

# OVERVIEW OF BEAM INSTRUMENTATION AND DIAGNOSTICS FOR THE NSLS-II PROJECT\*

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## Abstract

A new, ultra-bright 3rd generation light source, the NSLS-II Project, is planned to be built at Brookhaven National Laboratory. The light source being developed will have unprecedentedly small beam horizontal emittance and will provide the radiation sources with a brightness of  $3 \times 10^{21}$  photons/sec/0.1%BW/mm<sup>2</sup>/mrad<sup>2</sup>. In this paper we present the detailed specifications and a comprehensive description of the planned beam instrumentation system and the first results of the ongoing instrumentation R&D activities on beyond state-of-the-art subsystems.

## INTRODUCTION

The NSLS-II project will be a state-of-the-art synchrotron radiation facility [1,2] featuring ultra-high photon brightness with extremely low emittance. It consists of a 170–270 MeV S-band linac, 0.2–3 GeV ramping booster, transport lines and 3 GeV storage ring [3,4,5] with the latest available beam instrumentation and diagnostics systems. The storage ring consists of 15 identical superperiods, each consisting of two mirror symmetric DBA cells. There are alternating ID straights of 8.6-m long with high horizontal  $\beta$  for injection, RF, damping wigglers (DW), and high flux user ID's; and 6.6-m long with low  $\beta$  for narrow gap ID's for high brightness X-ray beams. Top-off injection once per minute will be necessary to maintain the stored beam current at  $500 \pm 5$  mA. The main beam diagnostics related parameters for the storage ring are shown below in Table 1.

Table 1: NSLS-II Storage Ring Parameters

Parameter	Nominal Value
Energy	3.0 GeV
Circumference	792 m
RF frequency	499.68 MHz
Harmonic number	1320
Revolution period, $T_0$	2.642 $\mu$ s
Number of bunches filled	1056 (~80%)
Tunes - $Q_x, Q_y$	32.42, 15.15
Emittance Bare Lattice $\epsilon_0$ (H/V)	2.05/0.01 nm-rad
Emittance with 8-DWs $\epsilon$ (H/V)	0.51/0.008 nm-rad
Bunch length, rms natural	2.9 mm; 10 ps
$\beta$ -function at 8.6m ID ( $\beta_x, \beta_y$ )	20/3.0 m
$\beta$ -function at 6.6m ID ( $\beta_x, \beta_y$ )	2.0/1.3 m
X,Y,E Damping times at 3 GeV	5.4/5.1/2.5 ms
Synchrotron frequency, $f_s$	3.0-3.6 kHz

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To realize the benefits of the high brightness and small sizes of NSLS-II sources, photon beams must be exceedingly stable both in position and angle to the level of better than 10% of beam sizes and divergence. Table 2 provides the electron beam sizes and angular divergences for selected NSLS-II sources.

Table 2: The Electron Beam Sizes and Divergence

Types of source	8.6m ID	6.6m ID	Bend magnet	1-T 3-Pole wiggler
$\sigma_x$ ( $\mu$ m)	108	29.6	44.2	175
$\sigma_{x'}$ ( $\mu$ rad)	4.6	16.9	63.1	14
$\sigma_y$ ( $\mu$ m)	4.8	3.1	15.7	12.4
$\sigma_{y'}$ ( $\mu$ rad)	1.7	2.6	0.63	0.62

The most stringent beam measurement and stability requirement will be for the vertical position at the short ID source ( $\sigma_y=3.1 \mu$ m); this will require special consideration for measuring both electron and photon beams. Instrumentation requirements for measurements are further discussed in the storage ring section.

## INJECTION DIAGNOSTICS

The diagnostics for the injection system will be procured with the subsystems with exception of beam transfer lines. The specifications for the required instrumentation will be provided for vendors by NSLS-II project team.

### Linac

The linac beam instrumentation comprises two integrating current transformers for monitoring total bunch train charge and one fast current transformer (FCT) to monitor the distribution of charge. In routine operations, the beam trajectory will be monitored with three monopulse beam position monitors. Fluorescent screens will complement beam position monitoring during studies periods and for measuring beam emittance and energy spread at the linac exit. Wall current monitors formed by equally spaced broadband ceramic resistors mounted on a flexible circuit board, wrapped around a short ceramic break, will also give information on beam charge as well as longitudinal profiles of electron bunches. Linac diagnostics are summarized in Table 3.

### Booster

The following booster beam parameters will be monitored:

- orbit,
- working point (tunes),
- circulating current and filling pattern,
- emittances for both planes,
- bunch length.

