

# A PPS Compliant Stored Beam Current Monitor At NSLS-II

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**Abstract:** A requirement for top-off operations at the NSLS-II facility is at least 50mA stored ring current. The Stored Beam Current Monitor (SBCM) is part of the NSLS-II Top Off Safety System (TOSS) that determines the storage ring current based on Pick-Up Electrode (PUE) readings. The SBCM downconverts the 500 MHz component of the PUE signal to 2 MHz. The 2 MHz signal is rectified, averaged down to a bandwidth of 500 Hz, and compared to a threshold voltage equivalent to 55mA of stored beam. A redundant SBCM system was also constructed and these two systems must agree that the stored beam is above the threshold to enable top-off operations. The SBCM is also required to remain accurate over wide range of possible fill patterns up to a total current of 500 mA. Under normal conditions for top-off operations the SBCM measurement accuracy is about 1%. The SBCM was commissioned in 2015 as part of the Top-Off Safety System (TOSS) which is responsible for ensuring safe top-off operations at NSLS-II.

## Introduction

The NSLS-II facility operates in top-off mode where charge is injected into the storage ring at about one minute intervals while beamline safety shutters are open in order to maintain a relatively constant stored current. The TOSS is a multi-levelled interlock designed to ensure that top-off operations at NSLS-II are executed safely. One requirement of the TOSS is that there be at least 50mA of stored beam in the ring. The detection of stored beam indicates that critical ring systems, such as RF and magnet power supplies, are working correctly. The SBCM is a sub-system of the TOSS that performs the stored current measurement.

The SBCM processes PUE signals generated by the beam in order to determine the stored current. The RF cavity frequency of 500 MHz organizes the ring into 1320 RF buckets with the beam typically occupying 80% of these buckets during top-off operations. The gap formed by the empty buckets modulates the 500 MHz PUE signals at the ring rotation frequency of 378.78 KHz (Fig. 1).

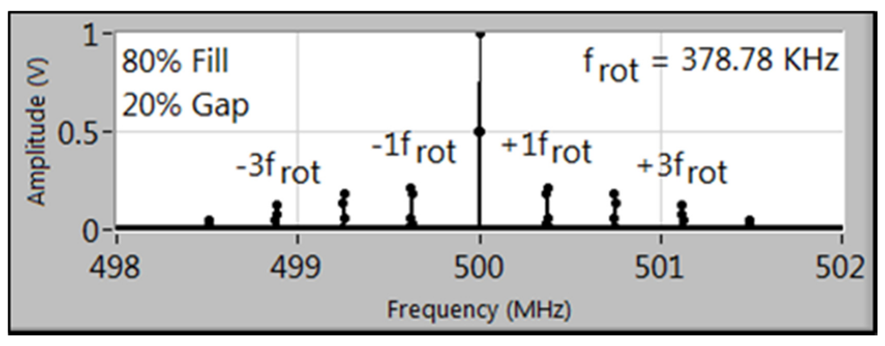


FIGURE 1: Modulated PUE Signal

At the frequency range shown in Figure 1 parasitic elements in the analog circuit would make the current measurement difficult to perform. If the PUE signal is mixed with a 498 MHz local oscillator the pattern shown in Figure 1 is regenerated at 2 MHz and at 998 MHz. A 20 MHz low-pass filter blocks the signals centered on 998 MHz. The current information encoded on the PUE signal is preserved on the downcoverted 2 MHz signal. The modulation of the PUE signal is also downconverted as shown in Figure 2.

