NSLS2 DIAGNOSTIC SYSTEMS COMMISSIONING AND MEASUREMENTS*

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Abstract

As the newest and most advanced third generation light source, NSLS2 commissioning has started recently. A total of 50mA stored beam was achieved in the storage ring. Most of the diagnostic systems have been commissioned with beam and proved to be critical to the success of machine commissioning. This paper will present beam commissioning results of various diagnostic systems in the NSLS2 injector and storage ring, including profile monitors, current monitors and position monitors. We will discuss some preliminary machine measurements as well, like beam current and lifetime, tune, beam stability, filling pattern etc.

INTRODUCTION

NSLS2 is an advanced third generation light source recent constructed at Brookhaven National Laboratory. It includes a 200MeV S-band LINAC, 200MeV to 3GeV Booster, LINAC to Booster (LtB) transfer line, Booster to storage ring (BtS) transfer line and 3GeV storage ring.

Injector commissioning was carried out from Nov 2013 to Feb 2014. 3GeV ramped beam was established in the Booster on last day of 2013. The injector is capable to deliver high charge in multi-bunch mode, as well single bunch beam to the storage ring. So far the storage ring had finished two phases of commissioning. The phase 1 beam commissioning, from Mar 26 to May 12, was using PETRA 7-cell normal conducting cavity. Small gap damping wiggler chambers were installed in three long straight sections. For the phase 1 commissioning, 25mA stored beam was achieved after fixing issues like hanging springs in the vacuum chamber. Many of the storage ring diagnostic systems had seen beam and commissioning during this period. Super-conducting RF cavity was installed during the shutdown together with several other in-vacuum undulators and beamline front end, and beam commissioning was resumed from Jun 30 to Jul 14, 50mA stored beam was achieved with super-conducting RF cavity. To eliminate the effect of insertion devices, all damping wigglers and IVUs were fully open. Beam commissioning will be continued in coming months to close the insertion devices and send X-rays down to beamlines.

Figure 1 shows the storage current and lifetime when 50mA beam was achieved. The stored average current was measured by in-flange type DCCT which is commercially available [1]. Filling pattern monitor system was used to measure the bunch to bunch current, BPM buttons SUM signal was send to high speed digitizer or oscilloscope. Figure 1 bottom snapshot gives the oscilloscope filling pattern at around 50mA, when one long bunch train was filled. Green trace (Ch2) is storage ring revolution clock while yellow trace (Ch1) is four button SUM signal from dedicated BPM.

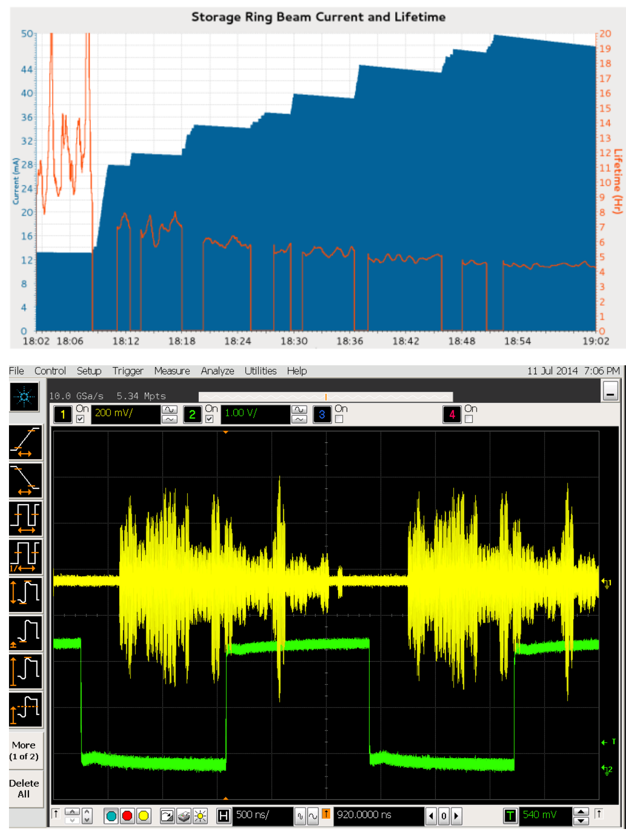

Figure 1: (top) storage ring DCCT measured current and lifetime history plot when fill up to 50mA; (bottom) filling pattern at around 50mA.

Table 1 lists major parameters of NSLS2 storage ring. There are 30 double bend achromatic (DBA) cells in the ring with bare emittance of 2 nm.rad. Horizontal emittance decreases to < 1 nm.rad with three damping wigglers.

