ISBN: 978-3-95450-247-9 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2024-FRXN1

BEAM INSTRUMENTATION FOR ADVANCING ACCELERATORS

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Abstract

Beam instrumentation is of critical importance for the operation and optimization of modern particle accelerators. With advancing accelerator technology and the increasing requirements for higher quality beams, it is an ever-present challenge that beam diagnostics must similarly progress. In this paper the instrumentation considered most impactful for the progress of fourth generation storage ring light sources is presented with reference to possible lessons learned, applicability to other accelerators and potential future directions.

INTRODUCTION

Advancing accelerators depend on the development of enhanced diagnostics capabilities. This includes improved resolution, data rates, reliability and future-proofing. Although applicable to all particle accelerators, in particular this is highly relevant for synchrotron radiation facilities currently undergoing or planning upgrades to fourth generation diffraction-limited storage rings [1–3].

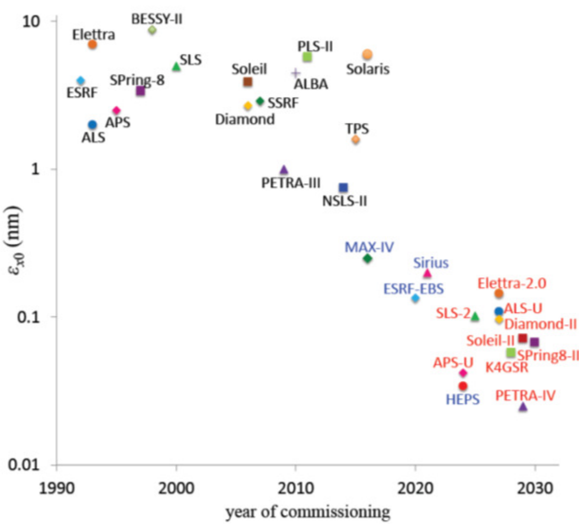

Figure 1: Overview of fourth generation synchrotron light source upgrades [4].

Figure 1 provides an overview of the evolution of synchrotron light sources where a common theme is the reduction in horizontal emittance of the electron beam. This is achieved through the utilisation of multibend achromat lattices, since the general trend (subject to lattice design constraints) is

$$\varepsilon_x \propto \frac{E}{N^3} \quad (1)$$

where ε_x is the horizontal emittance of the electron beam, E is the beam energy and N is the number of dipole (bending) magnets. Increasing the number of bending magnets, reduces the bending angle per unit-length to consequently reduce the equilibrium emittance [5].

The purpose of the ultra-low emittance is to maximise brilliance and coherence for user beamline experiments [3]. For diffraction-limited rings, the emission of synchrotron radiation from the electron beam is almost indistinguishable from that of a single electron (normalising for intensity). To deliver such high quality beams requires the operation of state-of-the-art diagnostics instrumentation and feedback systems. Readers are advised to refer to [6] for a comprehensive overview of beam diagnostics in ultra-low emittance storage rings. Here the main challenges for beam diagnostics are presented, with some insights into lessons learned and potential future directions already under investigation.

CHALLENGES FOR BEAM DIAGNOSTICS

Table 1 shows a comparison of typical parameters for third and fourth generation light sources [6] including the latest operational facilities such as MAX IV [7], SIRIUS [8], the ESRF-EBS [3] and HEPS [9]. Although beam energy and current remain largely unchanged, significant performance improvements are evident in the areas of emittance and beam stability.

Beam Stability

Beam Position Monitors (BPMs) using capacitive button pick-ups are paramount for beam control and have undergone a variety of designs in recent years for optimal performance [10]. For nominal beam conditions in fourth generation rings, the typical resolution and bandwidth requirements are < 50 nm RMS and ≥ 10 kHz respectively with approximately 100 kHz fast acquisition data rates for orbit feedback [6, 11]. The position drift due to BPM electronics including cables over both the short-term (<1 s) and long- term (1 s – 1 week) timescales must be minimal by design and mitigated using compensation schemes such as switching or pilot tone [12]. There has also been a steep rise in the number of BPMs distributed around the ring for improved sampling of the beam orbit.