Table 3: Linac Diagnostics

System	Quantity	Monitor type	Beam parameter
Electron source	3	Wall current monitor	intensity, longitudinal beam characteristics
Linac	3	Fluorescent screen	position, profile
	2	Current transformer	intensity

Booster instrumentation is summarized in Table 4.

Six fluorescent screens will be installed to facilitate booster commissioning and troubleshooting. The screen material will be YAG:Ce, which has excellent resolution of the beam image and exhibits high sensitivity and high radiation hardness. Booster orbit will be monitored with 20 BPMs with turn-by-turn capability. The BPM receivers will be the same as in the storage ring, to simplify maintenance. The sum signal from the receivers can be used to monitor fast history of the beam current.

Table 4: Beam Instrumentation for the Booster Ring

Monitor	Quantity	Beam parameter
DC current transformer	1	Beam current
4-button pick-ups	20	Beam position, beam current
Fluorescent screens	6	Injection position, beam profile
Set of striplines and amplifier	2	Betatron tunes, bunch cleaning system
Fast current transformer	1	Filling pattern
Optical beamline with streak-camera	1	Bunch length
Firewire camera	1	Beam position, profile (emittances)

Circulating current will be measured with DCCT installed over ceramic break in the vacuum chamber, while bunch pattern will be monitored with a fast current transformer. For tune measurement, the electron beam will be excited with white noise using striplines. The beam response will be observed with a real-time spectrum analyzer connected to the dedicated BPM buttons with the front end. There will be an extra set of striplines for a bunch cleaning system, for users who need a specific fill pattern in the storage ring.

Synchrotron radiation from a dipole will be used to observe the beam during ramp and emittance measurements. The capability to monitor bunch length with a streak-camera will be also provided.

### Transfer lines

Transfer line diagnostics will consist of monopulse BPMs for measuring beam position in the top-up mode,

and fluorescent screens, which will provide information on beam position and size. After the septum in the storage ring injection straight there will be a screen with two active positions. At the first position the beam will be intercepted immediately after the septum. In the second position beam will be observed after the first turn. During regular operation this screen will be fully retracted. Integrating current transformers will provide information on beam charge at different locations and hence on the beam losses during the injection cycle.

## STORAGE RING DIAGNOSTICS

### RF Diagnostics

The beam diagnostics system is designed to provide a complete characterization of the beam and the accelerator system, including beam closed orbit, size, tune, circulating current, fill pattern, lifetime, chromaticity, beam loss pattern, beam density distribution, emittance, and bunch length. A large number of beam monitors/drivers and beam loss monitors will be installed on the storage ring. The types and quantities of these devices are given in Table 5.

Table 5: NSLS-II SR Particle Beam Monitors (total number of cells = 30)

#	Beam Monitors/ Drivers	Quantity
1	DC Current Transformer	1
2	Fast Current Transformer	1
3	4-button pick ups	6 to 9 per cell
4	Stripline Monitors	2 sets 1 set = 4 electrodes
5	Stripline Drivers	2 sets – 1 set = 4 electrodes
6	PIN Diode Type Loss Monitors	2 per cell
7	Scintillation Loss Monitors	10
8	Scrapers	2 sets per plane 1 set = 2 blades

**Circulating current DC measurement** – A high-precision DC current measurement will be provided by using a commercially available radiation-hardened new parametric current transformer (NPCT). The NPCT device provides a resolution of better than  $1\mu\text{A}/\sqrt{\text{Hz}}$  and has large dynamic range/ bandwidth, making it a versatile device for measuring lifetime and injection efficiency. Such a small noise will allow measurement of the expected 60 hours lifetime for 25 mA circulating in 1 minute with 2% accuracy (assuming a 1 Hz update rate).

**Filling pattern measurement** – A high-speed current transformer (FCT) will provide electrical signal proportional to the charge of individual bunches (bandwidth  $>1.75\text{ GHz}$  and rise time  $<200\text{ ps}$ ). A fast ADC digitizer, sampling at RF or a multiple of RF frequency, will enable measurement of the fill charge distribution of each bunch. This information is critical for top-up operation to smooth out the fill pattern as much as possible.

**Beam position monitors** – Fig. 1 provides a layout of one cell, showing RF and X-ray beam position monitors and magnets. Each cell will have six standard RF BPMs mounted on elliptical chambers, up to three user RF BPMs located in the ID straight section; and up to two X-ray photon BPMs per beamline. The number of user RF and X-ray BPMs will be determined by the type of beamline. For example, a canted beamline will require three user RF BPMs.