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Table 1: NSLS2 Storage Ring Parameters

Energy	3.0 GeV
Circumference	792 m
Number of Periods	30 DBA
Length of Straights	6.6 & 9.3 m
Emittance (h,v)	< 1nm, 0.008 nm
Momentum Compaction	0.00037
Dipole Bend Radius	25 m
Energy Loss per Turn	< 2 MeV
Energy Spread	0.094 %
RF Frequency	499.68 MHz
Harmonic Number	1320
RF Bucket Height	> 2.5 %
RMS Bunch Length	15ps – 30ps
Average Current	500 mA
Current per Bunch	0.5 mA
Charge per Bunch	1.3 nC
Touschek Lifetime	> 3 hrs
Top-Off Injection	1/min

NSLS2 DIAGNOSTICS

Various diagnostic systems have been built and installed in the NSLS2 machine complex to measure electron beam position, current, profile and other parameters. Table 2 is a summary of diagnostics in NSLS2 machines.

Table 2: NSLS2 Diagnostics Systems

	LN	BR	LtB	BtS	S.R.
Button BPM	5	37	6	8	180
ID BPM					2 or 3 per ID
Photon BPM					1 or 2 per BL
Faraday cup	1		2	1	
WCM	5				
FCT/FPM		1	2	2	1
ICT			2	2	
DCCT		1			1
Screen	6	6	9	9	1
X-ray diag. BL					1
Visible diag. BL		2			1
Energy slit			1	1	
Tune monitor		1			1
BxB feedback					1H, 1V
Scraper					3H + 2V
BLM					5 CBLM 2 NBLM

Button type beam position monitors (BPM) are widely used to measure beam centroid along the injector and in the storage ring. Different button sizes and chamber profiles are available, details of the button BPM design and performance can be found in earlier papers [2, 3]. There is 1 or 2 photon BPM planned for each user's beamline, only one photon BPM is installed at this time and it will be commissioned together with the beamline commissioning. In-house developed BPM electronics [4-6] report raw ADC data, turn-by-turn data, 10kHz fast acquisition data as well as 10Hz slow acquisition data. Same hardware platform works for single-shot beam and circulating beam.

Faraday cup in LINAC front end, wall current monitors (WCM), fast current transformers (FCT) are used to measure bunch to bunch currents in LINAC, Booster and transfer lines. Broadband pickup signals (> 1GHz) were feed to high speed digitizers with sampling rate up to 8GHz. Processed filling patterns are updated on control's operational panel at 1Hz injector ramping rate. Faraday cups and integrated charge transforms (ICT) in the LtB/BtS transfer lines are used to measure beam charge per shot at selected locations. ICTs were calibrated before the commissioning started. There is one DCCT in Booster and storage ring, to measure the average current of circulating beam. DCCTs are well calibrated like ICT. In-situ calibration is possible with standard DC calibrator current source and related control software. DCCTs and ICTs are considered to be reliable tools to measure beam current/charge. Beam transfer efficiency and injection efficiency can be calculated based on the measured data on the same injection cycle.

Different types of screen monitors are used to measure the beam profile. LINAC and Booster screen monitors use YAG:Ce material, plenty of photons are generated even at very low charge. However the YAG screen resolution is not as good and saturation had been observed at high charge. LtB/BtS profile monitors have two selectable screens – YAG and OTR. OTR screen has less photon but improved resolution. Screens are moved by pneumatic actuators. There is a multi-position screen monitor in the storage ring injection straight, located right after the pulsed septum [7]. The screen is controlled through a linear stage and motor to see injecting beam, one turn beam or bumped stored beam. To measure stored beam size and emittance, one X-ray diagnostic beamline was constructed with source point at non-dispersion location. A second planned X-ray diagnostic beamline at dispersion was not fully built due to budget constraints. Energy spread measurement will be possible utilize the visible synchrotron light monitor (SLM), where the source point locates at the beginning of second bend in DBA cell. SLM beamline is equipped with streak camera to measure bunch length as well as other setups [8, 9]. Two synchrotron light monitor ports are available in the Booster ring to measure beam profiles during ramp.

Besides three major types of diagnostics to measure beam position, current and profile. There are other diagnostics to measure the betatron tune, beam losses, transverse bunch-by-bunch feedback etc. In the following sections, beam commissioning results and some physics measurements using these diagnostics will be discussed.

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BPM COMMISSIONING RESULTS

Incorporating the newest digital technologies, BPMs in NSLS2 are capable to measure 117MHz ADC raw data, turn-by-turn (TbT) data, 10kHz fast acquisition (FA) and 10Hz slow acquisition (SA) data. LINAC and transfer line BPMs measure the beam position in single shot mode, hence the raw ADC data and first turn of turn-by-turn data are particular interesting for these BPMs. 10kHz data was used to measure the beam orbit during booster energy ramping. There are six BPMs in the each storage ring cell, with total of 180 BPM mounted in multipole chambers. ID straight sections and injection straight have BPMs installed and see the beam. Storage ring BPMs' FA data is streaming out the fiber port to cell controller and used for fast orbit feedback. SA data is always available for orbit monitor and correction. ADC, TbT and FA waveform data are available from BPM IOCs. The waveform data can be retrieved on Internal/External triggers. External trigger to all BPMs around the ring guarantee sampling beam position/trajectory synchronized.

