

NLSL-II RF BEAM POSITION MONITOR COMMISSIONING UPDATE

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Abstract

The National Synchrotron Light Source II (NLSL-II) is a third generation light source currently in the commissioning stage at Brookhaven National Laboratory. The project includes a highly optimized, ultra-low emittance, 3GeV electron storage ring, linac pre-injector and full energy booster synchrotron. Successful commissioning of the booster began in November 2012, followed by the ongoing commissioning of the NLSL-II 3GeV electron storage ring which began in March 2014. With those particles first injected came a value realization of the in-house developed RF Beam Position Monitor (RF BPM). The RF BPM system was envisioned and undertaken to meet or exceed the demanding applications of a third generation light source. This internal R&D project has since matured to become a fully realized diagnostic system with over 250 modules currently operational. Initial BPM performance and applications will be discussed.

INTRODUCTION

NLSL-II, a 3 GeV ultra-low emittance third generation light source, currently in the commissioning stage of construction at Brookhaven National Laboratory [1,2]. It includes a 200MeV LINAC, LINAC to Booster (LtB) transfer line, 200MeV to 3GeV Booster, Booster to storage ring (BtS) transfer line and 3GeV storage ring [3,4]. Injector commissioning was conducted from Nov 2013 to Feb 2014 and 3GeV ramped beam was established in the booster at the end of 2013. Storage ring commissioning began in March 2014 and 25mA of stored beam was achieved by May 2014. After a 2 month shutdown to install the super-conducting RF cavity, commissioning resumed at the end of Jun 2014 for a few weeks and the goal of 50mA of stored beam was achieved by mid July 2014. Commissioning is expected to resume in October of 2014. The NLSL-II storage ring is equipped with 180 RF BPMs (2 per each multipole girder, 3 multipole girders per ring cell) plus a number of “specialized” BPMs, 4 in injection straight, and (eventually) two or more per every ID straight.

BPM ELECTRONICS OVERVIEW

The NLSL-II RF BPMs incorporate the latest technology available in the RF, Digital, and Software domains. A single design has been achieved that strives to meet all NLSL-II operational requirements for all the

injection components as well as the storage ring. During the linac and then booster commissioning BPMs performed very well, easily meeting the corresponding specifications. However, it is the storage ring performance specs, especially the resolution and long term drift that impose the strictest requirements [5]. The architecture of the rf bpm electronics has been carefully conceived to provide robust design with substantial flexibility to serve as a platform for other systems.

The rf bpm electronics system consist of 1) a chassis, housing an analog front-end (AFE), digital front-end (DFE) & power supply (PS) modules, shown in Fig. 1; and 2) a pilot tone combiner (PTC) module mounted in the tunnel near rf buttons, shown in Fig. 2.



Figure 1: NLSL-II RF bpm electronics chassis.

The AFE topology is based on band-pass sampling architecture which subsamples the 500MHz impulse response of the SAW band-pass filter at ~ 117 MHz. The response of the filter produced for a single bunch results in an impulse of approximately 30 samples or ~ 300 ns in length. Coherent timing is derived from an external 378 KHz revolution clock via differential CML. An analog phase-locked loop is used to synchronize VCXO ADC clock synthesizer [7,8]. The received revolution clock is transmitted to the DFE to serve as a time reference for the DSP engine.

The DFE is responsible for all DSP of the button signals and communication of the results with the control system. The DFE is based on a Xilinx Virtex-6 Field Programmable Gate Array (FPGA). The fixed-point DSP engine calculates TbT position based on a single-bin DFT algorithm. The FOFB 10KHz data and 10Hz slow acquisition data are derived directly from the TbT calculation.

The bpm system is parametrically configured for single-pass, booster or storage ring. The digital signal processing (DSP) architecture is also generic; all three operational modes use the same firmware.

*Work supported by DOE contract No: DE-AC02-98CH10886.