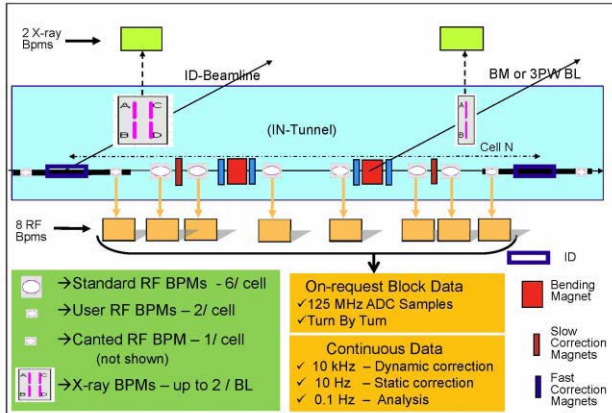


Fig 1: Layout of RF and X-ray BPMs and magnets in a storage ring cell

To achieve the highest level of orbit measurement resolution, the optimization of the button geometry for both standard and user BPMs is in progress [6]. The four high-precision pick-up electrodes will be mounted on elliptical or small-gap chambers with optimized button diameter size and geometry locations. Although, the vertical separation of buttons is pretty much defined by chamber vertical apertures, the horizontal separation of buttons will be optimized to obtain a high level of BPM resolution. The Table 6 provides sensitivities results with three cases of buttons' horizontal separation for elliptical

chamber. Case 1, with 32 mm horizontal separation, can be achieved by using a commercially available 34-mm flange, but this results in the worst vertical sensitivity ( $0.04 \text{ mm}^{-1}$ ). As horizontal separation is reduced to 10 mm (case 3), vertical sensitivity improves three fold; however to achieve this separation, either BPM buttons mounted on 34 mm flanges have to be mounted longitudinally or custom flange, housing two buttons, needs to be developed. Other effects such as linearity and operational range will be further explored. Case 2, 18 mm of horizontal separation, may be an acceptable solution with two-fold improvement in vertical sensitivity. Although horizontal sensitivity reduces as horizontal separation reduces, the resolution requirement is less stringent in this plane.

Table 6: Sensitivities ( $\Delta/\Sigma$ ) vs. Horizontal Separation (Button Diameter=10mm; Vertical Separation = 25mm)

#	Buttons Horizontal Separation	Vertical $\Delta/\Sigma, \text{mm}^{-1}$	Horizontal $\Delta/\Sigma, \text{mm}^{-1}$
1	32 mm	0.04	0.12
2	18 mm	0.08	0.10
3	10 mm	0.12	0.06

The user BPMs will be located in the ID straight section and will require high mechanical and thermal stability. This is discussed further in the R&D section.

Commercially available, fast digital design based BPM electronics are being considered to meet various requirements and provides outputs such as 1) 125 MHz block and turn-by-turn block data for fast diagnostics, 2) 10 kHz data for fast orbit feedback, 3) 10 Hz data for slow orbit correction and 4) 0.1 Hz data for analysis and logging (shown in Fig 1). Table 7 gives a comprehensive position measurement resolution requirement within several time scales and intensity levels for standard BPM. The requirements for 100 mA to 500 mA are further subdivided, based on electronics and mechanical effects, so that there is a budget for each kind of effect. The

Table 7: Position Measurement Resolution Requirements

Parameters/Subsystems			Conditions	Standard BPM System Requirements		
				Vertical	Horizontal	
Single bunch, single turn resolution (@378 kHz)			0.05 nC charge	500 $\mu\text{m}$ rms	500 $\mu\text{m}$ rms	
			5.0 nC charge	20 $\mu\text{m}$ rms	20 $\mu\text{m}$ rms	
Single bunch, stored beam resolution (0.017-200 Hz BW)			0.02 mA	10 $\mu\text{m}$ rms	10 $\mu\text{m}$ rms	
			2.0 mA	1 $\mu\text{m}$ rms	1 $\mu\text{m}$ rms	
100-500 mA stored beam resolution, 20-100% duty cycle	BPM receiver electronics	Assuming no contribution from bunch charge/fill pattern	0.017-200 Hz	0.2 $\mu\text{m}$ rms	0.3 $\mu\text{m}$ rms	
			200-2000 Hz	0.4 $\mu\text{m}$ rms	0.6 $\mu\text{m}$ rms	
			1 min to 8 hr	0.2 $\mu\text{m}$ pk-pk	0.5 $\mu\text{m}$ pk-pk	
	Mechanical motion limit at pick-up electrodes assembly (ground and support combined)	Vibrations	Bunch charge/fill pattern effects only	DC-2000 Hz	0.2 $\mu\text{m}$ rms	0.3 $\mu\text{m}$ rms
				50-2000 Hz	10 nm rms	10 nm rms
				4-50 Hz	25 nm rms	25 nm rms
	0.5-4 Hz	200 nm rms	200 nm rms			
	Thermal	1 min to 8 hr	200 nm rms	500 nm rms		

resolution requirements for user BPMs are expected to be better by a factor of 2.