BPM Synchronization

Due to BPM pickup physical location and cable length difference, BPM electronics need to be timed well to get real turn-by-turn data. At the early stage of commissioning, before BPMs timed well, raw ADC waveform supplied powerful diagnostic information. Fig. 2 shows an example of storage ring BPMs ADC waveform data. The data was acquired when beam survived for 5-6 turns. One can see 180 storage ring BPMs were roughly timed but not perfect aligned.

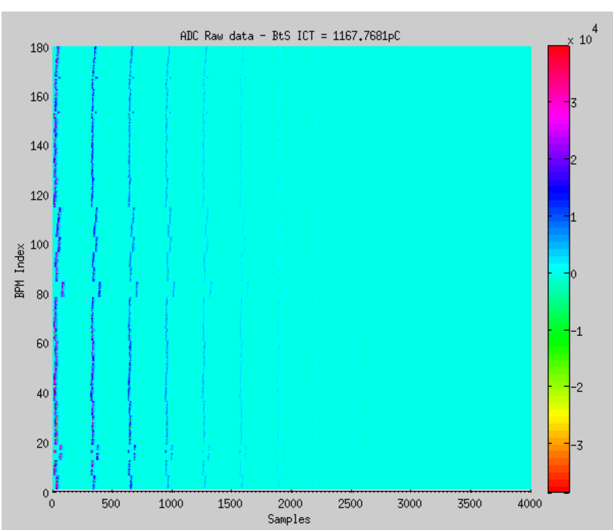

Figure 2: ADC waveform data from 180 SR BPMs, beam survived for about 5 turns. There are 310 ADC samples per turn.

Once BPMs timed well, all BPMs in the ring will see exactly same turn data. Fig. 3 shows all Booster BPMs 4-button SUM signal when timed right. Upon injection, all Booster BPMs saw the first turn beam on TbT sample #4. Beam was ramped for about 382ms in the Booster, BPMs have sufficient memory to capture turn-by-turn data during the whole ramp. Near extraction, only half of the ring sees beam on the extraction turn. Note that to read the extracted position data, BPM DDR memory had offset of 719236 turns. Beam was extracted on turn #3966 where only half of the Booster ring BPMs saw beam on that turn. Beam was circulating in the Booster for 723199 turns.

SUM Signal Diagnostics

From previous section, one might see 4-button SUM signal can be very useful to diagnose not only the time, but also the beam loss between BPMs. Even with same charge passing through the pickups, SUM signal varies due to BPM button size and chamber geometry difference, cable length and attenuation difference, SUM signal position dependency, attenuator settings etc. All these effects can be corrected to have meaningful comparison of beam charges from BPM to BPM.

