ISBN: 978-3-95450-249-3 ISSN: 2673-5350 doi: 10.18429/JACoW-IBIC2024-TUBI2

DESIGN OF HEPS BEAM DIAGNOSTICS*

Yanfeng Sui[1,†], Jun He, Dechong Zhu, Lingda Yu, Yaoyao Du, Taoguang Xu, Ying Zhao, Qiang Ye, Zhi Liu, Huizhou Ma, Xiaoyu Liu, Lin Wang, Wan Zhang, Shujun Wei, Fangqi Huang, Yanhua Lu, Fang Liu, Junhui Yue, Jianshe Cao[1]
Institute of High Energy Physics, Chinese Academy of Sciences, Beijing, China
[1]also at University of Chinese Academy of Sciences, Beijing, China

Abstract

High Energy Photon Source (HEPS) is a fourth-generation light source with a natural emittance of 34.82 pm, aiming to produce high-brilliance photon beams. The ultra-low emittance poses challenges for beam instrumentation, requiring high-resolution beam position and size measurements in the sub-micrometer range. The high current and multi-bunch operation necessitate a bunch-by-bunch feedback system to address beam instabilities. This paper will provide an overview of the beam instrumentation at HEPS.

INTRODUCTION

HEPS is the first fourth-generation synchrotron light source in China, located in Beijing. The HEPS project aims to establish a high-performance high-energy synchrotron light source with a beam energy of 6 GeV, and beam current of 200 mA, offering a radiation brightness potential of up to 1×10^{22} [photons$\cdot$ s^{-1} $\cdot$ mm^{-2} $\cdot$ mrad^{-2} $\cdot$(0.1% bw)$^{-1}$] in the typical hard X-ray regime [1]. The facility includes a 500 MeV S-band linac, a ramping booster spanning 0.5-6 GeV, transport lines, and a 6 GeV storage ring equipped with state-of-the-art beam instrumentation and diagnostics systems. The HEPS storage ring comprises 48 7BA cells grouped into 24 super-periods, with a circumference of 1360.4 m. The key beam parameters for the storage ring are detailed in Table 1.

Table 1: HEPS Storage Ring Parameters [2]

Parameters	**Value**
Energy	6.0 GeV
Circumference	1360.4 m
Main RF frequency	166.6 MHz
Harmonic cavity frequency	499.8 MHz
Harmonic number of main RF	756
Natural emittance	34.82 pm
Bunch Length	5.02 mm
Working point(x/y)	114.14/ 106.23
Bunch length (zero current)	5.02 / 29.70 (HC)
Damping time (x/y/z)	10.2 / 18.9 / 16.4 ms
Beam current	200 mA
Synchrotron frequency	$\sim 1.1 \times 10^{-3}$

In order to fully utilize the advantages of HEPS, such as high energy, high brightness, and small beam sizes, it is crucial that the photon beams remain extremely stable in both position and angle, with deviations ideally not exceeding 10% of the beam sizes and divergence. In the low beta section, where the beam size is approximately 3 µm in the vertical direction, users expect the orbit change to stay within 10% of the beam size itself (0.3 µm). To meet this requirement, the resolution of the beam position monitor should be better than 0.1 µm. Additionally, we require additional instrumentation to meet the requirements. The beam instrumentation to be installed at HEPS is detailed in Table 2.

Table 2: Beam Instrumentation in HEPS

Beam instrumentations	Linac	LB	BST	BR	RB	SR
BPM	8	8	80	11	13	578+24
ICT	7	2	-	2	2	-
NPCT	-	-	2	-	-	2
Bunch Current Monitor	-	-	1	-	-	1
OTR/YAG	7	2	-	2	2	-
Synchrotron Light Monitor	-	-	2	-	-	2
Tune measurement	-	-	1	-	-	1
Beam loss monitor	-	-	4	-	-	500
B&B feedback system	-	-	3	-	-	3
Streak camera	-	-	-	-	-	1
Bunch cleaning system	-	-	-	-	-	1
Energy analyse station	2					
Emittance	2					

INJECTION DIAGNOSTICS

The HEPS injector comprises a linear accelerator (Linac), a low-energy transport line (LB), two high-energy transport lines (RB & BR), and a booster (BST). Beam diagnostics within the injector are essential for monitoring the beam status and enhancing injection efficiency.