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The bpm's in a cell communicate with an industrial PC running an EPICS IOC via TCP/IP [6]. The communication protocol supports waveform monitoring for ADC raw data waveform (117 MHz), single pass, turn by turn waveform (TbT, 378 kHz), fast waveform (FA, 10 kHz) and slow data (SA, 10 Hz). The ADC raw, TbT and FA data is triggered on demand and supports a large 1 million sample history buffer (~32 Mbytes). Table 1 provides a summary for all data transfer capabilities.

Table 1: RF Bpm Data Transfer Capabilities

Data Type	Mode	Max Length
ADC Data	On-demand	256Mbytes or 32M samples per channel simultaneously
Single-Pass	Streaming	800hr circular buffer (1Hz Injection)
TbT	On-demand	256Mbytes or 5 M samples Va,Vb,Vc,Vd, X,Y,SUM, Q, pt va,pt vb,pt vc,pt vd
FOFB 10KHz	Streaming via SDI Link & on demand	Streaming - X,Y,SUM; For on demand: 256 Mbytes or 5 Msamples. Va,Vb,Vc,Vd, X,Y, SUM, Q, pt_va,pt_vb,pt_vc,pt_vd
Slow Acquisition 10Hz	Streaming and On-demand	80hr circular buffer Va,Vb,Vc,Vd, X,Y,SUM, Q, pt va,pt vb,pt vc,pt vd
System Health	Streaming & on-demand	80hr circular buffer AFE temp, DFE temp, FPGA Die temp, PLL lock status, SDI Link status

The PTC, shown in Fig. 2, is a passive module located on the girder below the rf button. A 1 m SiO₂ cable connects the rf button to the PTC module. A pilot tone generated on the AFE is carried out to the PTC module via a 5th cable, which is coupled into each of four forward beam signal channels. The pilot tone was to be used to provide dynamic calibration to mitigate long term drift. However, test has shown that the bpm long-term stability (< 200 nm) has been achieved by the use of highly stable ±0.1 °C thermally regulated racks. The pilot tone now is only used for system diagnostics and integration without beam [9].

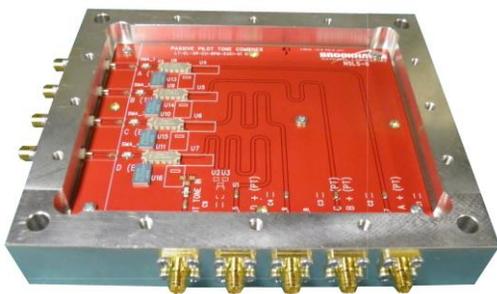


Figure 2: Pilot Tone Combiner (PTC).

BPM COMMISSIONING RESULTS

Initial tests were conducted to measure the performance of the bpm's, but due to limited time and administrative limits (25 mA total beam current towards the end of this commissioning period) the specs could not be fully tested. However, significant progress in verifying the resolution performance of BPMs was achieved at lower currents. Extrapolating these results to higher beam currents we should easily meet the resolution specifications. Separately, due to lack of time, no long term drift studies have been performed and these will be scheduled later.

Resolution Measurements

BPM resolution measurements were performed using a dedicated BPM button assembly located on girder 2 in cell 28. This assembly is not used in normal operations but was rather instrumented with an electronics module specifically for this test. The module was connected to the 4 bpm buttons using a combiner/splitter assembly to make the measurements independent of transverse beam motion. The connection scheme sums the 4 button signals with a 4:1 combiner and then splits the summed signal using a 1:4 splitter, which are then connected to the 4 input channels of the electronics. 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 using three different fill patterns; single bunch, 50 bunches, and approximately a 60% fill (~800 bunches). For each of these fill patterns beam was injected into the storage ring and then allowed to naturally decay. To help speed up the decay process, scrapers were inserted to a position which limited the beam life-time to approximately 15-30 minutes. Data was then collected from the BPM approximately every 5 seconds along with the beam current from the DCCT. The data collected from the BPM was; raw ADC data (1Mpts), TbT data (10Kpts), and FA data (18Kpts). Over 100 data files were collected for each fill pattern as the beam decayed. Figure 3 shows the resulting ADC data for each of the fill patterns.