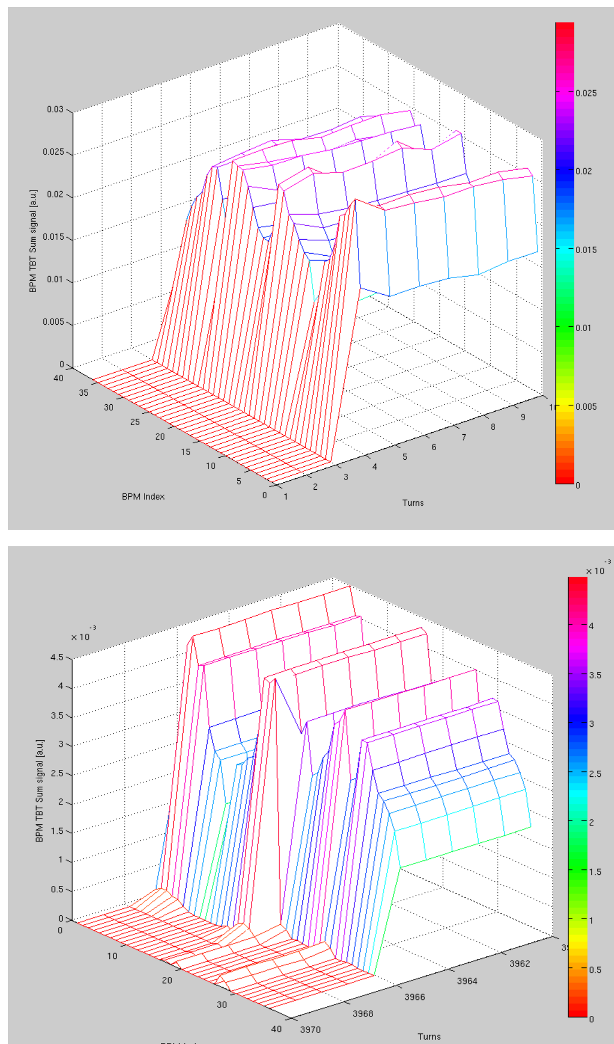

Figure 3: Booster BPM 4-button SUM signal in TbT mode. (top) Beam was injected on TbT sample #4, which is the first turn in Booster. All Booster BPMs saw the beam at same turn. (bottom) Beam was extracted on turn sample #3966 (Offseted by 719236 turns), only the first 18 BPMs saw beam on that turn.

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At early stage of storage ring commissioning, before the beam circulating the ring, BPM timing was roughly adjusted to capture the beam signal. First turns beam position and SUM signal was retrieved from ADC data. Shown in Fig. 4, are button A,B,C,D signals, x/y position and SUM signal processed from ADC waveform data. The SUM signal was corrected for button geometry, cable losses, attenuators and beam positions. The data was recorded when beam was circulating for less than 10 turns. Beam trajectory had large horizontal offset, likely came from mis-matched injection kickers. From all BPMs 4-button SUM signal, one can see there was partial beam lost at BPM #90 (C10 BPM4), this is the location where later an RF spring obstacle was found. With this BPM SUM signal beam loss tool, together with other evidence like limited local aperture, elevated radiation level in area when beam dumped, it was convinced there was obstacle in vacuum chamber. A hanging RF spring was found after break the vacuum in C10, at upstream of BPM 4.

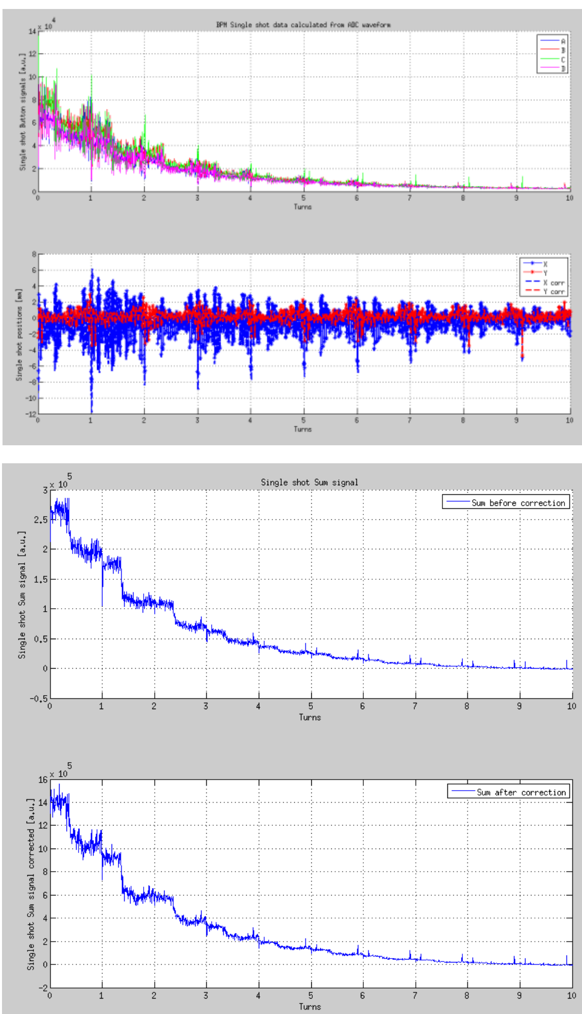

Figure 4: Beam circulating the storage ring for several turns, first turn trajectories and SUM signal from ADC data. There are 180 BPM data points in one turn. (top) four button signals and calculated x/y positions; (bottom) BPM SUM signal before and after corrections.

Electronics Resolution Measurements

BPM resolution measurements were performed using an extra BPM button assembly and electronics module installed in Cell 28 [10]. The electronics module was connected to the 4 BPM buttons using a combiner/splitter assembly to make the measurements independent of transverse beam motion. With this connection scheme each of the 4 channels of the electronics will see the same signal and electronics performance can be measured independent of beam motion.

The resolution measurements were performed for different fill patterns. A typical measured FA resolution at different single bunch current can be seen in Fig. 5, where single bunch was stored to and decayed while taking the data for analysis. At around 0.9mA, electronics resolution was measured to be ~2 µm.