**Tune measurement** – The vertical and horizontal betatron tunes will be monitored using a network analyzer. The signal from the receiver pick-up electrodes will be combined with hybrids to produce vertical or horizontal signals, which will be down-converted below the revolution frequency and fed to the input of the network analyzer.

**Transverse feedback** – A broadband signal, measuring the position of the individual bunches, will be provided by the stripline monitors. It will be sampled at 500 MHz fast ADC, and a digital filter will calculate the correction. The correction kicks, using a DAC, will be fed through a broadband amplifier and drive the electron beam using the second set of striplines. The detailed design of the striplines and a feedback system is in progress.

**Loss monitors** – NSLS-II will utilize a distributed beam loss monitoring system based on p-i-n diodes, which are commercially available. Two beam loss monitors per cell will be used for monitoring the special distribution of beam losses. For the temporal distribution of the last particles (on the scale of one turn) scintillation detectors (10) will be used. These can also be used for monitoring the losses of injected electrons near the injection and RF straights.

**Scrapers** – Two pairs of two-plane adjustable-position scrapers will be installed on the ring to be used both as protective devices as well as diagnostics instruments for accelerator studies. One set of scrapers (H/V) will be installed in the dispersive section to measure the energy distribution of the electron beam. Another set will be installed in a straight section with zero dispersion in order to have information on the transverse size of the electron beam, and to eliminate possible beam halos capable of affecting the insertion devices.

*Photon diagnostics*

The photon diagnostics for the NSLS-II storage ring will utilize visible and X-ray synchrotron radiation generated in a bending magnet and insertion devices. Table 8 shows the types and quantity of optical diagnostics for the NSLS-II storage ring.

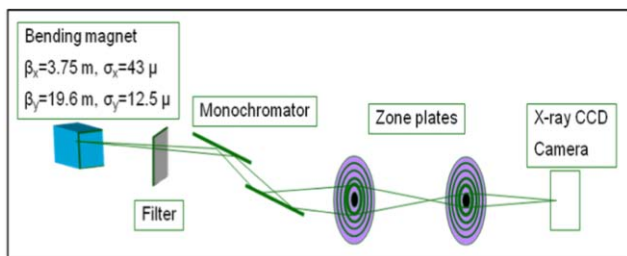


Fig 2: Emittance monitor layout with two zone plates

For measuring the ultra low vertical emittance of the storage ring, we included in the baseline design the direct imaging of the electron beam with two zone plates. This method was developed at KEK [7] for measuring ultra small beam sizes. A double crystal monochromator selects

the observation wavelength. The first zone plate focuses the monochromatic beam to small spot, while the second zone plate magnifies the image, making it suitable to observe by X-ray CCD camera. The optical setup is shown in Fig. 2.

The pinhole camera will utilize synchrotron radiation from a three-pole wiggler [8]. Its main function will be measurement of the electron beam energy spread and monitoring vertical beam size. Presently, we are optimizing the design of the pinhole camera beamline (see Research and Development section). If the obtained resolution will be sufficient, we will be able to measure vertical emittance with it.

Table 8: Complement of the optical diagnostics for the NSLS-II storage ring.

Monitor	Quantity	Function
Emittance monitor	1	Emittances in the both planes
Streak-camera	1	Bunch length
Pinhole camera	1	Beam size, energy spread
Photon BPMs	Up to 2 per BL	Position (angle) of ID radiation
Diagnostics undulator with pinhole camera	1	Horizontal emittance, energy spread, momentum compaction factor
Firewire camera	1	Beam profile

A double-sweep streak-camera will be used to measure the longitudinal beam dynamics. Its versatility and high sensitivity make it an excellent choice for monitoring the bunch length with high resolution and studying beam instabilities. The synchroscan feature provides low-phase jitter for synchronous summing of signals and tracking phase dynamics. The dual sweep is also available. We are considering to utilize either Optronis model SC-10 or Hamamatsu C5860 streak-camera.

Photon beam position monitors (PhBPMs) made by FMB-Berlin (shown in Fig. 3) are being considered for monitoring radiation from the insertion devices. The blades, of course, will be designed and optimized to suit the requirements of NSLS-II.

