].

A comparison of the best performing transverse profile/emittance measurement systems currently in use at synchrotron light sources is given in table 2. It should be kept in mind, that de-convolution always introduces an element of uncertainty, so a large ultimate resolution Σ_0 should only be used where it is precisely known (like in the case of projection). Both measurements at SLS were conducted under the same conditions, but the measurement of vertically polarised light is trusted more [28].

DIAGNOSTICS FOR TOP-UP

Top-up operation facilitates frequent injections with beamline shutters open to keep the stored beam current within a small range (typically less than 1%). To achieve just that, it will require no special diagnostics other than a PCT with its readout synchronised to the injection, so that the beam current can be read after every shot. Further requirements may arise from safety considerations, such as transfer efficiency measurements. These will require synchronous readings of charge at various locations in the injector, that need to be precise enough to produce reliable efficiency measurements even at low charge (individual shots might be <100 pC). In this case, standard ICTs are pushed to their resolution limits and systems based on resonant pickups are favourable [38].

Furthermore, while not strictly necessary, it makes sense to combine top-up with a fill pattern feedback, which is able to create and maintain arbitrary fill patterns. This requires not only to keep the total current within a tight range, but to keep individual bunches at their desired charge, thus compensating e.g. for the shorter lifetime of bunches with high charge. A typical application of this is ‘hybrid’ or ‘camshaft’ mode, where one strong single bunch is put into the gap of a 2/3 fill. Besides a flexible timing system to facilitate the programmed injection of bunches into the desired positions, a diagnostics system to measure the fill pattern is required[39]. The temporal information can be either retrieved from a fast electrical pickup like a button pickup, ring electrode or FCT or from the synchrotron light using an avalanche photo diode or fast PMT. Those systems based on measurement of the arrival time of photons have traditionally been used for bunch purity measurements, but they also provide a good tool for fill pattern measurement if the count rates are high enough to collect statistics within the required time (typically minutes between top-up injections). This can be achieved with modern time to digital converters as demonstrated at Diamond[40] and APS[41].

Finally, as beam lines are also potentially taking data during top-up injections (not all detectors can be gated), any disturbances to the beam from a non closure of the injection kick have to be minimised. In the first place, this is done by pulse current measurements of the kicker magnets, but ultimately the oscillations induced on the beam need to be quantified. Turn-by-turn data from EBPMs offer good information, but may underestimate the size of oscillations as individual bunches within the fill pattern can be displaced in opposite directions by the residual kick, thus leading to a cancellation in the calculation of the position over one turn. As an alternative, assessing the blow up of the beam using a fast pinhole camera [42] resembles the perspective of a beam line. Figure 3 illustrates how the size of the beam increases (the camera integrates for about 1 ms) while the intensity integrated over the area depicted by the rectangle drops.

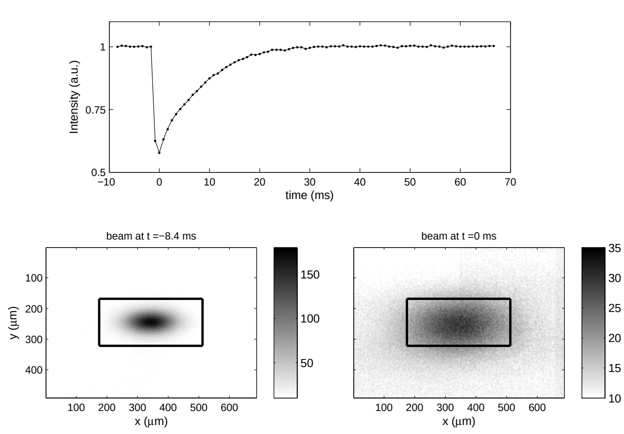

Figure 3: Beam blowup as a result of mismatched injection kickers. Top graph shows calculated temporal intensity evolution as it might be perceived by a beamline.

CONCLUSIONS

Diagnostics for 3rd generation light sources have evolved continuously over the recent years. While no revolutionary new techniques can be noted, a rather unique shift towards the use of the same type of commercially produced EBPM has been observed. This move can be justified by the delivered performance and the benefits from ‘community support’ for the integration into the control and fast orbit feedback systems.

For emittance measurement optimised pinhole cameras have proven to be the most reliable and popular systems with adequate resolution for current light sources, while some alternative approaches offer potentially higher resolution required for new projects.

Top-up operation in itself does not demand specific diagnostics, but for its optimisation a fast and precise fill pattern measurement as well as a method of accessing the disturbance from non-closure of the injection kick is helpful.

REFERENCES

[1] G. Kube et al, "Overview of the Diagnostics Systems of PETRA III", *this conference*, TUPC111.

[2] O. Singh et al, "Overview of Beam Instrumentation and Diagnostics for the NSLS-II Project", *Proceedings of Beam Instrumentation Workshop 2008*.

[3] J. Bengtsson, "Ultra Low Emittance Light Sources", *this conference*, TUXM01.

[4] A. Streun et al, "Coupling Control at the SLS", *this conference*, WEPC003.

[5] A. Luedeke et al, "Status of the Swiss Light Source", *Proceedings of EPAC 2006*, pages 3424–3426.

[6] M. Boege, "Achieving Sub-Micron Stability In Light Sources", *Proceedings of EPAC 2004*, pages 211–215.

[7] V. Schlott et al, "Performance Of the Digital BPM System for the Swiss Light Source", *Proceedings of DIPAC 2001*, pages 69–72.