There are a number of reasons for BPM upgrades not limited to fourth generation machines in addition to enhanced performance requirements, such as obsolescence, new capabilities and ensuring compatibility with other systems. Facilities must also decide whether to design BPMs (i.e. analogue signal conditioning, digitisation and post-processing) in-house or to procure commercially depending upon criteria such as performance specification, cost, manpower, expertise, volume, maintenance, platform form-factor and standardisation as well as attracting new talent. A survey of 22 hadron and electron facilities was conducted at the International Beam Instrumentation Conference 2023 (IBIC'23) with 60 % undertaking or planning BPM projects

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ISBN: 978-3-95450-247-9 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2024-FRXN1

Table 1: Comparison of Third and Fourth Generation Synchrotron Light Sources

Parameter		**3rd Gen. Light Source**	**4th Gen. Light Source**
Energy		≈ 1.5 – 6 GeV	≈ 2 – 6 GeV
Current		≈ 100 – 500 mA	≈ 200 – 400 mA
Horizontal Emittance		≈ 1000 – 10 000 pm rad	≈ 20 – 330 pm rad
Vertcal Emittance		≈ 3 – 10 pm rad	≈ 2 – 10 pm rad
Coupling		< 1 %	≈ 10 %
RMS Beam Size (h/v) at source point		≥ 100 µm / 10 µm	≈ 5 – 10 µm / ≈2 µm – 10 µm
Relative Short-term Beam Stability		10 % of beam size	2 – 3 % of beam size
Short-term Beam Stability	RMS Position	< 1000 nm	≈ 100 nm
	Frequency Range	0.01 – 300 Hz	0.01 – 1000 Hz
Long-term Beam Stability	RMS Position	≈ 1000 nm	≈ 1000 nm
	Time Period	day(s)	week