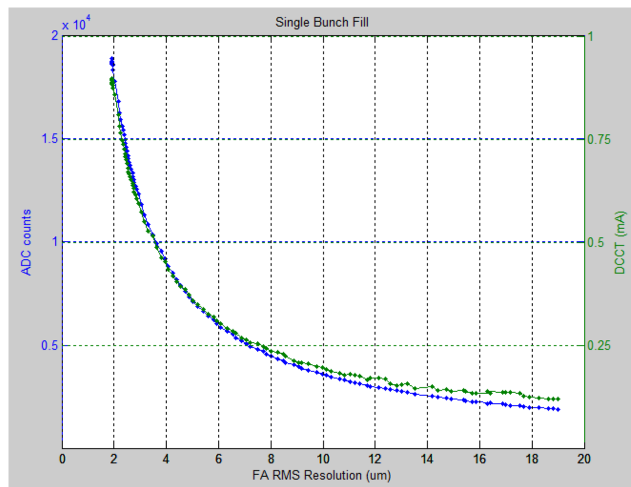

Figure 5: BPM FA data resolution with single bunch stored.

Beam Motion Spectrum

Using BPMs data, many physics measurements/ applications have been realized. BPMs are critical diagnostics for lattice measurement and correction; injection optimization; BPM TbT spectrum and tune measurement; beam based alignment; beam dynamics studies; beam instabilities studies etc. In this paper, we are not going to discuss details of these measurements. Only beam motion spectrum analyzed from BPM TbT/FA data is being presented.

Figure 6 gives a typical spectrum from storage ring BPMs TbT data. The spectrum was averaged for 180 storage ring BPMs. Beam was stored at 23mA in multi-bunches. Beam was unstable so that betatron sidebands were clearly visible. On horizontal spectrum, synchrotron sideband appeared at dispersive BPMs. From the integrated power spectrum density, there was about 3.6um w/o betatron motion in horizontal plan. The RMS motion

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will be ~26 um include betatron motion. In vertical plane, the RMS motion was 2.1um w/o betatron motion and 9.8um include betatron motion. To characterize the lower frequency beam motion spectrum, 10kHz FA data is more suitable.

Similarly to TbT spectrum, BPM FA data spectrum was analyzed with better precision. Beam motion was about 2 um for x/y spectrum, not including the synchrotron motion contributions. Extra 3-4 um was added to dispersive BPMs. Assume dispersion at BPMs was around 0.4m, energy jitter was ~ 0.001%. Hopefully this can be improved by optimize the low level RF controller. RMS beam motion up to 1kHz was measured to be ~ 1% of beam size horizontally and ~20% of beam size vertically. Fast orbit feedback, once commissioned, will keep the motion within 10% vertical beam sizes.

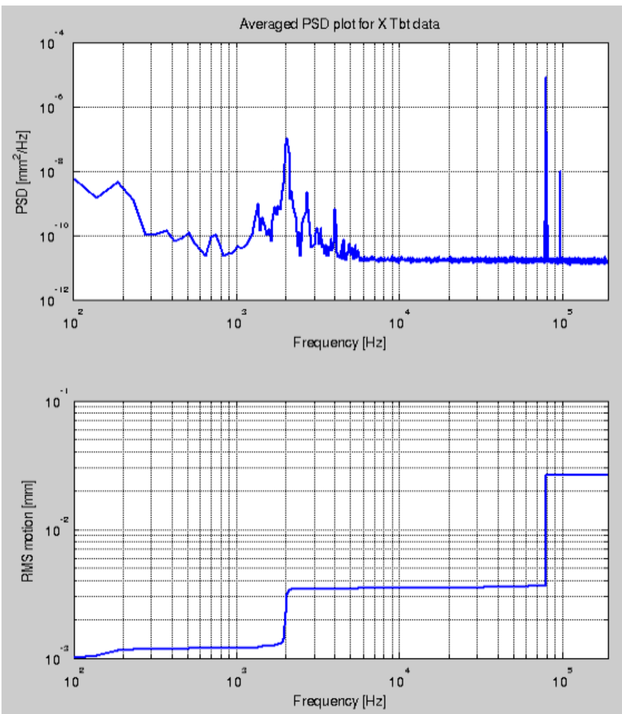

Figure 6: Averaged power spectrum density spectrum and integrated RMS motion plot from storage ring X TbT data. Beam was stored at 23mA.

CURRENT MONITORS

As shown in Table 2, there are different types of current monitor sensors to measure the AC/DC beam current. Many of these sensitive current monitors saw noises from pulse magnets and ground loops. Adding ferrite beads helped to kill common mode noises. Figure 7 gives Booster FCT signals measured when beam was circulating for multi-turns. FCT beam signal appeared each turn on top of the noises caused by Booster injection kickers. Zoom in gives the typical 20 bunches pattern in the train. Digitizer was configured at 8GHz sampling rate, there was about 16 samples per 2ns RF bucket period.