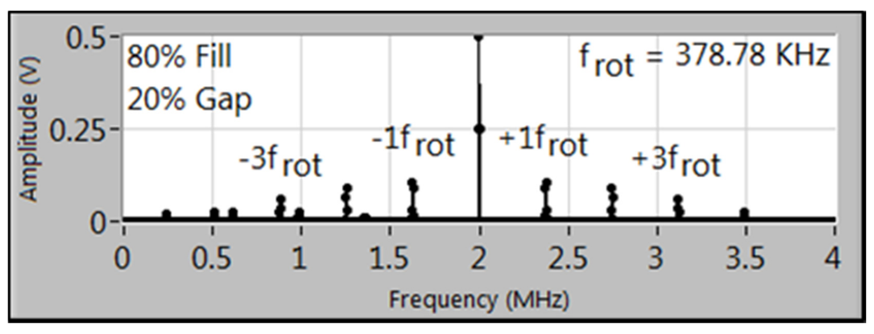


FIGURE 2: Downconverted PUE Signal

The downconverted PUE time-domain signal is shown on the left side of Figure 3. The plot shows about 2 ring revolutions of data. The right side of Figure 3 shows the absolute value of the downconverted signal.

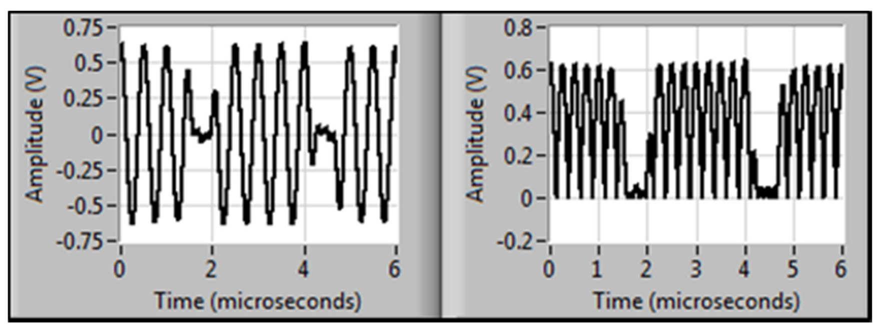


FIGURE 3: SBCM Time-Domain Signals

The absolute value is averaged over about 750 ring revolutions to obtain the SBCM reading. For a given fill pattern the relationship between the SBCM reading and the stored current is highly linear with nonlinearities below 1%. Different fill patterns will have slightly different proportionality constants. The fill pattern dependence will be discussed in depth later.

## The SBCM System

Figure 4 shows the block diagram for the SBCM. A 5:1 combiner module located on the girder with the PUEs performs the passive sum of the PUE signals and allows a test signal to be added into the sum for SBCM certification tests. Outside the storage ring a cabinet houses all SBCM components for both the primary and redundant systems. Two PCBs were developed for the SBCM, a mixer circuit and a rectifier circuit. In order to establish a safety rating both of these circuit designs were submitted for independent fault tree and thermal stress analyses. Both circuits received mean time between failure ratings above the required $10^6$ hours [1]. The output of the rectifier circuit controls a safety relay which indicates that the minimum required current is stored.