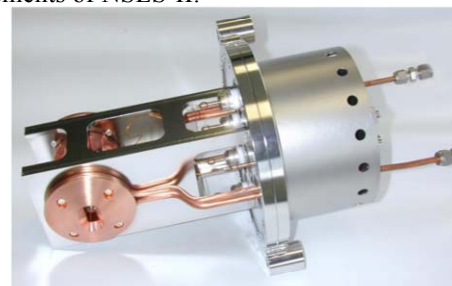


Fig. 3: Photon beam position monitor.

The PhBPMs are based on a development by Dr. Karsten Holldack at BESSY. The information obtained on the position of the photon beam will be incorporated into the orbit feedback system to provide the beam stability

required for user applications. In the baseline design we have one PhBPM per beamline. The PhBPM assembly will be mounted on a stable post and its location (elevation and transverse position) will be adjusted with 2D translation stages. Similar devices at APS enable pointing stability of the photon beam with peak-to-peak drift of less than  $2 \mu\text{rad}$  over six days [9].

An IEEE1394 (Firewire) camera will be used to observe the visible radiation from the electron beam. Such an approach eliminates the need for a frame-grabber and makes display of the beam on the control computer straightforward. The camera has an external trigger capability and exposure control from  $10 \mu\text{sec}$  to 5 sec.

The diagnostics undulator will allow independent measurement of the energy spread and horizontal emittance. The momentum compaction factor can be also measured. We plan to utilize one of the user beamline undulators in a 5 m straight; therefore, this tool is not included in the baseline design. This beamline will be equipped with an additional high-resolution fluorescent screen and a retractable pinhole. Use of the radiation from the undulator for diagnostic purposes will be restricted to periods when it is not needed by the users.

## RESEARCH AND DEVELOPMENT

The beam diagnostics research and development program is aimed at the most critical items for the NSLS-II project: beam stability and low emittance. Research on beam stability includes the evaluation of BPM receivers and the development of ultra-stable support for “user” BPMs surrounding insertion devices.

The user BPM consists of a special BPM block with BPM buttons, cooling fins and end flanges (Fig. 4). This assembly is mounted via four invar rods to the BPM support stand, made from carbon fiber composite. A carbon fiber composite can have thermal coefficient as low as  $0.2 \mu\text{m}/\text{m}/^\circ\text{C}$ . With tunnel temperature controlled to  $0.1^\circ\text{C}$ , one meter BPM stand will have a thermal expansion of no more than  $\pm 20 \text{ nm}$ .

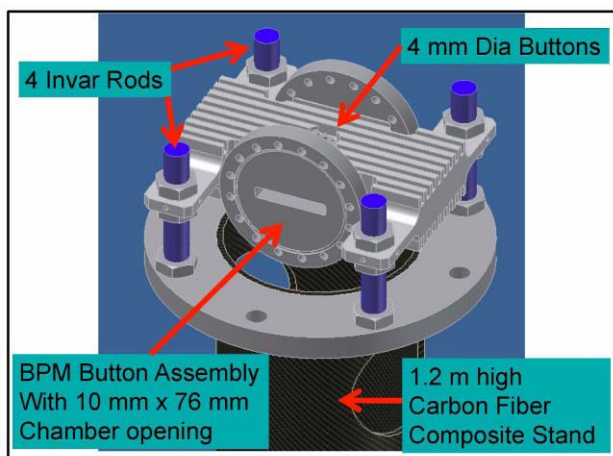


Fig. 4: User BPM support stand with a BPM block mounted at its mid-plane

The second focus of diagnostics R&D concerns an evaluation of ability for robust measurement of beam parameters. The vertical beam emittance of the electron beam will be extremely small to provide synchrotron radiation sources with diffraction limited size. The pinhole camera using a three-pole wiggler as a light source will provide measurement of energy spread and possibly also has sufficient resolution for measurement of vertical emittance [8]. The original plan was for emittances to be measured with a zone plates imaging system utilizing synchrotron radiation from a bending magnet. During R&D we will evaluate the replacement of this system with a less expensive and more robust pinhole camera as well, providing it has sufficient resolution with feasible design.

## SUMMARY

We have presented an overview of beam instrumentation and diagnostics for the NSLS-II project. The critical diagnostic systems, addressing beam stability and low emittance monitoring, are being investigated in the FY08 R&D program. Preliminary simulations optimizing the RF BPM buttons have been completed, providing insight into the selection of RF button geometry for prototype assembly. Preliminary design on various diagnostics systems has begun.

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