Linac

The linac beam instrumentation includes 6 integrating current transformers (ICT) for monitoring the total bunch train charge. During routine operations, the beam trajectory

* Work supported by NSFC No.12475167.
† syf@ihep.ac.cn

ISBN: 978-3-95450-249-3 ISSN: 2673-5350 doi: 10.18429/JACoW-IBIC2024-TUBI2

will be monitored using 8 beam position monitors, with 1 button-type and 7 strip-line type. Two screens (OTR/YAG) will be used for measuring beam emittance and energy spread at the exit of the first accelerator unit and the end of the linac. The other 4 screens are utilized for beam profile monitoring. The screens are constructed of YAG:Ce material, known for its excellent resolution of the beam image, high sensitivity, and high radiation hardness. However, in the high-energy section of the linac, Optical Transition Radiation (OTR) screens are installed to prevent YAG target saturation. Linac diagnostics are summarized in Table 2.

Booster

The circumference of the booster is approximately 454 m, allowing the beam energy to be ramped up from 0.5 GeV to 6 GeV. The booster orbit will be monitored using 80 Beam Position Monitors (BPMs) equipped with turn-by-turn capability. The BPM electronics will be aligned with those used in the storage ring to simplify maintenance procedures. The sum signal from the electronics can be used to monitor the beam current.

The average current will be measured using a commercially available radiation-hardened New Parametric Current Transformer (NPCT), while the bunch pattern will be monitored using BPM pickups and bunch-by-bunch electronics developed in-house. For tune measurement, the electron beam will be excited with white noise using stripline kickers. The beam response will be observed with a real-time spectrum analyzer connected to dedicated BPM buttons at the front end. Synchrotron radiation from a dipole will be employed to observe the beam during ramping and emittance measurements. There are two visible beamlines in the booster. Additionally, the capability to monitor bunch length with a streak camera will be provided [3].

Transfer Lines

There are three beam transfer lines in HEPS, named "LB", "BR", and "RB". They are utilized to transport electron beams from the LINAC to the booster (LB), from the booster to the storage ring (BR), and from the storage ring to the booster (RB), respectively. The primary purpose of the high-energy beam transfer line "RB" is to employ the booster as a high-energy accumulator [2].

The diagnostics for the transfer lines consist of Beam Position Monitors (BPMs) for measuring beam position, fluorescent screens for providing information on beam size, and Integrating Current Transformers (ICT) for measuring beam charge at various locations and determining the efficiency of the transfer line. Scintillation beam loss detectors are utilized to monitor beam loss along the beamline during injection and extraction commissioning.

STORAGE RING DIAGNOSTICS

Current Monitors

A high-precision DC current measurement will be achieved by utilizing a commercially available radiation-hardened new parametric current transformer (NPCT) from Bergoz. The NPCT device offers a resolution of better than 0.5 μArms/√Hz and features a large dynamic range and bandwidth, making it a versatile tool for measuring lifetime and injection efficiency with the integrating current transformers at the transfer line. Two sets of NPCT are installed in the HEPS storage ring for redundancy purposes.

A bunch current monitor with fast ADC sampling BPM sum signal is utilized to measure the bunch current and share the data with the injection control system for bucket selection.

Beam Position Monitors

To monitor changes in the beam orbit throughout the entire ring, each 7BA unit must be equipped with 12 BPMs, with black dots representing the BPM locations as shown in Fig. 1. Additionally, two BPMs is positioned at the injection and extraction points separately. HEPS will accommodate a total of 578 BPMs, with 24 sets of spare BPM blocks available for bunch-by-bunch feedback, bunch current monitoring, machine studies, and other potential applications. Due to the shape of the vacuum chamber, the BPM blocks are designed with three different geometries. There are 10 BPMs (1st to 7th, 10th to 12th) with a circular cross-section having a diameter of 22 mm, and two BPMs (8th and 9th) featuring a light-guiding slit. Figure 2 illustrates a schematic of a BPM with a synchrotron light-guiding slit [4].