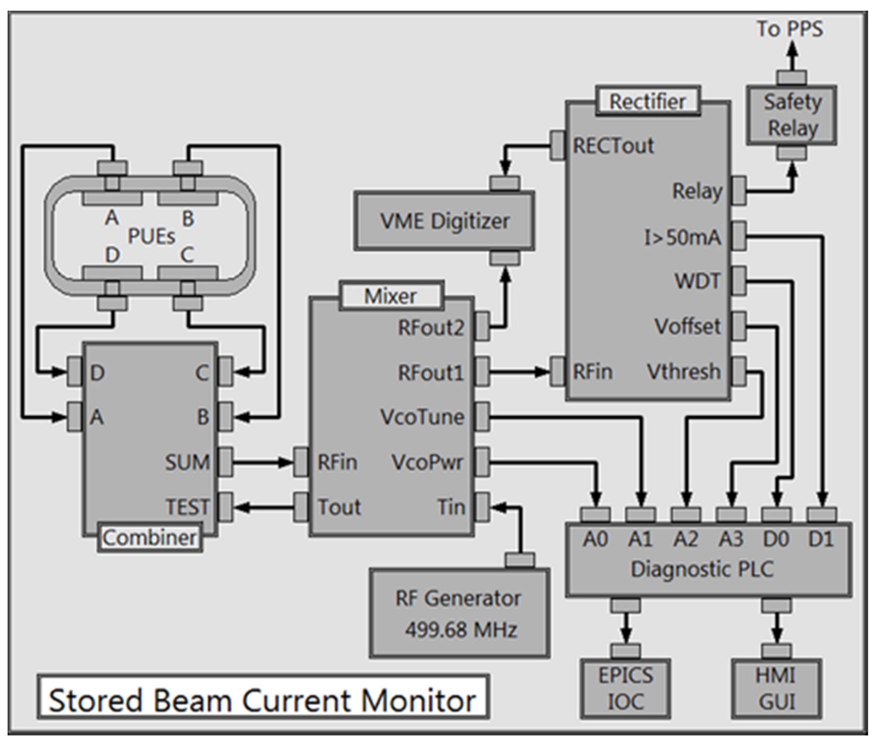


FIGURE 4: SBCM Block Diagram

The performance of the SBCM is monitored using a PLC which reads a number of diagnostic signals from the mixer and rectifier circuits. The PLC displays system information locally on the SBCM cabinet using a GUI on an HMI panel. The PLC also sends system information to an EPICS IOC for remote monitoring. A VME digitizer is used to monitor the 2 MHz downconverted signal. The diagnostic monitoring is not part of the safety function of this system and is not designed to that level. During SBCM certification tests an RF Generator is connected to the mixer circuit to provide a "fake" beam signal to the combiner module. The RF Generator is calibrated so that any value of simulated stored current can be created on demand.

*Combiner Module:*

The combiner module consists of two passive combiner components (Figure 5). A 500 MHz RF signal can be applied at the test input to provide "fake" beam for various tests otherwise that input is terminated. The RFout signal is the sum of all the input signals.

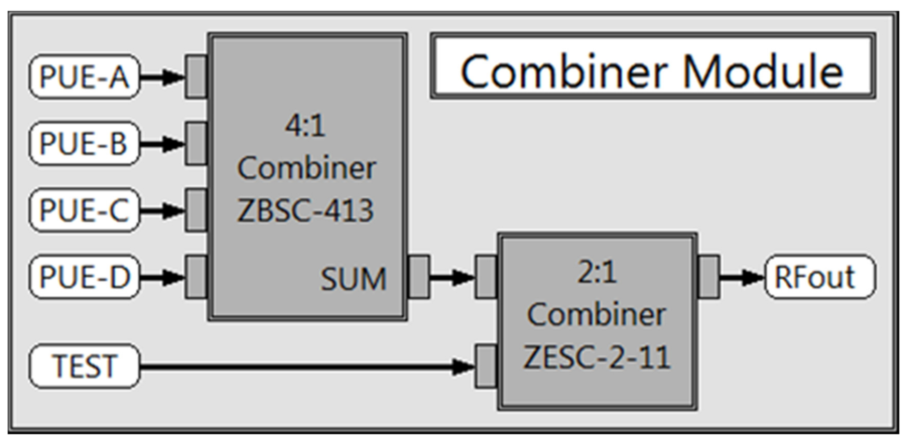


FIGURE 5: RF Signal Combiner Module

*Mixer Module:*

The block diagram for the mixer module is shown in Figure 6. The sum signal from the combiner module is sent to the mixer input (RFin). A bandpass filter passes the 500 MHz component of the input which is then mixed with a local oscillator. The oscillator is adjusted to 498 MHz and passed through a directional coupler. The through port of the coupler goes to the mixer and the coupled port goes to a RMS power detector to monitor the local oscillator power. Only the 2 MHz component of the mixer output is passed by the 20 MHz lowpass filter. That signal is split and sent to amplifiers to drive the two RF outputs. One RF output is sent to the rectifier module for further processing and the other output is sent to a VME digitizer to monitor the 2 MHz signal.

