# "BUNCHVIEW" A FAST AND ACCURATE BUNCH-BY-BUNCH CURRENT MONITOR

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*Abstract*

BunchView is a system for the direct measurement of the current from each bunch circulating in a storage ring based on the analysis of the RF-signals delivered by a set of striplines. This paper describes the development, achievements, operation, and results of this fast and accurate bunch current monitor built for the BESSY and MLS storage rings.

Using a combination of a 14/16Bit analog to digital converter (ADC), a high-speed FIFO, ECL technique, and FPGAs, a real-time measurement of the fill-pattern with high accuracy and bunch-by-bunch resolution was achieved. The results are identical to the fill-pattern determined by time correlated single photon counting based on synchrotron radiation detected with an avalanche photo diode.

BunchView is fully integrated into the EPICS control system. The data provided by the BunchView monitor give accurate bucket position in the ring and bunch current over a wide dynamic range. The smallest measured single bunch current is less than 100nA. In the future the system will be used in the top-up mode of operation in order to inject beam into the emptiest buckets and thus keep the fill-pattern stable over longer periods of time.

## INTRODUCTION

The BESSY machine is a third-generation light source operating at energy of 1.7 GeV with a stored current up to 300 mA. In the storage ring, electrons might be stored in any pattern consisting of up to 400 bunches. Knowledge of the fill-pattern of the buckets in a ring is very important, especially as more sophisticated time-resolved experiments are considered. At the time, BESSY has three modes of operation with special fill pattern: 1$^{st}$ the multi bunch (MB) mode with 350 consecutive filled buckets and a gap of 100 ns for ion-clearing, 2$^{nd}$ the single bunch mode (SB) with up to 20 mA, and 3$^{rd}$ the hybrid mode where a single bunch of 10 mA is injected in the middle of the gap. The operation in top-up mode [1] requires a real-time, high resolution determination of the current stored in each individual bucket.

## DIAGNOSTIC TASK

We looked for a detection system, which monitors the current in each bucket with more than 12 bit accuracy and updates the whole fill-pattern of 400 bunches in less than 100 ms. Moreover, the system must be synchronized to the timing control at BESSY and thus gets the bunch number and its corresponding current value as shown in Figure 1.

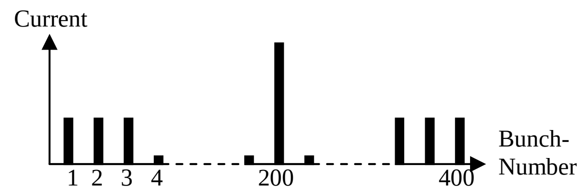



Figure 1: Fill-pattern in the storage ring.

Unfortunately, all commercial oscilloscopes have less than 8 bit amplitude resolution at the 500 MHz analog bandwidth.The best ADC-cards reach at best 10 bit resolution. The main reason is the track-and-hold (T/H) amplifier in the front-end of the ADC where the analog value is stored during the digitalisation process [2]. The hold time is essential for the amplitude resolution of the ADC. At present, many ADCs with a 14/16 bit amplitude resolution and an analog bandwidth of more than 500 MHz are on the market. But they all have a sampling rate below 130 MHz. Operating many ADCs in parallel would overcome this limit, however, would also lead to a more complicated design and a larger size. An alternative method for the data acquisition based on only one ADC and undersampling is used in our monitor and will be described in detail below.

## PRINCIPLE OF MEASUREMENTS

In the storage ring the bunches circulate with a well defined revolution time which is 800 ns in case of the BESSY storage ring. Thus every revolution time the same bunch passes by the monitor. It is not necessary to detect all the bunch currents during just one revolution because the distribution of electrons distributed over the buckets does not change that fast. In addition we wanted to average the bunch current values over longer times in order to get a better resolution. Therefore, we decided to use signal undersampling [3].

For a better understanding, first consider a model of the storage ring with only 16 bunches as shown in Figure 2. If only every fifth bunch is sampled we catch all bunches in 5 revolution times and we get the following array of digitized bunch intensities:

"1,6,11,16, 5,10,15, 4,9,14, 3,8,13, 2,7,12".

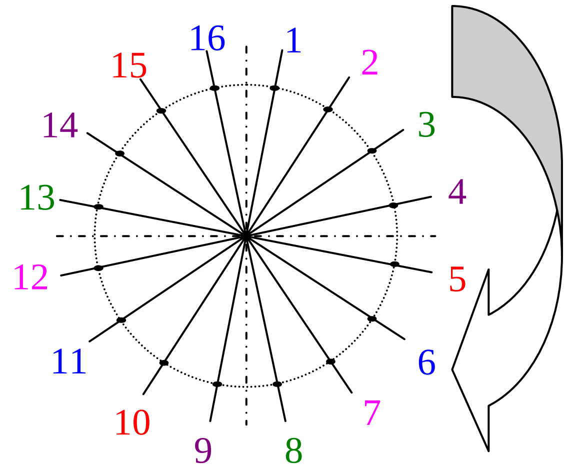



Figure 2: Simplified model with 16 bunches.

