BEAM DIAGNOSTICS FOR THE NSLS-II BOOSTER

V. Smaluk, E. Bekhtenev, V. Cherepanov, G. Karpov, V. Kuzminykh, O. Meshkov,
BINP, Novosibirsk, Russia
Om Singh, I. Pinayev, K. Vetter, BNL, Upton, Long Island, New York, USA

Abstract

For successful commissioning and effective operation of the projected NSLS-II Booster, a set of beam diagnostic instruments has been designed. Fluorescent screens are used for the Booster commissioning and troubleshooting. Closed orbit is measured using electrostatic BPMs with turn-by-turn capability. The circulating current and beam lifetime are measured using a DC current transformer. The fill pattern is monitored by a fast current transformer. Visible synchrotron radiation is registered for observation of the beam image. Betatron tunes are measured using two pairs of striplines, the first pair is for beam excitation and the second one – for beam response measurement. Design and performance of the Booster beam instrumentation are described.

INTRODUCTION

For the NSLS-II Booster [1], a number of beam parameters should be measured in real-time mode. The beam diagnostic instruments are listed in Table 1.

Table 1: Booster Beam Diagnostic Instruments

Diagnostic device	Beam parameter	Qty
BPM	Closed orbit, tunes, beta functions	37
DCCT	Beam current, lifetime	1
FCT	Filling pattern	1
Beam flags	Single-pass beam image	6
SR monitor	Transverse beam sizes	2
Tune meas. system stripline	Betatron tunes	1 2

The first step of the Booster commissioning is closing the first beam turn with the help of beam flags (fluorescent screens). If the beam passes through the beam position monitors without losses, the beam position can be measured even at the first turn.

The next step is providing betatron capture by orbit correction using the BPMs, with a design response matrix. The beam lifetime in the betatron mode is enough to measure the tunes using the tune measurement system and to set the design working point. Analysis of the turn-by-turn BPM data at injection allows us to measure and correct the position and momentum errors of injected beam. Measurement and correction of chromaticity, betatron functions and dispersion functions is carried out with the accelerating RF cavities turned on. The response matrix for orbit correction can also be measured.

For optimization of the energy ramp, the beam energy is increased step-by-step with a set of intermediate points. The measurement of response matrices, as well as the measurement and correction of tunes, closed orbit, chromaticity and beta-functions are performed at each intermediate point and the machine operation modes are stored to be used for regular ramp.

For the Booster beam diagnostics, an EPICS-based control system will be developed according to NSLS-II standards.

BEAM POSITION MONITORS

To provide the accuracy of orbit measurement, which is sufficient for good orbit correction, it is recommended to use at least 4 BPMs per one period of betatron oscillation. Since the horizontal betatron tune is 9.65, 36 BPMs are required for the Booster. Two types of electrostatic pickup have been designed, the 1st type for the arcs and the 2nd type for the straight sections. The pickups have an elliptical cross-section: 41×24 mm for the 1st type and 62×22 mm for the 2nd type.

The vacuum-tight feedthrough with mounted button electrode and 50 Ω SMA plug is produced by MPF Products, Inc. This part of pickup is exactly the same as for the NSLS-II beam transport lines. The button assemblies are mounted on the pickup housing with flanges, the housings are to be installed into the vacuum chamber by welding. Manufacturing of the pickups of both types has been started in the BINP workshop.

Spatial linearity of the pickups has been estimated using both analytical formulae [2] obtained by solution of the Poisson's equation utilizing Green's reciprocation theorem, and the BINP-developed computer code SAM [3]. The linear area is limited by about 1/3 of the pickup aperture, as usual. So for a small beam offset, the beam position can be calculated with sufficient accuracy using the common formulae $X = R_x(V_A-V_B-V_C+V_D)/\sum V_i$, $Y = R_y(V_A+V_B-V_C-V_D)/\sum V_i$, where V_i are the electrode voltages. The linear scale factors calculated using SAM code are: R_x=9.9 mm, R_y=11.7 mm for ellipse 41×24, and R_x=7.0 mm, R_y=11.9 mm for ellipse 62×22.

To estimate the BPM sensitivity, a response of button electrode to a single-bunch beam is analyzed using the model [4]. The voltage induced on the button by a 0.5 nC beam is about 25 mV.

The signal processing electronics for NSLS-II BPMs is designed by BNL [5]. It provides turn-by-turn beam position measurements and the beam orbit measurement. The RF BPM architecture consists of a passive RF Processor located in the tunnel and the BPM receiver including Analog Front End and Digital Front End. The button electrodes of each pickup are connected to the RF Processor via 4 short (about 1 m) pieces of SiO_2 coaxial cable. To minimize the influence of eddy currents induced by variable magnetic fields, the shield of each cable is galvanically separated from the pickup ground using capacitors.