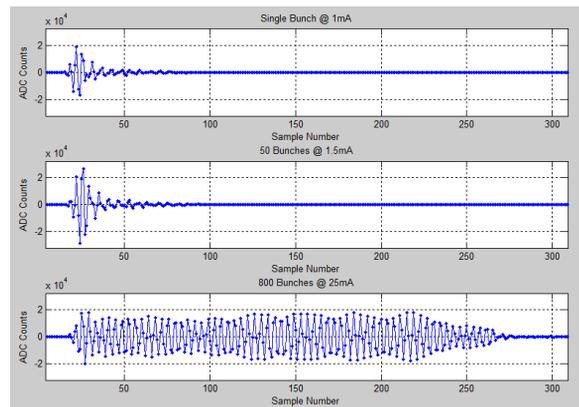


Figure 3: Raw ADC data for different fill patterns.

The single bunch resolution performance of the electronics is shown in Figure 4 for TbT data and in Figure 5 for FA data. The digitizer on the BPM has 16 bits of resolution so the maximum value is 3.2767×10^4 . The maximum ADC value of each of the four channels was found and the mean value of these maximums is plotted on the ordinate of the resolution plots. At the time of these tests the maximum single bunch beam current that could be stored in the ring was about 1mA, which was not enough to bring the ADC's of the electronics to full scale, so the full scale resolution could not be measured. At around 1/2 full scale the resolution is about 12um for TbT data and 2um for FA data. A resolution gain of a factor of six is expected from TbT positions to FA positions, since the bandwidth reduction is a factor of 38.

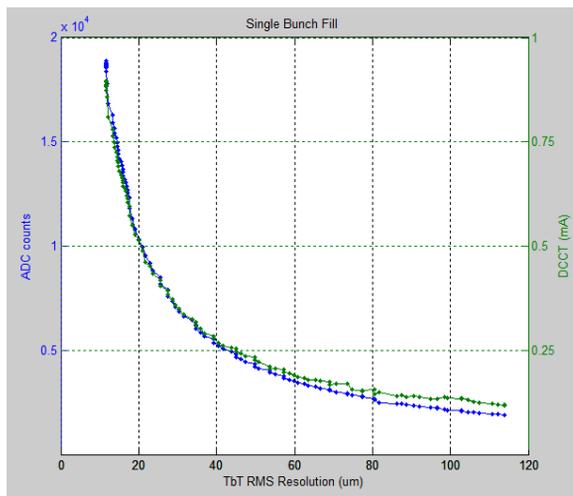


Figure 4: TbT data resolution with single bunch.

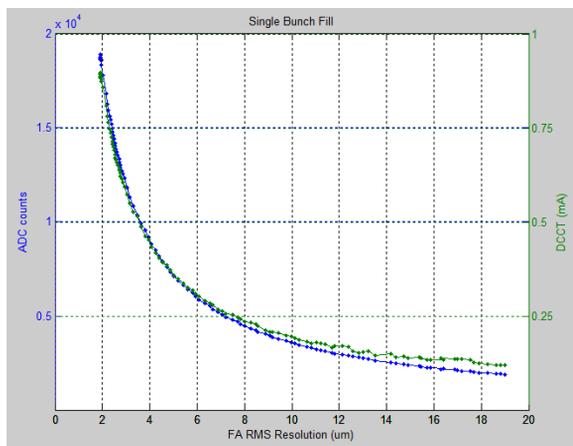


Figure 5: FA data resolution with single bunch.

For a 50 bunch fill pattern the results are shown in Figure 6 for TbT data and in Figure 7 for FA data. With this fill pattern the BPM's reached saturation at about 1.6mA of beam current. At full scale the resolution was measured at 7um for TbT data and just over 1um for FA data.