With 400 bunches we can not sample every $5^{th}$ bunch, because we will not catch all bunches in this case.

For 400 and 80 we decided to take a divisional number 7, and so we sample each seventh bucket in the storage rings. In this way we have in 800*7 ns (BESSY) the complete fill-pattern (the whole current information from each bunch) as shown in Fig. 3 and thus the sample rate is reduced to 71.4 MHz (500 MHz/7) well within the specifications for our ADC .

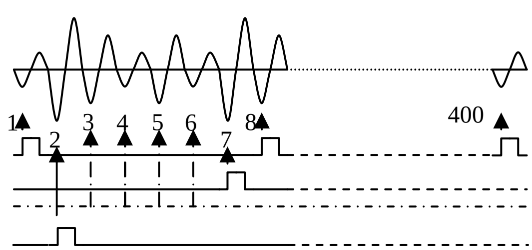



Figure 3: If every 7th bunch is sampled it takes 7 revolution times to acquire the information from each bunch once.

## HARDWARE AND SOFTWARE

The original charge of each bunch can be converted in an electric pulse with different special current sensors in the vacuum pipe of the storage ring. We have knob-type BPM pick-up electrodes, a ring electrode and a set of 4 striplines at BESSY. The pick-up electrodes are not used, because they deliver a rather low signal. The ring electrode provides a 1.5 V peak to peak signal for a charge of 0.8 nC corresponding to 1 mA current in the bunch. This sensor is immune to orbit fluctuations in the ring and requires only one vacuum feed through in the vacuum pipe. We have achieved the best results with a set of 15 cm long striplines. They provide a 4.5 Volt signal for 1 mA bunch current. As shown in Fig. 4 the signal has a very good time response with 50 ohm input impedance.

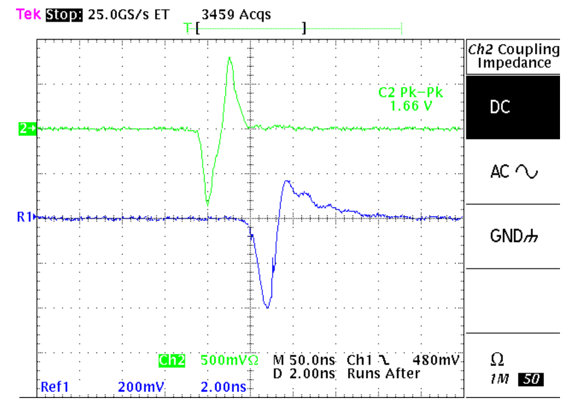



Figure 4: Voltage signals from stripline (in green) and ring electrode (in blue) for a single bunch (0.4 mA) circulating in the storage ring BESSY acquired by a real-time oscilloscope with bandwidth of 500 MHz.

A fast current sensor with high sensitivity and low loss cables are very important for accurate measurements. Bad cables and poor connections to the ADC-board lead to impedance mismatch and cause reflections. A major problem of the current sensor is the time response. The signal from bunches in a train should not overlap. Even with the stripline electrodes the signal of a single bunch extends over 2.3 ns. Note, the bunch spacing could be 2 ns. In order to compensate that, we reshaped the pulse response with a 500MHz low pass filter (LPF) so that influences from neighbouring bunches on the signal are minimized (Fig. 5).

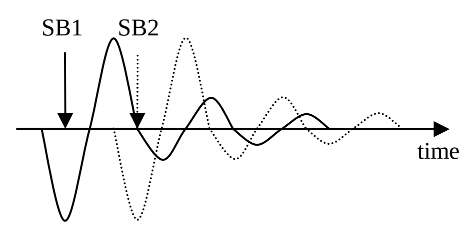



Figure 5: Sampling of the signal from equally populated neighbouring bunches. Signal interference has been reduced with a LPF.

The assembly of the electronics system consists of three main parts. The evaluation board ADC from the Analog Divices, Inc., our control development system and one PXI PC with a FPGA card from the National Instruments, Inc. (Fig. 6).