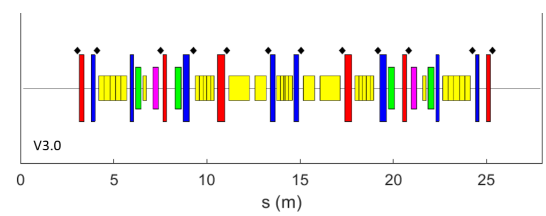

Figure 1: Layout diagram of BPM in a 7BA unit of the storage ring.

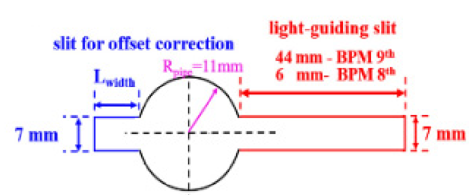

Figure 2: The cross-section of BPM with light-guiding.

The BPM support shown in Fig. 3 made from carbon fiber and Invar composite. Natural frequency of the bracket is over 55 Hz with concrete pouring. Carbon fibre square tube can have thermal coefficient -1.0E-6/K. Super Invar Alloy can have thermal coefficient 0.63E-6/K [5]. With tunnel temperature controlled to 0.1℃, the BPM stand with 1.2 meter will have a thermal expansion smaller than ±20 nm.

ISBN: 978-3-95450-249-3 ISSN: 2673-5350 doi: 10.18429/JACoW-IBIC2024-TUBI2

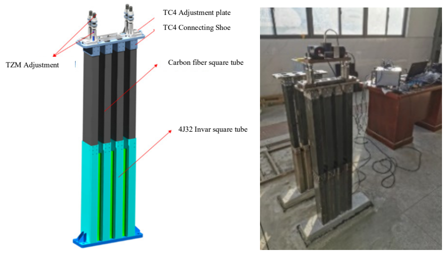

Figure 3: Carbon fiber and Invar composite bracket for BPM.

All Beam Position Monitors (BPMs) will be utilized during machine operation for slow orbit acquisition and orbit correction. Home-made BPM electronics will provide 220 kHz turn-by-turn data for fast diagnostics, 22 kHz data transferring from an independent network for the Fast Orbit Feedback, and 10 Hz data for slow orbit correction. Additionally, all BPMs will serve machine interlock purposes. During the initial commissioning phase, all BPM electronics can acquire 256 turns of turn-by-turn data and will be used for beam orbit correction.

After installing the BPM blocks, the button-to-button transmission will be measured using the Lamberson method to estimate the offset caused by variations in button sensitivity. The same measurement will be carried out after the installation and bake-out process is completed to verify the performance of each block [6]. A correction factor will be applied to the signals of each button to compensate for their sensitivity.

The alignment group will provide a measurement of the mechanical offset of each BPM, which will be used to correct the beam position during the commissioning phase. The final BPM offset will be determined through beam-based alignment once there is adequate beam current and beam lifetime in the storage ring.

Beam Loss Monitor

The Beam Loss Monitor (BLM) system consists of 192 photomultiplier-scintillator based Beam Loss monitors, with 4 monitors per cell, powered and controlled by 48 self-developed electronics based on open hardware RedPitaya. The BLMs are calibrated relative to each other, but they cannot measure absolute dose. The system can provide information on fast losses. During injection when more losses occur, and the signal is integrated over 1 turn, similar to the turn-by-turn (TBT) data of the BPM. During the initial commissioning phase, the electronics can provide 30 turns of TBT beam loss data, which will be valuable for identifying any potential issues that may arise during this period.