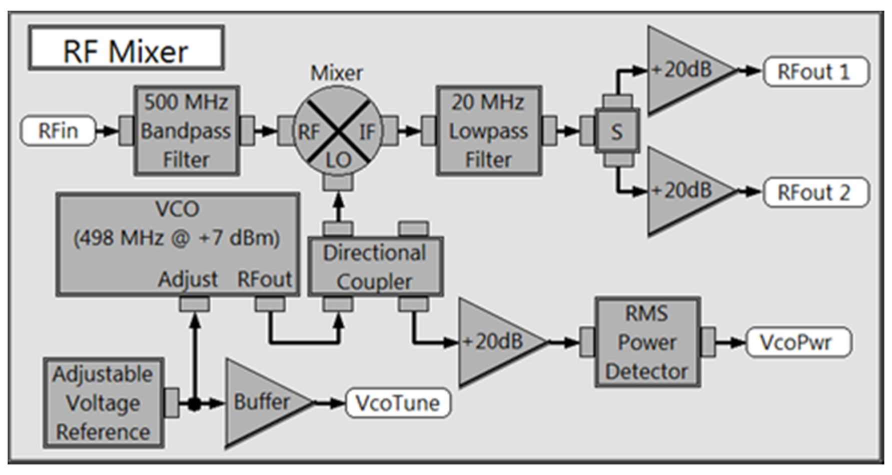


FIGURE 6: RF Mixer Module

*Rectifier Module:*

The block diagram for the rectifier module is shown in Figure 7. The mixer output is sent to RFin and the absolute value is formed using the circuit shown in Figure 8. The rectified signal is averaged using a 500 Hz lowpass filter. A voltage reference is adjusted to provide a threshold level equivalent to 55mA of stored ring current. A comparator is used to determine if the averaged rectified signal is above the threshold. Hysteresis is applied to the threshold voltage to keep the transitions of the comparator output clean.

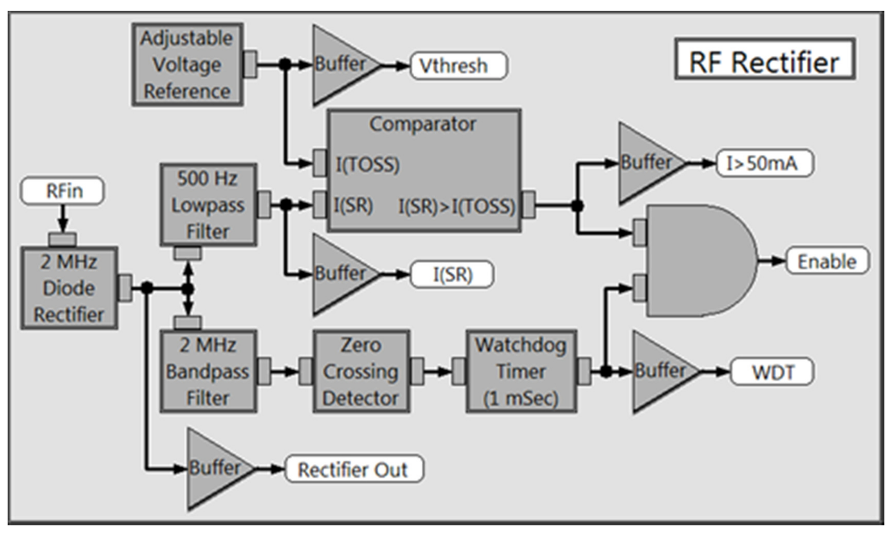


FIGURE 7: Rectifier Module

The absolute value circuit (Fig. 8) works well for RF inputs below 5 MHz. Above 5 MHz the effects of parasitic capacitance cannot be ignored. The offset voltage acts as a zero adjustment. The circuit is set up with a gain of 10.