Storage ring filling pattern was measured from a dedicated 4-button BPM SUM signal. Broadband hybrid SUM signal was send to high speed digitizer or 20GHz oscilloscope. Bunch filling pattern was calculated from pulse area or peak amplitude. Meanwhile bunch centroid can be used to measure beam synchronous phase. This could be useful tool to detect the transient beam loading effect with long bunch train and ion gap fill. Shown in Fig. 8 is a typical bunch pulse observed on storage erring filling pattern monitor, using 20GHz oscilloscope. Red diamonds are the raw sampled data with 50ps separation. To retrieve the peak amplitude and location with better resolution, 10 times interpolation was applied to the raw data. Interpolated data points are plotted as blue circles. Searched peak of interpolated point gives the green square in the figure, its amplitude was considered to be bunch current and its position was measured synchronous phase. Interpolated points have 5ps separation, the measured synchronous phase shall have accuracy better than 5ps, not including the trigger jittering.

To validate the synchronous phase measurement method, preliminary study was done by varying RF cavity voltage and recording the synchronous phase. From the synchronous phase vs. cavity voltage curve, energy loss per turn was estimated to be ~ 275 keV, this is close to theoretical value of 287 keV.

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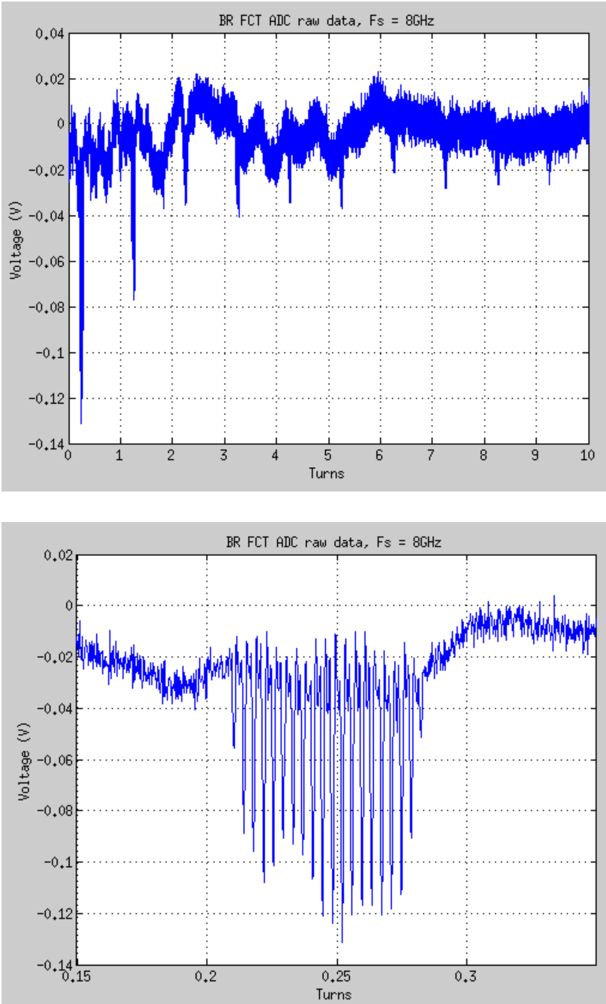

Figure 7: Booster FCT measurements shown beam was circulating for multi-turns (top). 20 bunches were detectable from 8GHz sample rate data (bottom).

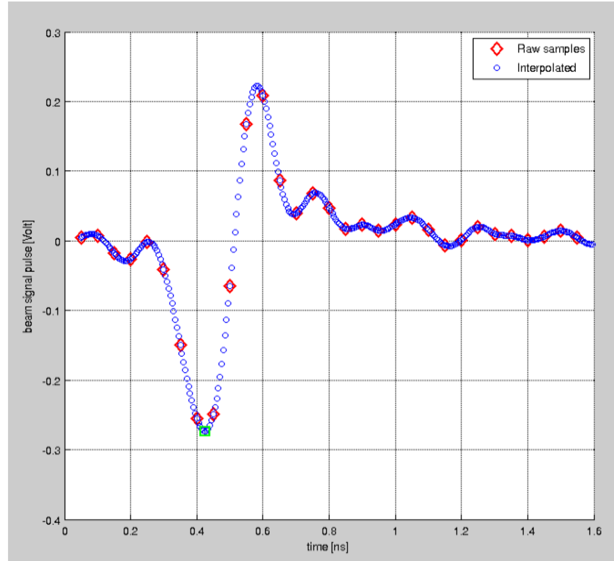

Figure 8: Storage ring filling pattern monitor signal from 20GHz real time sampling scope. Red diamonds were raw sample data points while blue circles were interpolated points by a factor of 10. Green Square is the searched peak of interpolated point, its amplitude was considered to be bunch current and its position was measured synchronous phase.