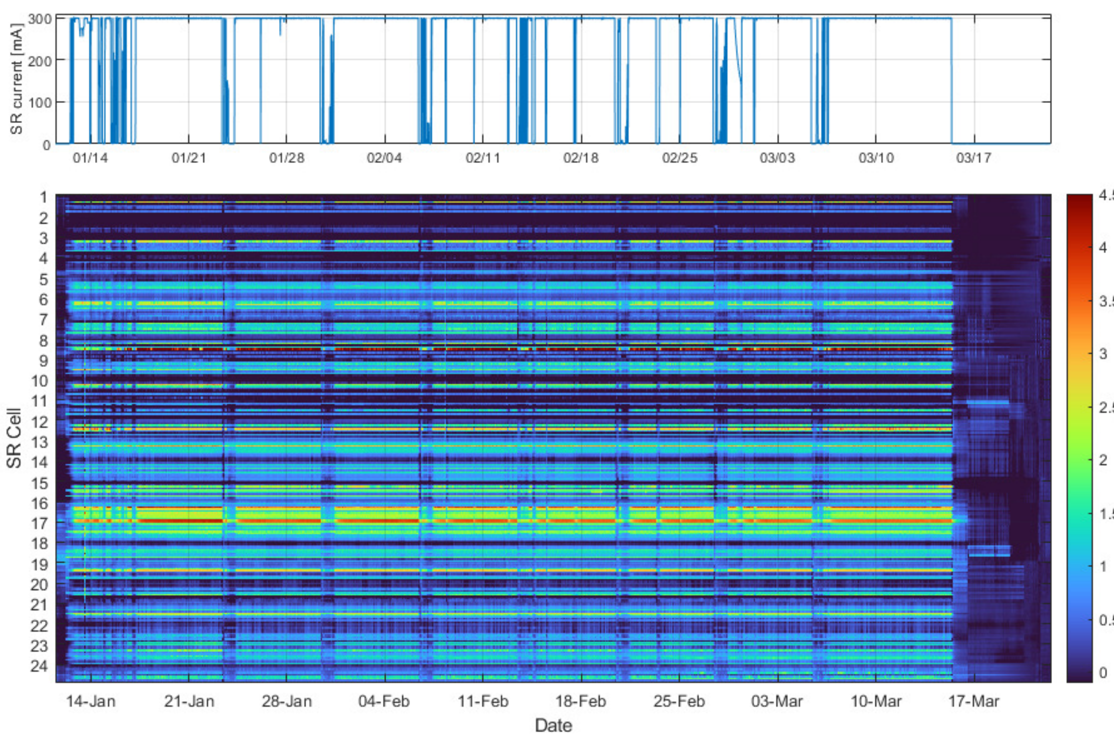

Figure 2: Storage ring air temperature monitoring in close proximity to the beam pipe over one user run at Diamond Light Source: (top) beam current and (bottom) measured absolute air temperature in degrees Celsius with subtraction of the average temperature for no beam for each cell [13].

in-house, 30 % opting for commercial solutions and 10 % unknown or undecided with differing architectures, compensation schemes and platforms (e.g. 19" rack modules, MicroTCA, VME etc.).

Lessons have been learned in relation to beam drift observed in the event of beam trips and the necessary stabilisation time for the accelerator to reach thermal equilibrium. This has highlighted the importance of environmental monitoring especially given that for optimal performance BPM compensation schemes require subsystems inside the tunnel near the beginning of the RF chain (downstream of the button pick-ups). At Diamond Light Source (DLS) it has been observed that whilst the tunnel air handling system controls the temperature around the ring to ±0.1 °C, larger air temperature variations are seen in close proximity to the girders. In preparation for Diamond-II [14], a temperature monitoring project was recently completed seeing the deployment of 262 girder-mounted air temperature sensors distributed every 2 m around the storage ring. Initial results from this system are presented in Fig. 2.

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Emittance

Synchrotron radiation at visible and X-ray wavelengths is often exploited for beam size and emittance measurement [15]. Due to their relative simplicity and robustness, X-ray pinhole cameras (XPC) are well established instruments for transverse beam profile monitors [16, 17]. Diffraction from the pinhole aperture is unavoidable, resulting in a minimum beam size resolution of approximately 5 µm at 25 keV photon energy. As shown in Table 1, this may be insufficient for nominal beam in fourth generation light sources or when the beam is squeezed during dedicated accelerator physics studies.

X-ray Fresnel Diffractometry (XFD) may offer an upgrade path to existing pinhole cameras to resolve micron-scale source sizes [18]. With a common geometry to the XPC, and only requiring the inclusion of a monochromator and slit it may be feasible to install an interchangeable XPC and XFD system.

Although light extraction is more challenging given mechanical constraints due to the reduction in beam pipe diameter in fourth generation machines, visible light diagnostics remain relevant [15]. Imaging using large orbital collection angles ($\Delta\theta_x \leq 15$ mrad, $\Delta\theta_y \leq 7$ mrad) at MAX IV has demonstrated sensitivity to emittance of a few pm rad [19]. Figure 3 shows the experimental setup using synchrotron emission from a bending magnet, planoconvex lens and camera [19].

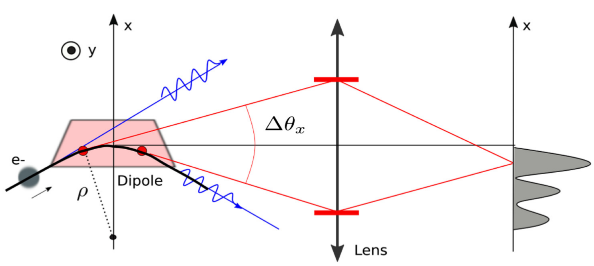

Figure 3: Experimental setup for imaging at large orbital collection angles [19].

POTENTIAL FUTURE DIRECTIONS

Diagnostics research is progressing to match the needs of advancing accelerators. A few areas where promising new diagnostics for a variety of machines, measurements and applications are highlighted in this section.