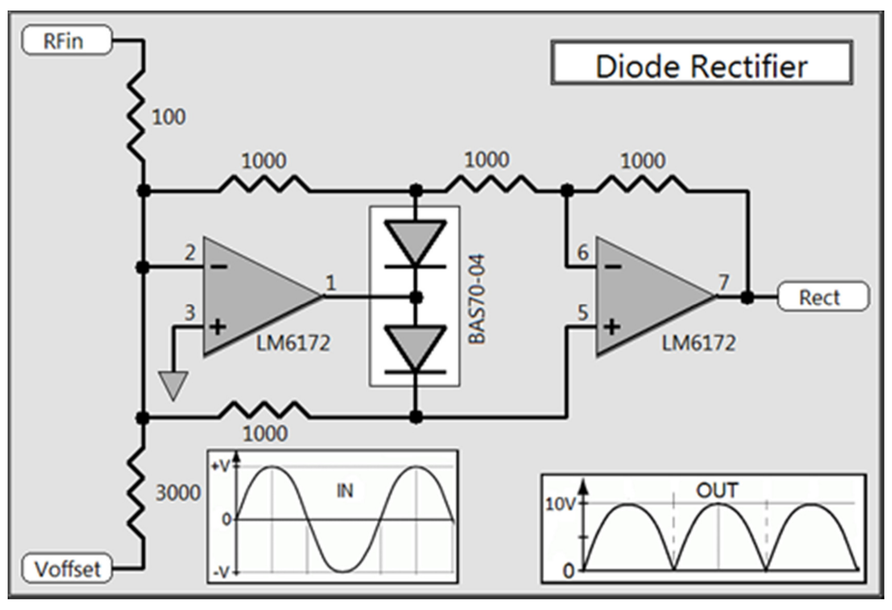


FIGURE 8: Diode Rectifier Schematic

A second copy of the rectified signal is passed through a 4 MHz bandpass filter to remove the DC offset. A zero-crossing detector and a watchdog timer determine if transient signals are present. This is done to ensure that the output of the circuit in Fig.8 has the proper time structure. If the threshold comparison and the watchdog timer are satisfied then an enable signal closes a safety relay that ties directly into the TOSS.

## Bunch Pattern Dependency

Top-off operations normally use an 80% fill pattern however other fill patterns are permitted. The TOSS specification demands that the SBCM disable top-off operations whenever the stored current is below 50mA for any fill pattern between 20% and 100%. Since the vast majority of top-off operations use an 80% fill pattern the SBCM is calibrated to that pattern. The threshold setting for the SBCM is chosen so that the measurement error for other fill patterns does not result in a violation of the TOSS specification. Figure 9 shows the changes in the modulation sidebands induced in the downconverted PUE signal for an 80% and 20% fill pattern with the same total current. Note that a 100% fill pattern would have no modulation sidebands.

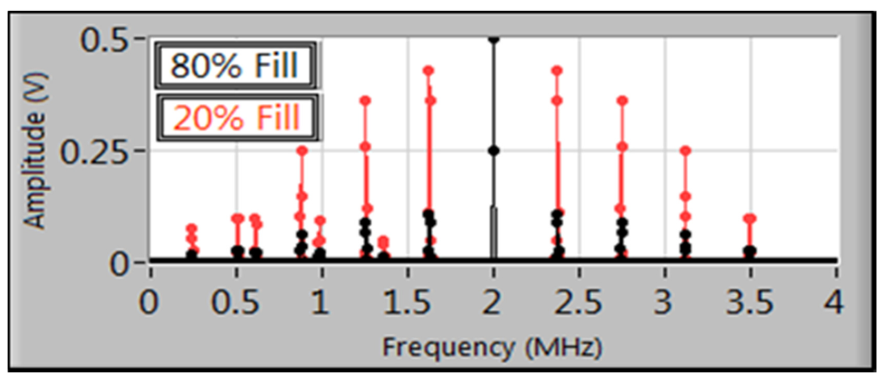


FIGURE 9: Harmonic Content vs Fill Pattern

The modulation sidebands will contribute differently to the average of the diode rectifier signal for different fill patterns. For a given fill pattern the relationship between the stored current and the SBCM reading is linear however different fill patterns have different slope terms as shown in Figure 10.