The RF Processor output signals are transferred via 4 long (30-100 m, depending on the pickup location) coaxial cables to the BPM receiver placed in the Injector Service Area outside the accelerator hall. One more coaxial cable is used for a calibration signal. To minimize the signal attenuation, the racks with BPM receivers are located as close as possible to the proper pickups. For additional decrease of the cable insertion loss, thicker cables (9 dB/100 m @ 500 MHz) will be used for longer runs (1^{st} and 2^{nd} arcs), whereas standard cables (18 dB/100 m @ 500 MHz) will be used for shorter runs (3^{rd} and 4^{th} arcs). The maximal signal attenuation introduced by the coaxial cable is 9 dB, so the minimal signal value at the BPM receiver input is about 2 mV. To provide additional noise attenuation, all BPM cables will be placed into a separate shielded tray with a top cover.

BEAM CURRENT TRANSFORMERS

DC Current Transformer

A DC Current Transformer is used to measure the beam current, lifetime and injection efficiency. For the NSLS-II Booster, the device should provide current measurements in 0-50 mA range with <5 $\mu A/Hz^{1/2}$ resolution in the DC-10 kHz. A Bergoz New Parametric Current Transformer (NPCT) has been chosen to meet the requirements.

The second-harmonic detection technique is used in NPCT, two transformers are cascaded in a common feedback loop. The output signal is a voltage proportional to the beam current. The In-Flange NPCT with radiation-tolerant sensor will be installed at the Booster. The In-Flange transformer is mounted in the vacuum chamber between two flanges, has short axial length and includes a ceramic gap vacuum-brazed on kovar. It does not require bellows, wall current bypass, nor electromagnetic shield and is suitable for ultra-high vacuum conditions down to 10^{-10} mbar.

The readback electronics should comply with integration specifications for the NSLS-II control system. The digital front end should contain an ADC for the DCCT data acquisition; a DAC for the calibrator set point; and a 2-bit Output Register to control the calibrator status.

Fast Current Transformer

A fast current transformer (FCT) is used to measure individual bunch charges and filling pattern. To fulfil the Specifications, a device should provide sensitivity ≥1.25 V/A, bandwidth ≥1.75 GHz, rise time ≤200 ps; bipolar output signal, and 50-Ω characteristic impedance. The wideband current transformer Bergoz FCT has been chosen. The In-flange.FCT is designed to be bolted in place as part of the accelerator vacuum chamber.

Composite magnetic cores of Cobalt-based amorphous and nanocrystalline alloys provide high permeability and very fast rise time of the device. The FCT frequency response measured on the bench shows upper cut-off frequency of 1 GHz (−3dB). The on-beam tests performed at Petra-II show the measured rise time of 374 ps and fall time of 356 ps.

The readback electronics will comprise a compact PCI 8-bit ADC Acqiris DC271A with up to 4 GS/s sampling rate and 1 GHz bandwidth. The ADC will comply with integration specifications for the control system. Since the beam signals are stretched because of the rise time of electronics, 250 ps per sample would be enough to identify the signals of individual bunches.

OPTICAL INSTRUMENTS

Beam Flags

Six fluorescent screens (beam flags) will be used to measure transverse beam profile and position in single-pass mode. This beam-destructive diagnostics usually plays a key role during commissioning of a machine.

The beam flag consists of an integrated system of components that can be reconfigured and interchanged, whereby a screen can be easily taken out of a UHV-compatible body. Typical resolution of the fluorescent screen made of Cerium-doped Yttrium-Aluminium Garnet (YAG:Ce) is about 50 µm within the visible field of 20 mm. The thickness of YAG:Ce plates produced by Crytur Company is 0.1 mm.

The screen is placed inside a cylindrical volume made of stainless steel, which can move between two fixed positions inside and outside the vacuum chamber. The extreme positions are equipped with end switches for monitoring of the flag status. The bottom of the device body will serve as a wake-field shield, when the beam flag is removed out of the chamber.

The objective lens M118FM25 made by Tamron is used for the beam image focusing. The image registration is provided by the CCD camera Prosilica GC1290 (Allied Vision Technology) with 1280×960 resolution, 3.75×3.75 mm pixel size and Gigabit Ethernet interface. The CCD-camera is placed outside the median plane of the accelerator and is radiation-protected with the lead shield. The camera positioning and focusing lens tuning are performed using the screen mesh. Any replacement of the equipment does not need violation of the vacuum.

The scattering angle of the electrons after crossing the 0.5 mm-thick stainless steel wall was calculated using the empirical formula [6]. At the injection energy of 200 MeV, the scattering results in about 0.12 mm enlargement of the beam image on the screen, this enlargement is quite small and should not distort the output data.

To move the beam flag, a remotely-controlled pneumatic drive DSNU-25-80-PPS-A (FESTO Company) is used. It includes the round cylinder barrel made of stainless steel with piston diameter of 25 mm, bearings and end caps made of wrought aluminium alloy. The working pressure of the cylinder is 6 bar.