Novel Emittance Control

Emittance control in the vertical plane is typically achieved through the coupling of dispersion using skew quadrupoles. Beam enlargement can also be introduced by white noise excitation [20, 21]. An alternative method, using transverse multi-bunch feedback (TMBF) to excite the synchrotron sideband of the betatron tune has recently been demonstrated. This technique is based on the the Pulse-Picking by Resonant Excitation (PPRE) developed at BESSY-II [22] with the potential of emittance control in both horizontal and vertical planes as shown from initial tests at DLS [23].

The application of machine learning for optimisation, fault finding, beam control and virtual diagnostics is underway at many accelerator facilities [24]. Rather than a traditional emittance feedback system, source size stabilisation using a feed-forward (FF) neural network (NN) was demonstrated at the ALS. In Fig. 4 the rms vertical beam size variation ($\Delta\sigma_y$) with the FF off and on is 1.5 µm and 0.2 µm respectively [25].

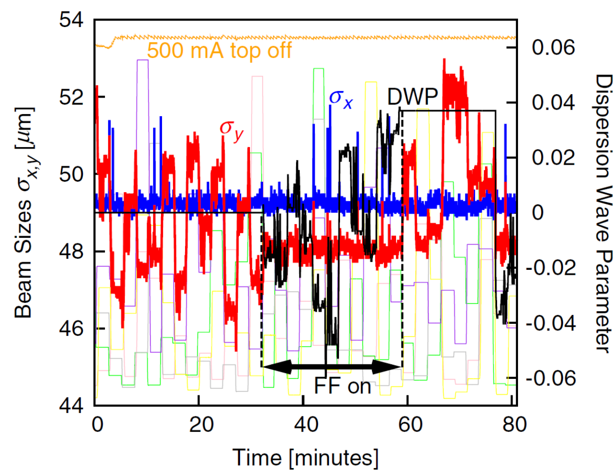

Figure 4: Demonstration of transverse beam size control at ALS using a feed-forward neural network [25].

Chemical Vapour Deposition Diamond

Chemical Vapour Deposition (CVD) diamond has a range of applications within diagnostics instrumentation due to its unique properties of extremely high thermal conductivity, high charge carrier mobility and broad band optical transparency [26]. To address the challenge of in-vacuum mirror deformation for visible light extraction CVD diamond has been tested as a suitable substrate at SuperKEKB [27]. For monochromatic X-ray BPMs pixelated diamond detectors have been developed using surface electrodes and embedded graphitic wires [28]. In addition to photon beams, diamond based sensors have been utilised for charged particle beam diagnostics such as beam loss monitors and dosimeters as tested on the FERMI free electron laser using electron bunches with energy up to 1.5 GeV, 35 pC, sub-picosecond duration, and transverse size down to approximately 0.1 mm [29].

Cherenkov Diffraction Radiation

Cherenkov Diffraction Radiation (ChDR) is emitted when a charged particle moves in the vicinity of a dielectric medium. The properties of coherent and incoherent ChDR have shown sensitivity to a variety of beam parameters making it a promising candidate for exploitation in future beam diagnostics. Particularly interesting applications include the use of ChDR for beam position monitoring using button pick-

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ups (see Fig. 5), and the discrimination of co-propagating electron and proton beams for AWAKE [30].

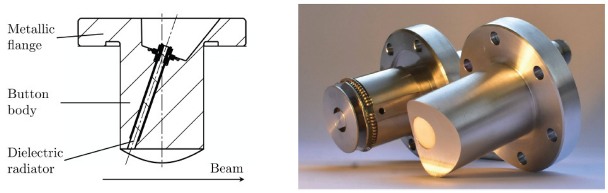

Figure 5: ChDR button: (left) cross-section schematic and (right) a photograph of a ChDR button (front) compared to a capacitive button pick-up (back) [30].

CONCLUSIONS

This paper provides an overview of diagnostics challenges, lessons learned and potential future directions for advancing accelerators. Detailed discussion on the challenges of beam diagnostics for beam stability and emittance for fourth generation synchrotron light sources is presented. Considerations such as in-house development projects for new diagnostics compared to procurement of existing solutions is discussed. Future directions not limited to light source applications are shown considering measurement techniques and methodologies, and materials.