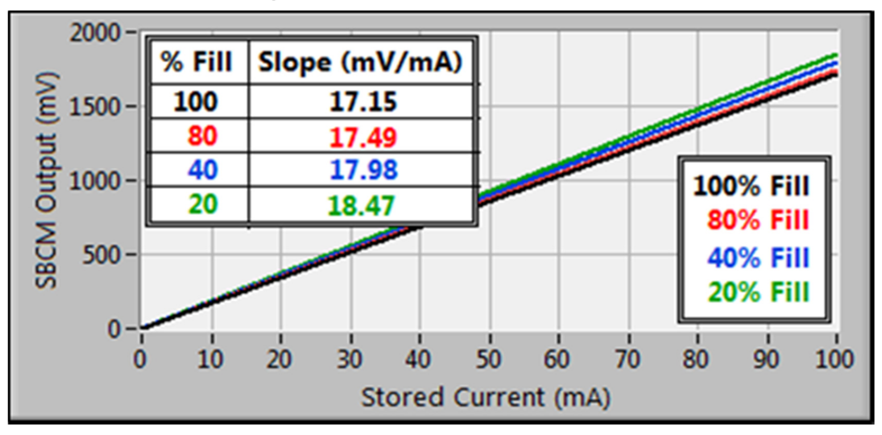


FIGURE 10: Calibration Slope vs Fill Pattern

In Fig. 11 the data in Fig. 10 is expanded around the threshold level for the SBCM:

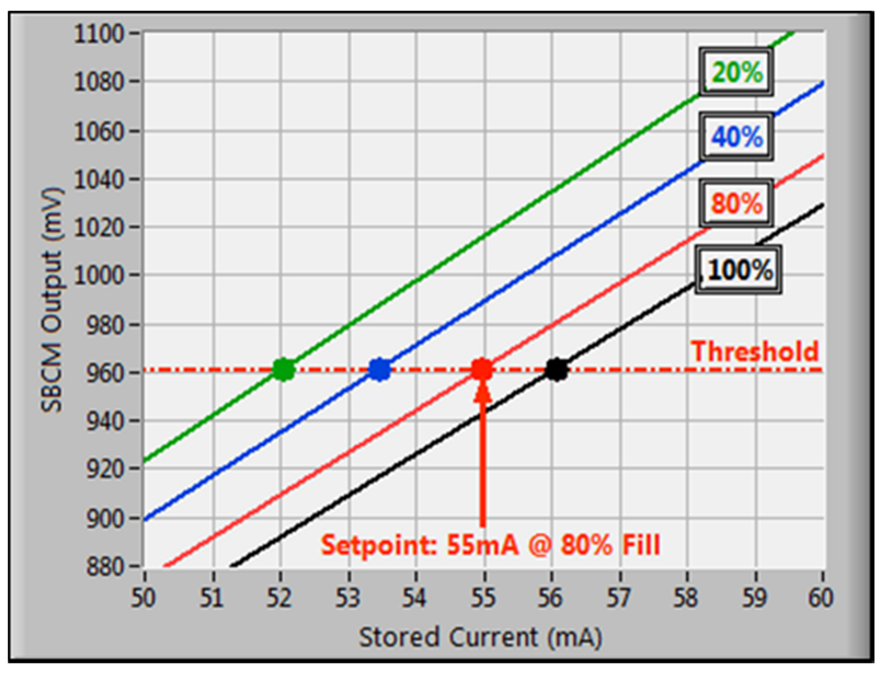


FIGURE 11: Determining Threshold for SBCM

The SBCM threshold is set to the SBCM output for 55mA of stored current with an 80% fill pattern. This setting ensures that the TOSS specification for the SBCM is never violated for any fill pattern between 20% and 100%. Figure 12 shows the percent error generated by the fill pattern for the SBCM output as compared to the SBCM output of an 80% fill pattern.