Tune Measurement

The working point measurement system consists of a button-type beam position probe, a 180º high-frequency hybrid, a mixer, a strip electrode exciter, a power amplifier, and a spectrum analyzer. The system extracts the differential signal containing the horizontal and vertical beam position information using a 180º hybrid. This signal is then filtered and amplified by a bandpass filter and amplifier before being sent to the mixer to mix with the ring RF signal. After filtering by a low-pass filter, the signal is sent to the spectrum analyzer, allowing the measurement of the transverse oscillation signal of the beam. The sweeping signal generated by the signal generator is amplified by the power amplifier and then applied to the strip line kicker to provide transverse excitation to the beam.

Synchrotron Radiation Based Beam Diagnostics

At HEPS, there are two beam diagnostic beamlines for measuring transverse beam sizes and longitudinal bunch length. Both beamlines utilize the first dipoles after the straight sections as their source points, located at the sectors of injection or RF to avoid interference with ID beamlines. The X-ray diagnostic beamline (XBL) is specifically designed for capturing beam images and measuring beam sizes using X-ray pinhole and KB mirror imaging. Figure 4 is the layout of XBL. A streak camera (SC) is employed at the visible light diagnostic beamline (VBL) for bunch length measurements.

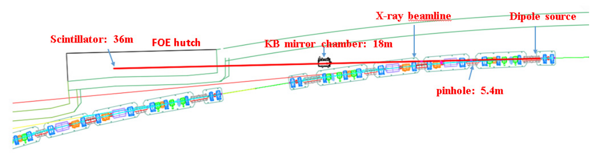

Figure 4: Schematic diagram of X ray diagnostic beamline.

Bunch by Bunch Feedback

HEPS operates in a high-intensity, multi-bunch mode, which can lead to instability of coupled bunches. The main sources of impedance causing these instabilities are the high-order modes generated by the high-frequency cavities and the wall impedances of the beam pipes. High-order modes and wall impedances can result in severe transverse instabilities of the beam, leading to reduced beam lifetime and even causing the beam intensity threshold. Therefore, a feedback system is needed to suppress the instability of the coupled bunches.

HEPS will use bunch-by-bunch digital feedback systems to suppress transverse coupled bunch instabilities. A typical bunch-by-bunch digital feedback system consists of three main parts: the bunch oscillation signal detection section, the digital signal processing section, and the power amplifier and kicker section. Three sets of beam feedback systems will be installed for the suppression of horizontal, vertical, and longitudinal instabilities.

REFERENCES

[1] Y. Jiao *et al.*, "The HEPS project", *J. Synchrotron Radiat.*, vol. 25, no. 6, pp. 1611-1618, 2018. doi:10.1107/S1600577518012110

[2] H. Xu, C. Meng, Y. Peng, *et al.*, "Equilibrium electron beam parameters of the High Energy Photon Source", *Radiat. Detect. Technol. Methods*, vol. 7, no. 2, pp. 279-287, 2023. doi:10.1007/s41605-022-00374-w

[3] D. Zhu *et al.*, "Design of High Energy Photon Source Booster beam size monitor", *High Power Laser and Particle Beams*,

ISBN: 978-3-95450-249-3 ISSN: 2673-5350 doi: 10.18429/JACoW-IBIC2024-TUBI2

vol. 33, p. 044005, 2021.
doi:10.11884/HPLPB202133.200268

[4] J. He *et al.*, "Beam position monitor design for the High Energy Photon Source", *Meas. Sci. Technol.* vol. 33, p. 115106, 2022. doi:10.1088/1361-6501/ac8277

[5] W. Anxin *et al.*, "Structural optimization design for beam position monitor support of High Energy Photon Source", *High Power Laser and Particle Beams*, vol. 33, p. 044006, 2021. doi:10.11884/HPLPB202133.200297

[6] J. He *et al.*, "Design and fabrication of button-style beam position monitors for the HEPS synchrotron light facility", *Nucl. Sci. Tech.* vol. 33, p. 141, 2022. doi:10.1007/s41365-022-01126-7