The camera control and image acquisition will be performed by the EPICS IOC running on a Linux-based

PC. Each beam flag also requires one binary output for pneumatic valve control, two binary inputs from end switches, one trigger signal from the timing system, and one DAC for illuminator control.

Synchrotron Radiation Monitor

The synchrotron radiation (SR) monitor provides routine measurements of transverse beam profiles and beam sizes. It is used for the Booster performance optimization, operation monitoring and various beam physics studies.

Two SR output ports have been designed, their locations have been chosen according to the maximal vertical beam size and maximal free length of the vacuum chamber. The most suitable points of SR generation are in the BD dipole magnets. The first SR port is located in the 3^{rd} arc, the second port designed for the Booster commissioning is close to the SD section. At the extraction energy of 3 GeV, the computed values of beam sizes are σ_x=0.26 mm, σ_y=0.1 mm at the 1^{st} port and σ_x=0.27 mm, σ_y=0.2 mm at the 2^{nd} port.

A pre-aligned fixed mirror will be installed inside the vacuum chamber to reflect the visible part of SR out of the chamber. The fixed mirror is made of copper, the reflecting side is aluminium-plated. The mirror design also includes water cooling equipment. The vertical size of mirror is 24 mm, the maximum allowed deviations at the SR source points are: ±12 mm for vertical beam position, ±16 mrad for vertical angle, and ±3.5 mm for horizontal beam position. The SR power on the mirror is 0.42 W/mrad, so the total power is 4.54 W.

Fine alignment of the light beam is provided by two remote-controlled mirrors with optical diameter of 2" placed outside the chamber. The external mirrors are mounted on the motorized mirror mounts 8MBM24 produced by STANDA Company. These mounts are optimized for use in closed systems and provide precise positioning with homing-repeatability better than 10 arcsec. Integrated opto-electrical end switches prevent damage of the devise.

The controller of the mirror mounts is Geo BRICK LV DRIVE made by DELTA TAU Company. It is a full-featured motion controller with Ethernet, USB, and RS232 communications. Each axis includes incremental encoder inputs for position feedback and optically isolated motor I/O flags.

The synchrotron light passed through a light output window is focused by a lens and registered by a CCD camera Prosilica GC1290 (the same as for beam flags). The synchrotron light monitor requires the same control functions as the beam flags except the pneumatic valve control.

TUNE MEASUREMENT SYSTEM

The tune measurement system should provide measurement of the fractional part $\nu_{x,y}$ of betatron tunes with the precision of 0.0005 in the range of ±0.5 (in units of the revolution frequency f_0) around the design working point. The measurement has to be performed for a single bunch charge of 100 pC and for a train of 150 bunches with 10 pC per bunch for each injector cycle. A single measurement of ν_x and ν_y takes time of about 4 ms. So for the total ramp duration of 0.5 s (0.25 s in 2 Hz mode) the system can provide 128 (64) tune measurements.

Two identical sets of four 50-Ω striplines are used, one set is a kicker for beam excitation; another one is a pickup for measurement of a beam response signal. The stripline electrodes are mounted at 45° angle. The length of stripline is 450 mm, which is about $3\lambda/4$ (λ is the RF wavelength, f_{RF}=500 MHz). A beam with 15 nC charge oscillating with 1 mm amplitude generates a stripline signal with amplitude of approximately 30 mV.

The beam is excited by radio frequency (RF) pulses with the frequency close to $(1+\nu_{x,y})f_0$, duration of the RF pulse is 100-500 µs. After the exciting RF pulse, the signal of betatron oscillation received by the stripline pickup is transferred to the signal processing electronics, where it is digitized by an ADC with sampling frequency of $62f_0\approx117$ MHz and is processed by a Field Programmable Gate Array (FPGA) circuit. Digital processing performed by the FPGA includes synchronous detecting, filtering and Fast Fourier Transform (FFT) with the Hann window. The FPGA also contains two Direct Digital Synthesizers generating a sinusoidal signal or a noise-type signal for beam excitation. The beam excitation electronics consists of two Power Amplifiers (100 W, 0.08-16 MHz), bridge transformers and 50 Ω loads. The scheme provides selective or simultaneous excitation of both horizontal and vertical betatron oscillations.

The system has two modes of operation: the search mode and the measurement one. In the search mode, the exciting frequency is scanning within a specified range of $(1.5\text{-}2.0)f_0$. For each frequency, the signal is recorded and its amplitude spectrum is calculated. The maximum of the spectrum corresponds to a rough value of the betatron tune. In the measurement mode, the exciting frequency is set close to this value.

A prototype of the Signal processing electronics has been manufactured and tested in BINP. The signal-to-noise ratio is estimated using the results of testing of the Signal Processing electronics prototype with a test signal. For all beam charge range of 1-30 nC, the signal-to-noise ratio at the ADC output is approximately 100-300. For the minimal beam charge of 1 nC and the oscillation damping time of 1 ms, the signal-to-noise ratio increased by FFT is about 2000. This value is sufficient to achieve required tune measurement accuracy.

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