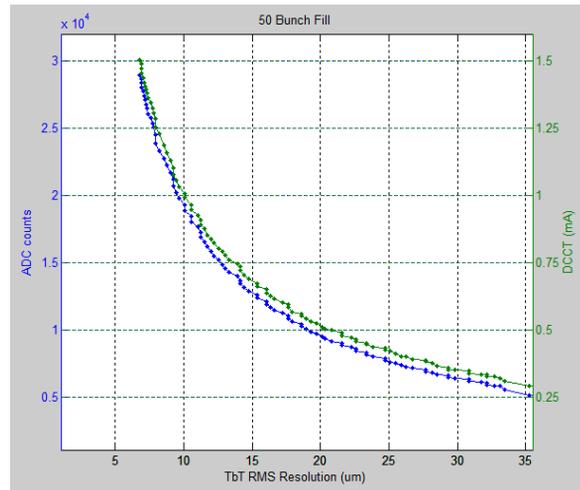


Figure 6: TbT data resolution with 50 bunches.

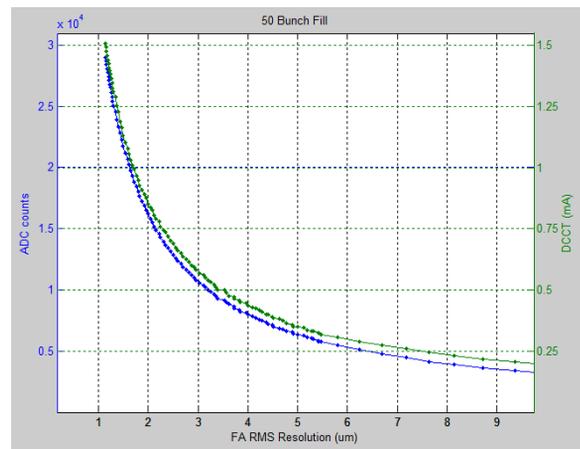


Figure 7: FA data resolution with 50 bunches.

The final measurement was done with a fill pattern of about 800 bunches, or 60% fill. The limiting factor for this test was the administrative limit of 25mA maximum beam current, so the BPM's didn't quite reach their full scale range. At beam currents above 15mA the results became irregular as the maximum ADC count values began to fluctuate greatly between data sets and stopped monotonically increasing as beam current continued to increase. This can be seen in Figures 8 and 9. Above 15mA of beam current the maximum ADC values smear out, which could be an indication of longitudinal instabilities at these higher beam currents. Even with these issues the TbT resolution easily meets the specification of < 3um rms with an 80% fill.

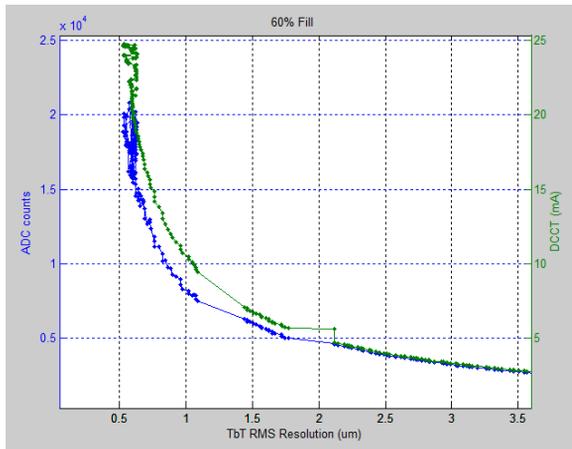


Figure 8: TbT data resolution with 60% fill pattern.