REFERENCES

[1] Henry N. Chapman, "Fourth-generation light sources", *IUCrJ*, vol. 10, no. Pt 3, p. 246, May 2023. doi:10.1107/S2052252523003585

[2] Seunghwan Shin, "New era of synchrotron radiation: fourth-generation storage ring", *AAPPS Bulletin*, vol. 31, no. 1, 2021. doi:10.1007/s43673-021-00021-4

[3] Pantaleo Raimondi *et al.*, "The Extremely Brilliant Source storage ring of the European Synchrotron Radiation Facility", *Communications Physics*, vol. 6, no. 1, pp. 1–11, 2023. doi:10.1038/s42005-023-01195-z

[4] Victor Smaluk and Timur Shaftan, "Electron beam emittance at operational intensity in fourth-generation synchrotron light sources", *arXiv*, 2024. doi:10.48550/arXiv.2402.05204

[5] Alexander Wu Chao, Karl Hubert Mess, Maury Tigner, and Frank Zimmermann, "Handbook of accelerator physics and engineering, second edition". World Scientific Publishing Co., Jan. 2013, pp. 1–830. doi:10.1142/8543

[6] V. Schlott, "Beam Diagnostics for Ultra-Low Emittance Storage Rings", *67th ICFA Advanced Beam Dynamics Workshop on Future Light Sources, Luzerne, Switzerland*, 2023.

[7] MAX IV Detailed Design Report, https://www.maxiv.lu.se/beamlines-accelerators/accelerators/accelerator-documentation-2/,

[8] L. Liu, R. T. Neuenschwander, and A. R.D. Rodrigues, "Synchrotron radiation sources in Brazil", *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, vol. 377, no. 2147, 2019. doi:10.1098/rsta.2018.0235

[9] Yi Jiao *et al.*, "The HEPS project", *Journal of Synchrotron Radiation*, vol. 25, no. Pt 6, p. 1611, Nov. 2018. doi:10.1107/S1600577518012110

[10] Stefano Cleva *et al.*, "Button-Type Beam Position Monitor Development for Fourth-Generation Synchrotron Light Sources: Numerical Modeling and Test Bench Measurements", *Sensors*, vol. 24, no. 9, 2024. doi:10.3390/s24092726

[11] I. Kempf, M.G. Abbott, L. Bobb, G.B. Christian, S. Duncan, and G. Rehm, "Fast Orbit Feedback for Diamond-II", in *Proc. 12th Int. Beam Instrum. Conf. (IBIC'23)*, Saskatoon, Canada, Sep. 2023, pp. 1–6. doi:10.18429/JACoW-IBIC2023-MO2I02

[12] G. Rehm, "Review of BPM Drift Effects and Compensation Schemes", presented at the IBIC'22, Kraków, Poland, Dec. 2022, paper MO3I1, unpublished.

[13] C. Bloomer, "Storage Ring Air Temperature Monitoring at Diamond Light Source", unpublished.

[14] Diamond-II Technical Design Report, https://www.diamond.ac.uk/Home/News/LatestNews/2022/14-10-22.html,

[15] N. Samadi, X. Shi, L. Dallin, and D. Chapman, "Source size measurement options for low-emittance light sources", *Physical Review Accelerators and Beams*, vol. 23, no. 2, p. 024801, Feb. 2020. doi:10.1103/PhysRevAccelBeams.23.024801

[16] P Elleaume, C Fortgang, C Penel, and E Tarazona, "Measuring Beam Sizes and Ultra-Small Electron Emittances Using an X-ray Pinhole Camera.", *Journal of synchrotron radiation*, vol. 2, no. Pt 5, pp. 209–14, Oct. 1995. doi:10.1107/S0909049595008685