The power combiner makes the signal less sensitive to the beam position. The filtered bipolar and attenuated sum signal is digitized with the ADC. The sample clock signal for the ADC is derived from the RF master

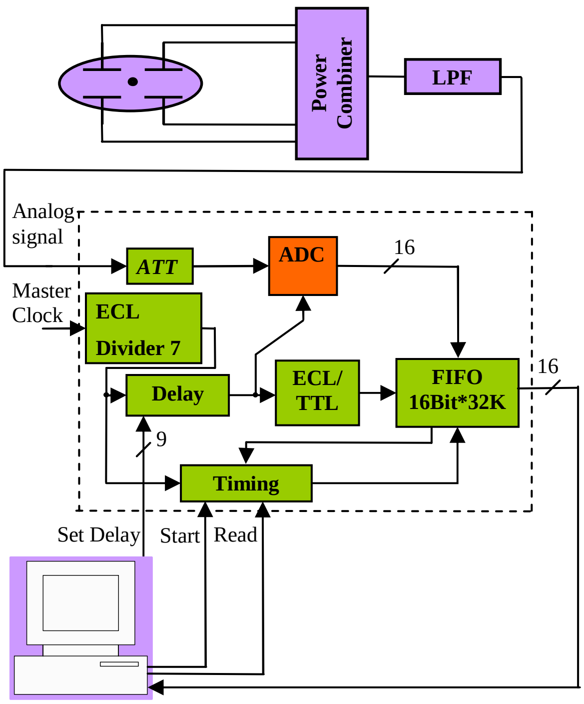



Figure 6: Hardware of the measurement system BunchView.

clock (500 MHz). A low jitter ECL divider and an ECL delay [4] are used in order to create the appropriate sampling times for the acquisition of the top of the signal amplitudes (Fig 3 and 5). The digital data delivered by the ADC are stored in the FIFO. In the 32K*16 bit FIFO up to 80*400 values can be stored. In the next step the data is transferred into the FPGA card (Fig. 7).

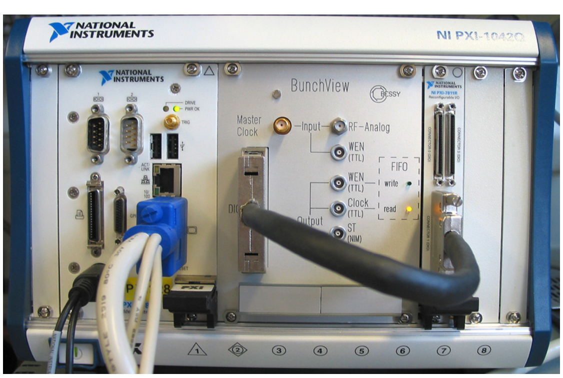



Figure 7: PXI Chassis containing an Embedded System Controller, the BunchView module and the FPGA card.

The fast digital processing in the FPGA card under LabVIEW averages the bunch current for each of the 400 buckets and stores them in the system controller. The LabVIEW host program sorts the data in the right order of bunch number, converts the ADC bits to current (Fig.8), calculates the injection rate, life time, etc. and updates the corresponding EPICS variables.

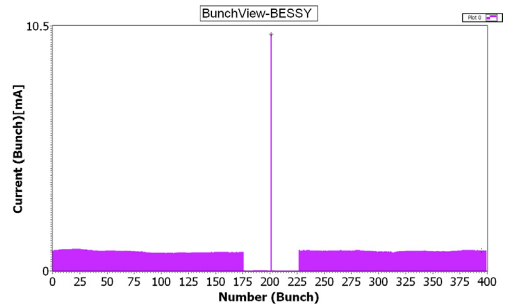
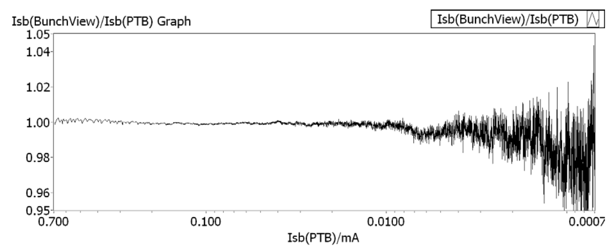



Figure 8: Typical Hybrid fill-pattern at BESSY measured with the BunchView system.

## SENSITIVITY AND LINEARITY

For the test of the sensitivity and the linearity of the BunchView system, a current of 1 mA was injected into the storage ring and a scraper was used to reduce the current gradually over a period of two hours. During this time, the SB current was measured simultaneously with our two DCCTs, a photodiode of the PTB [5], and the BunchView system. The results are shown in Figure 9.




Figures 9: Confirmation of the very good linearity and high sensitivity of the BunchView system between 0.7 mA and 700 nA.

## SUMMARY

BunchView, a bunch-by-bunch current diagnostics system, based on digital sampling of beam induced stripline signals with a 14/16Bit ADC, has been developed at BESSY and was installed successfully in the BESSY and MLS storage rings. The visualization of details of the fill-pattern already during the injection process gives the operator important information: like false SB position and poor SB purity, poor gap clearing efficiency, etc, which can be immediately corrected. The system is also an indispensable tool for low intensity studies during machine development runs.

## REFERENCES

[1] P. Kuske, et al., “Preparations of BESSY for top-up operation” , EPAC'08, Genoa (2008).
[2] National Semiconductor “Specifications and Architectures of Sample-and-Hold Amplifiers”,
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[5] R.Thornagel, et al., “The electron storage ring BESSY II as a primary source standard from the visible to the X-ray range” Metrologia, 2001.