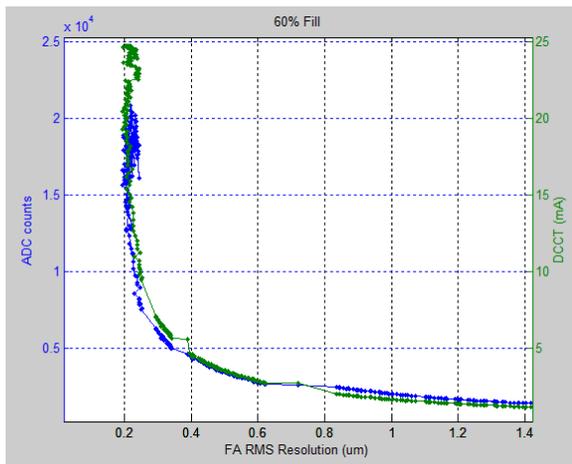


Figure 9: FA data resolution with 60% fill pattern

Timing Adjustment

The Beam Position Monitor Electronics calculates a single horizontal and vertical position for every revolution. To function correctly the electronics needs to have its timing signals properly adjusted. This involves the adjustment of two different delay values, one being a fine adjustment and one a coarse adjustment. The fine adjustment, called the geographic delay, provides a delay of the machine clock (Frev) signal which is received from the timing system. The delay resolution is approximately 8.5ns, which is the ADC sampling clock period, and the range of the delay is a single revolution, which is 2.6us. The machine clock signal provides the critical signal to instruct the DSP engine to begin a new position calculation. For every machine clock signal received a new position calculation is performed. The function of this delay is to provide a knob to the user to permit compensation for various cabling delays and beam transit delays between BPM's, thus allowing all BPM's in the ring to perform their position calculation on the same bunches. The BPM calculates a new position for every revolution, but unless a trigger signal is received via the timing system, the results are not saved to memory. This

is where the coarse adjustment, called the trigger delay, comes into play. This value delays the trigger signal so that the desired revolutions of the beam are saved to memory. Once a trigger is received the next N ADC samples and position calculations are saved to memory. For the storage ring BPM's this value was found to be a value of 10,795,750 which corresponds to an actual delay of about 92ms to properly align to the first injected revolution. The timing was done experimentally, one BPM at a time, using the CSS panel shown below in figure 10. This CSS panel helped streamline the operation by allowing changes and showing the results for an entire cell. In theory, all trigger delays should be equal, and only the geographic delays should change as a function of its location in the ring. For most cases this was found to be true, but some anomalies were discovered. The reason we believe is from timing cables with inverted polarity, plus perhaps cell to cell timing discrepancies. We are currently investigating these issues. Regardless, the flexibility of the BPM timing architecture permitted us to overcome these issues and still properly align the timing. All 180 storage ring BPM's were successfully timed in and operational in under 2 hours.

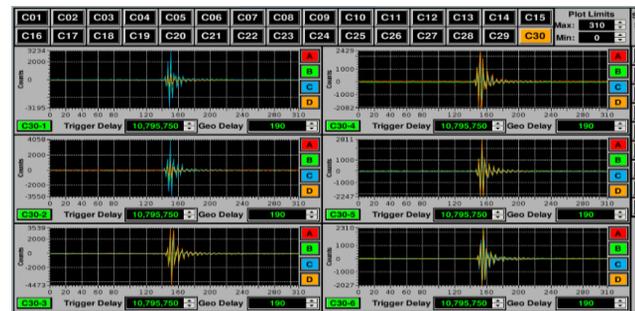


Figure 10: BPM Timing CSS Panel.

Triggering Modes

The flexibility of the BPM architecture permits it to be triggered in various modes and configurations. The raw ADC data, turn-by-turn (TbT) data, and Fast Acquisition (FA) data are all on-demand data streams and are only available to the user if a trigger signal is received by the BPM. After the trigger signal is received, up to millions of data points from each data stream are stored to the large DDR memory on the BPM. Depending on beam conditions, the trigger scenarios may vary. During the initial operation when first turn was being attempted, the BPM's were set to trigger on the booster extraction event (Event 66). In that scenario, the BPM's could capture the data for the first few million turns after injection. After stored beam was achieved the BPM's were set to trigger on the 1 Hz event (Event 32), so that BPM data would be constantly refreshed to users. In this mode limited record lengths are available do to the communication of long waveforms through the control system. If a user wanted to capture a single shot, long data record, the BPM's can be placed into internal trigger mode and then issued a global single shot event. In this mode the BPM's will trigger only once, to allow time for large records to be

offloaded from the local DDR memory through the control system and to the high level applications. These were the main triggering modes of operation used during commissioning. About halfway through commissioning it was observed that if the targeted injection bucket was greater than 200, the BPM's would start reporting positions on incorrect turns. After discussions with the timing system experts, it was learned that the timing of this event (66) was relative to targeted bucket and therefore moved with respect to the machine clock. Since different BPM's need different geographic delays, this timing shift could cause inconsistent results between BPM's. The problem was solved by adding another event (47) to the timing system which always has a fixed timing relationship to the machine clock.