[17] Cyrille Thomas, Guenther Rehm, Ian Martin, and Riccardo Bartolini, "X-ray pinhole camera resolution and emittance measurement", *Physical Review Special Topics - Accelerators and Beams*, vol. 13, no. 2, p. 022805, Feb. 2010. doi:10.1103/PhysRevSTAB.13.022805

[18] Mitsuhiro Masaki, Shiro Takano, Masaru Takao, and Yoshito Shimosaki, "X-ray Fresnel diffractometry for ultralow emittance diagnostics of next generation synchrotron light sources", *Physical Review Special Topics - Accelerators and Beams*, vol. 18, no. 4, p. 042802, Apr. 2015. doi:10.1103/PhysRevSTAB.18.042802

ISBN: 978-3-95450-247-9 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2024-FRXN1

[19] M. Labat, O. Chubar, J. Breunlin, N. Hubert, and Å. Andersson, "Bending Magnet Synchrotron Radiation Imaging with Large Orbital Collection Angles", *Physical Review Letters*, vol. 131, no. 18, p. 185001, Nov. 2023. doi:10.1103/PhysRevLett.131.185001

[20] P. L. Morton, "Artificial Beam Enlargement", in *Proc. PAC'73*, San Francisco, CA, USA, June 1973, pp. 862–863.

[21] A. Franchi *et al.*, "Vertical emittance reduction and preservation in electron storage rings via resonance driving terms correction", *Phys. Rev. ST Accel. Beams*, vol. 14, no. 3, p. 034002, Mar. 2011. doi:10.1103/PhysRevSTAB.14.034002

[22] "Single bunch X-ray pulses on demand from a multi-bunch synchrotron radiation source", *Nature Communications*, vol. 5, no. 1, p. 4010, 2014. doi:10.1038/ncomms5010

[23] S. Preston, L. Bobb, A. F. D. Morgan, and T. Olsson, "Measurements for Emittance Feedback based on Resonant Excitation at Diamond Light Source", in *Proc. IBIC'22*, Kraków, Poland, Dec. 2022, pp. 492–495. doi:10.18429/JACoW-IBIC2022-WEP37

[24] E. Fol, J.M. Coello de Portugal, and R. Tomás, "Application of Machine Learning to Beam Diagnostics", in *Proc. 7th International Beam Instrumentation Conference (IBIC'18), Shanghai, China, 09-13 September 2018*, Shanghai, China, Jan. 2019, pp. 169–176. doi:10.18429/JACoW-IBIC2018-TUOA02

[25] S. C. Leemann *et al.*, "Demonstration of Machine Learning-Based Model-Independent Stabilization of Source Properties in Synchrotron Light Sources", *Physical Review Letters*, vol. 123, no. 19, p. 194801, Nov. 2019. doi:10.1103/PhysRevLett.123.194801

[26] Diamond Materials, CVD diamond booklet, https://www.diamond-materials.com/site/assets/files/1095/cvd_diamond_booklet.pdf,

[27] J W Flanagan *et al.*, "Thermal Performance of Diamond SR Extraction Mirrors for SuperKEKB", in *Proc. 8th Int. Beam Instrumentation Conf. (IBIC'19)*, 2019, pp. 332–335. doi:10.18429/JACoW-IBIC2019-TUPP017

[28] C. Bloomer, M. E. Newton, G. Rehm, and P. S. Salter, "A single-crystal diamond X-ray pixel detector with embedded graphitic electrodes", *Journal of Synchrotron Radiation*, vol. 27, no. 3, pp. 599–607, May 2020. doi:10.1107/S160057752000140X

[29] S. Bassanese *et al.*, "Diamond detectors' response to intense high-energy electron pulses", *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, vol. 1047, p. 167801, Feb. 2023. doi:10.1016/J.NIMA.2022.167801

[30] E. Senes *et al.*, "Beam Position Detection of a Short Electron Bunch in Presence of a Longer and More Intense Proton Bunch for the AWAKE Experiment", in *Proc. IBIC'21*, Pohang, Korea, Nov. 2021, pp. 75–79. doi:10.18429/JACoW-IBIC2021-MOPP17