There is one in-flange type DCCT installed in Booster and storage ring. The DCCT sensor has same chamber profile to nearby sections to minimize the beam impedances. CompactPCI digitizer ICS 710A is used to sample the DCCT output signal. The digitizer can be programmed to have different anti-alias low pass filter. Maximum sampling rate of the digitizer is 216 kHz. Storage ring beam current decays due to: 1) Elastic scattering (Columb scattering) or inelastic scattering (Bremsstrahlung) with residual gas; 2) Collisions between electrons (Touschek scattering); 3) Photon emission (Quantum lifetime) or 4) Trapped ion or macro dust in beam potential. High brightness synchrotron light sources operating at low emittances and large beam current are usually lifetime limited from Touschek scattering. For a short period of time much less than beam lifetime, one can linear fit the measure bunch current data point, linear fit slope will be $-1/\tau$. During SR phase-1 commissioning, large noise signals were picked up by DCCT electronics. A programmable low pass filter was added before the digitizer to eliminate the noises. DCCT noise was able to decrease from 40uA to 3uA.

PROFILE MONITORS

As described there are many screen (flag) monitors in the injector to measure transverse beam profile. Transfer line profile monitors have selectable YAG or OTR screens. Beam emittance and energy spread can be measured. Figure 9 is an example of LtB second flag monitor which is located with dispersion. Assume dispersion is known, beam energy spread can be measured from the profile distribution. Absolute beam energy was measured based on the upstream dipole current settings.

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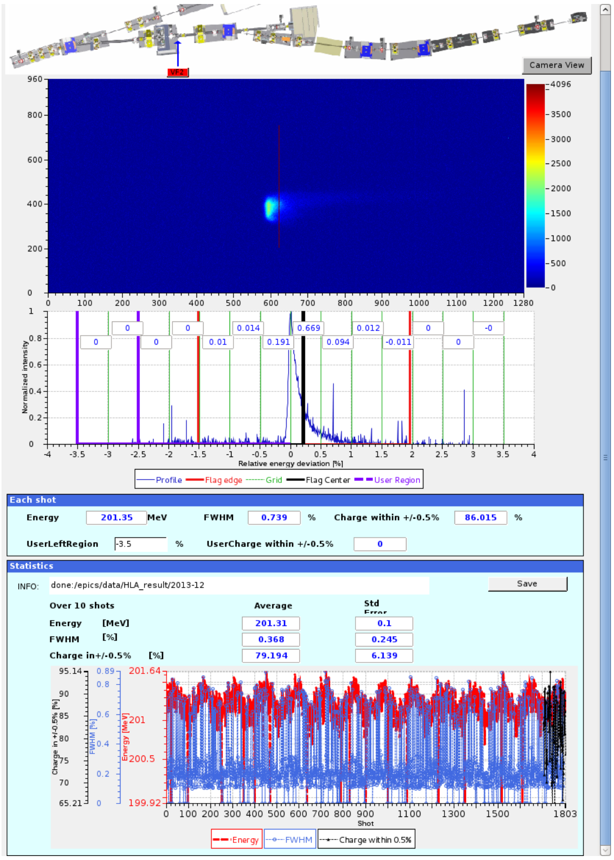

Figure 9: LINAC beam energy jitter and energy spread measurement using LtB VF2.

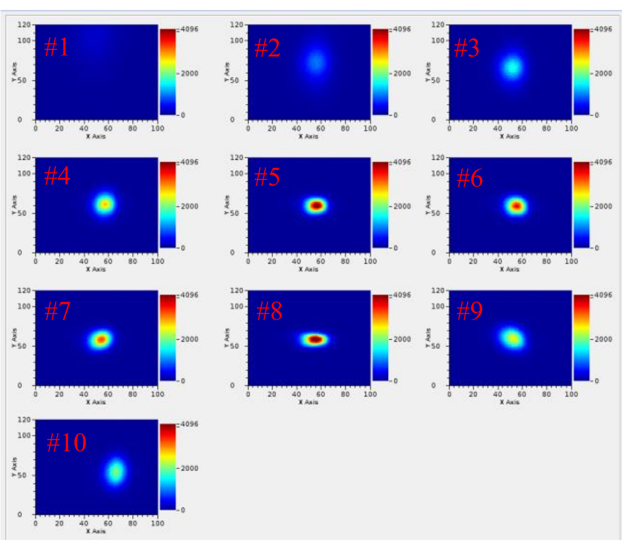

Figure 10: Booster A1 SLM ten burst images during energy ramp. The images were acquired with separation of 40ms.

Two synchrotron light monitors in the Booster tunnel were able to capture beam profiles during energy ramp. CCD camera can be triggered with a burst of pulses so that same ramp profiles at different energy ramp time can be captured. As seem in Fig. 10, ten burst images were captured from the same ramp, the burst images were separated by 40ms.