SUMMARY

BPMs were by far the most heavily used diagnostics during the commissioning. A great number of high level applications make use of BPM data. These include, to name just a few, stored beam orbit measurement, correction, and (slow) feedback (typically using SA data); various linear lattice diagnostics tools (LOCO from SA, tune measurement from TbT, etc.); dynamic aperture and other non-linear lattice diagnostics tools relying on kicked TbT beam response and many others.

It is also worth emphasizing, that even without running any sophisticated tools, the ability to quickly check BPM ADC signals at any ring location or glance through minimally processed TbT data around the ring was absolutely crucial for the ring commissioning. For instance, the very first turn around the ring was closed and confirmed simply by looking at ADC-sum BPM signals all around the ring. Similarly, an aperture in cell 10 (which later turned out to be a hanging RF seal) was first suspected from the fractional drops of kicked beam TbT BPM sum signal which persistently showed up on BPMs at that particular location [10].

So far the overall experience with BPMs was very positive, especially after additional triggering modes were added. Of course, as is typical for any commissioning, we did encounter and fixed some of the newly discovered issues with the BPM system. During the SR commissioning proper, the hardware issues with BPMs turned out pretty minimal, i.e. two units (out of 236) had to be replaced because of a failed PLL module. Rather, the majority of the issues were related to the communication between the BPMs to the IOCs as well as from the IOCs to the rest of the control system. Most of these issues were not anticipated prior to the commissioning but rather resulted from the evolution of the requirements from the BPM users, which naturally evolved during the commissioning.

Additional BPM system commissioning studies must be performed in the future. Even though the initial BPM resolution measurement results are very encouraging, to fully verify the compliance with the specs, similar

measurements should be repeated at higher currents, as well as with long bunch trains (when stable). When larger amounts of dedicated beam time are provided, long term drift studies should also be performed. In addition, studies to characterize orbit sensitivity to the fill pattern changes and as well as to the changes of BPM attenuation should be performed (the latter have only been done with the pilot tone, not real beam). These will allow us to decide whether automated adjustments of BPM attenuation should be implemented in the control system, and if so, how. Another important issue for physics applications is the correction of the non-linearity at large transverse beam displacements (this is unrelated to the BPM electronics). So far the linearity is corrected using the coefficients obtained from BPM button geometry (essentially solving the Laplace equation). Experimental verification of these would be extremely beneficial, and it could be accomplished, for instance, by comparing the BPM readout with large transverse beam offset vs. the positions on the nearby flag.

REFERENCES

- [1] NSLS-II preliminary design report", <http://www.bnl.gov/nsls2/project/PDR>
- [2] F. J. Willeke, "Status of NSLS-II project", PAC11, New York, USA, (2011).
- [3] T. Shaftan, "Status of NSLS-II Injector", IPAC13, Shanghai, China, (2013).
- [4] R. Fliller, "Results of NSLS-II Linac Commissioning", IPAC13, Shanghai, China, (2013).
- [5] S. Krinsky, "Accelerator physics challenges for the NSLS-II Project", PAC09, Vancouver, Canada, (2009).
- [6] Kiman Ha, "NSLS2 beam position monitor embedded processor and control system", ICALEPCS11.
- [7] K. Vetter, "NSLS-II RF beam position monitor", PAC11, New York, USA, (2011).
- [8] K. Vetter, "NSLS-II RF beam position monitor update", BIW12, Newport News, Virginia, USA, (2012).
- [9] O. Singh, "NSLS-II BPM and fast orbit feedback system", IBIC13, Oxford, UK, (2013).
- [10] W. Cheng, "NSLS2 Diagnostic Systems Commissioning and Measurements", IBIC2014, Monterey, CA, USA, (2014).