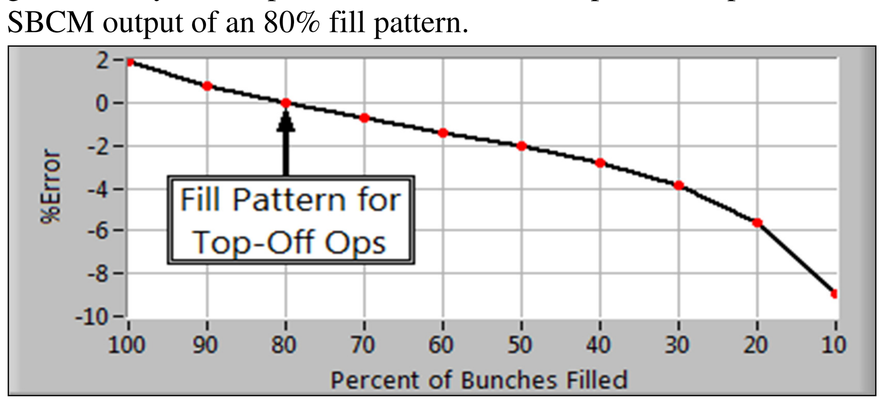


FIGURE 12: Measurement Error vs Fill Pattern

The SBCM is calibrated against a Bergoz DCCT current reading using an 80% fill pattern. While operating with this fill pattern the SBCM is as accurate as the DCCT. In fact the SBCM was used to diagnose a previously undetected fill pattern dependency of the DCCT itself.

The case where a fill pattern has more than one gap was also studied carefully. For example, measurements were made for an 80% fill pattern with 1 gap, 2 gaps, 4 gaps and so on. The multiple gaps tend to push some of the modulation sidebands out of the passband for the RF mixer circuit and will therefore bring the SBCM measurement closer to the measurement with a 100% fill pattern. The gap number dependency for the SBCM was determined to be less than 1% for one to four gaps and any fill pattern between 20% and 100%.

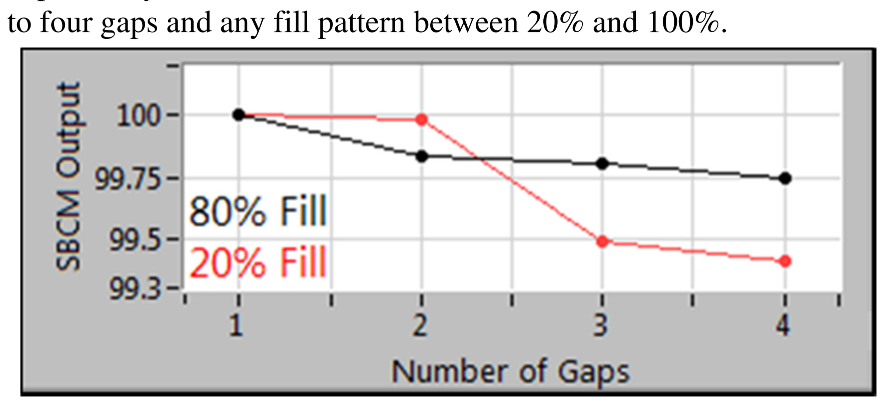


FIGURE 13: Gap Number Dependency for SBCM

The SBCM dependency on beam position relative to the PUEs is not significant for typical beam motions which may be present during operations. The dependency on the storage ring RF frequency or the local oscillator frequency is also not significant for the deviations in these frequencies typically seen during operations.

## Summary

Safely executing top-off operations are vital to fulfilling the mission of the NSLS-II facility. It can be very difficult to meet all the requirements for a safety rated system when a complex measurement must be made. The SBCM distills the current measurement down to a small number of reliable analog components while maintaining the accuracy and stability required for this safety system. Although the SBCM displays a fill pattern dependency it was found to be within the measurement tolerance over the require range of 20% to 100% fill patterns. For the 80% fill pattern predominantly used during top-off operations the SBCM is still one of the most accurate stored current measurements at the NSLS-II facility and the only current measurement which is PPS compliant.

[1] SBCM MTFB Reports, www.bnl.gov :
- LT-EL-SR-BI-TSS-0103-93, LT-EL-SR-BI-TSS-0103-94
- LT-EL-SR-BI-TSS-0103-97, LT-EL-SR-BI-TSS-0103-98