Storage ring visible synchrotron light monitor (SLM) diagnostic beamline utilizes the radiation from C30 BM-B, which is the second dipole after injection. Nominal source point is ~2.75mrad into the dipole. The beamline has acceptance of +/-1.5mrad horizontal and +/-3.5mrad vertical. Visible light from the dipole synchrotron radiation is reflected by in-vacuum mirror. The visible light is then relayed into SLM hutch locates on the C30 experimental floor. There are various optics setups on the 4'x10' optical table, currently there are three branches setup: CCD camera branch; fast gated camera branch and streak camera branch. Visible light can be guided to different cameras. Due to excellent alignment work, SLM beamline was able to see the first synchrotron light even for first turn beam. More information for the SLM commissioning is available at [9].

OTHER DIAGNOSTICS

Different methods have been used to measure the betatron tune. It can be measured by BPM turn-by-turn data Fourier spectrum of kicked beam doing betatron oscillation. Tune can be measured from Bunch-by-bunch feedback system by watching the notch on the spectrum. NSLS2 storage ring has dedicated sweeping tune measurement system (TMS). The system uses button BPM delta signal from Hybrid to detect the horizontal and vertical betatron motion. Mixer IF output baseband signal is sent to a network analyzer to measure the transfer function. Beam is excited by 15cm stripline with diagonal kicks. Two 75W broadband amplifiers are used to feed the stripline. Network analyzer can be controlled through EPICS CSS panel, sweeping time of the NA is programmable and it's typically takes seconds. TMS operation panel with measured tune spectrum is given in Fig. 11. RTD sensors are installed to monitor the stripline feedthrough and chamber temperatures.

Scraper blades are controlled with linear motors with 1um resolution and 3um repeatability. When electron particle hits the scraper, it losses energy hence will be bend inward towards the chamber wall. Glass rods are installed at selected locations to detect the lost electrons outside the vacuum. When electron passes through the Glass rod, it generates Cherenkov light which will be reflected towards the end of glass rod. Optics setups in the end boxes include photo diode and PMT and related signal condition electronics. Cherenkov light converted in to electrical pulse signal to be detectable with digitizers. There are 2 neutron detectors as part of the beam loss monitoring system installed on top of the injection septum. During the beam commissioning, scrapers had been used for fault studies as well as limit the beam lifetime for some shifts. Cherenkov and neutron beam loss monitors had been calibrated with injecting beam.

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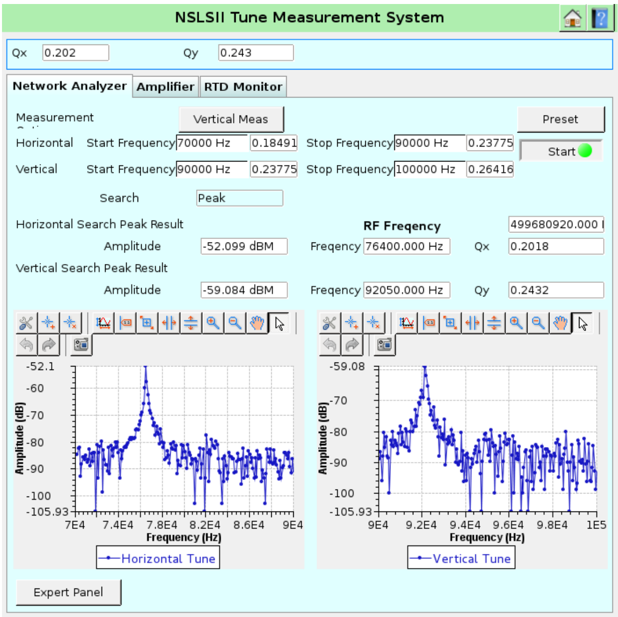

Figure 11: Storage ring sweep tune measurement system operational panel showing the x/y tune spectrums.

There are fiver scrapers and five Cherenkov beam loss monitors (CBLM) installed in C30 and C01, where high density concrete is used for better shielding. The purpose of this configuration is to have beam losses in a controllable manner near injection area so that beam loss at other part of the ring is minimized. [11]

Transverse bunch by bunch feedback system installed at C16 has been commissioned. The system helped to suppress multi-bunch instabilities which are likely ion induced. Single bunch instability was suppressed by the feedback system and threshold bunch current can be increase from 1mA to more than 6mA. [12]

SUMMARY

During past months of NSLS2 injector and storage ring commissioning, Most of the diagnostic systems have seen beam and commissioned. 50mA stored beam were achieved in the storage ring. Varity of diagnostic tools has proved to be critical for the success of beam commissioning. We expect these tools to continue play important roles for the future high intensity, high stability commissioning and operation of NSLS2.

We thank the diagnostic group for enormous construction, installation and testing work and operation team for commissioning the machine.

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