[8] S. Sasaki et al, "Renewal of BPM Electronics of Spring-8 Storage Ring", *Proceedings of DIPAC 2007*.

[9] E. Plouviez et al, "Upgrade of the Global Feedback of the ESRF Storage Ring", *Proceedings of DIPAC 2005*.

[10] www.bergoz.com

[11] www.i-tech.si

[12] N. Hubert et al, "Commissioning of SOLEIL Fast Orbit Feedback system", *this conference*, THPC115.

[13] G. Rehm et al, "Digital EBPMs at Diamond: Operational Experience and Integration into a Fast Global Orbit Feedback", *Proceedings of DIPAC 2007*.

[14] Y.-R.E. Tan et al, "Commissioning of the Australian Synchrotron with Libera EBPPs and Matlab", *Proceedings of APAC 2007*, pages 404–406.

[15] Y. Yan et al, "Data Acquisition and Analysis in SSRF BPM System", *this conference*, TUPC015.

[16] M. Lonza et al, "BPM detectors upgrade for the ELETTRA Fast Orbit Feedback", *Proceedings of DIPAC 2007*.

[17] M. Heron et al, "Performance and Future Developments of the Diamond Fast Orbit Feedback System", *this conference*, THPC118.

[18] A. Olmos et al, "Measurements on Libera Electron and Libera Brilliance BPM electronics", *Proceedings of Beam Instrumentation Workshop 2008*.

[19] C. Kuo et al, "Fast Orbit Feedback System Upgrade with New Digital BPM and Power Supply in the TLS", *Proceedings of DIPAC 2007*.

[20] H. Bui et al, "Performance of FPGA-based Data Acquisition for the APS Broadband Beam Position Monitor System", *Proceedings of Beam Instrumentation Workshop 2008*.

[21] B. Keil et al, "The PSI DSP Carrier (PDC) Board: a Digital Back-end for Bunch-to-bunch and Global Orbit Feedbacks in Linear Accelerators and Storage Rings", *this conference*, THPC123.

[22] I. Pinayev et al, "Research and Development Program on Beam Position Monitors for NSLS-II Project", *this conference*, TUPC082.

[23] R. Bartolini et al, "Turn-by-turn Data Analysis at the Diamond Storage Ring", *this conference*, THPC053.

[24] G. Kube, "Review of Synchrotron Radiation Based Diagnostics for Transverse Profile Measurements", *Proceedings of DIPAC 2007*.

[25] M.-A. Tordeux et al, "Ultimate Resolution of Soleil X-Ray Pinhole Camera", *Proceedings of DIPAC 2007*.

[26] C. Thomas et al, "Pinhole Camera Resolution and Emittance Measurement", *this conference*, TUPC086.

[27] M.J. Boland, "Beam Profile Measurement and Analysis with X-ray Pinholes", *this conference*, TUPC009.

[28] A. Andersson et al, "Recent Results from the Electron Beam Profile Monitor at the Swiss Light Source", *Proceedings of DIPAC 2007*.

[29] I. Pinayev et al, "Evaluation of Pinhole Camera Resolution for NSLS-II Storage Ring", *Proceedings of Beam Instrumentation Workshop 2008*.

[30] S. Takano et al, "The X-Ray Beam Imager for Transversal Profiling of Low-Emittance Electron Beam at the Spring-8", *Proceedings of DIPAC 2005*, pages 241–243, June 2005.

[31] C. David et al, "A Zone Plate Based Beam Monitor for the Swiss Light Source", *Proceedings of DIPAC 2001*, pages 133–135, June 2001.

[32] H. Sakai et al, "Improvement of Fresnel zone plate beam-profile monitor and application to ultralow emittance beam profile measurements", *Physical Review Special Topics Accelerators and Beams*, 10(4):042801–18, April 2007.

[33] A. Snigirev et al, "A Compound Refractive Lens for Focusing High-Energy X-rays", *Nature*, 384:49–51, November 1996.

[34] T. Weitkamp et al, "Electron Beam Size and Profile Measurements With Refractive X-Ray Lenses", *Proceedings of EPAC 2000*, pages 1824–1826.

[35] A. Andersson et al, "Beam Profile Measurements with Visible Synchrotron Light on MAX-II", *Proceedings of EPAC 1996*, pages 3424–3426.

[36] K.B. Scheidt, "Measurement of Vertical Emittance with a System of Six -In-Air-X-Ray- Projection Monitors at the ESRF", *Proceedings of DIPAC 2007*.

[37] S.T. Boogert et al, "A Micron Size Laser-wire System at the ATF Extraction Line", *this conference*, TUPC011.

[38] G. Naylor, "Measurement of Electron Beam Charge in the ESRF Accelerator Complex for Absolute and Injection Efficency Measurements Using an FPGA Based Digital BPM Electronics", *Proceedings of DIPAC 2007*.

[39] B. Kalantari, "Bunch Pattern Control in Top-Up Mode at the Swiss Light Source", *Proceedings of EPAC 2004*, pages 2885–2887.

[40] C. Thomas "Bunch Purity Measurement for Diamond", *NIM-A 566 (2006)* , pages 762-766.

[41] W.E. Norum, "A Novel FPGA-based Bunch Purity Monitor System at the APS Storage Ring", *Proceedings of PAC 2007*, pages 4384–4386.

[42] C. Thomas et al, "Fast Pinhole Camera for the Optimisation of Top Up Injection", *Proceedings of Beam Instrumentation Workshop 2008*.