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Measurement of the Real Time Fill-Pattern at the Australian Synchrotron

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Abstract

This article describes the development, commissioning and operation of a Fill-Pattern Monitor (FPM) for the Australian Synchrotron that measures the real-time intensity distribution of the electron bunches in the storage ring. Using a combination of an ultra-fast photo diode and a high-speed digitizer, real-time measurement of the fill-pattern at bunch-by-bunch resolution was achieved. The results compare very well with current methods of measuring the fill-pattern, such as a pick-up style detector. In addition, the FPM is fully integrated into the EPICS control system. The data provided by the FPM gives accurate RF bucket position and bunch current over a wide range of currents, from 0.01 mA in a single bunch to 200 mA total beam current. The FPM monitors the success of an injection attempt into the storage ring and is used on a feedback loop to determine where to target the next injection. Using the FPM a beam top-up mode was successfully tested, resulting in a near constant beam current by periodic targeted injections over an 8 hour shift. Results are presented for dynamically topped up real-time injection, where the beam pattern was squared using an intensity-dependent injection algorithm.

1. Introduction

The Australian Synchrotron is a third-generation light source operating at an energy of 3.0 GeV with an expected electron bunch-width of 20 ps. The storage ring has a harmonic number of 360, a period of revolution of 720.5 ns, and each RF bucket has a width of 2 ns[1].

Knowledge of the fill-pattern profile of electrons in a synchrotron ring is important, especially as more sophisticated time-resolved experiments are considered. For experiments that are spatially and temporally sensitive, it is necessary to have a source with a known temporal-intensity profile in order to be able to analyze the effects of the radiation source on the results. The standard for fill-pattern measurement is a pick-up type monitor, which measures the voltage induced by the bunches as they pass through the vacuum chamber. An alternate method is to use optical synchrotron radiation and ultra-fast diodes to measure the emitted radiation intensity directly. The detector described in this paper uses the latter method to measure the

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fill-pattern of the stored electron beam. An accurate real-time measurement of the intensity profile allows the implementation of methods to alter the fill-pattern dynamically. These may include protocols to perform beam top-up modes, where electrons are periodically injected into the ring to compensate for losses, or to create custom fill patterns to meet the needs of particular beam-line users. Dynamic beam top-up mode is particularly attractive as it leads to a stable beam intensity, thus preventing thermal strain on optical components as well as providing predictable experimental synchrotron radiation for experiments.

2. Experimental Setup

A key feature of the Australian Synchrotron is a dedicated optical diagnostic beamline. It consists of an optical chicane, a focussing lens that forms a 1:1 primary image of the beam, and an optical bench that contains all the diagnostic instruments [2]. In this experiment this facility was used to align the diagnostic beam onto the small (200^{1}m2) active area of a Hamamatsu G4176-03 ultra-fast MSM photodiode. This diode has a rise time of 30 ps, and is ideally suited for bunch-resolution measurements. Alignment of the incoming synchrotron radiation with the active area of the diode was achieved using an optical stage with three degrees of freedom.

Practical constraints in coupling the photodiode to the synchrotron light source limited the induced photocurrent to approximately 10^{1}A. Therefore a series of Minicircuits ZX60-14012L high bandwidth amplifiers were used to provide an adequate signal. High-speed digitization of the signal was accomplished using an Agilent Acqiris U1065A 8 GS/s CompactPCI card housed in a 3U CompactPCI crate. A computer, embedded in the crate, allowed local analysis of the data. Synchronization with the stored electron beam was achieved by triggering the FPM acquisition-cycle with the orbit clock, which is provided by the central timing system and has a frequency equal to the orbit frequency of the stored electron beam. Configuration, control and data displays of the FPM were provided remotely through an EPICS interface. Calibration parameters, trigger delays and refresh rates could be customized for specific applications. Because EPICS is based on a distributed client/server model, with TCP/IP messages created each time a variable is changed, it is unable to handle the throughput of the raw data flow from the FPM. To overcome this limitation, some local preliminary processing of the data was provided by the crate processor.

Figure 2 shows a comparison between fill-pattern measurements made simultaneously by the capacitive strip detector and the Fill Pattern Monitor (FPM).

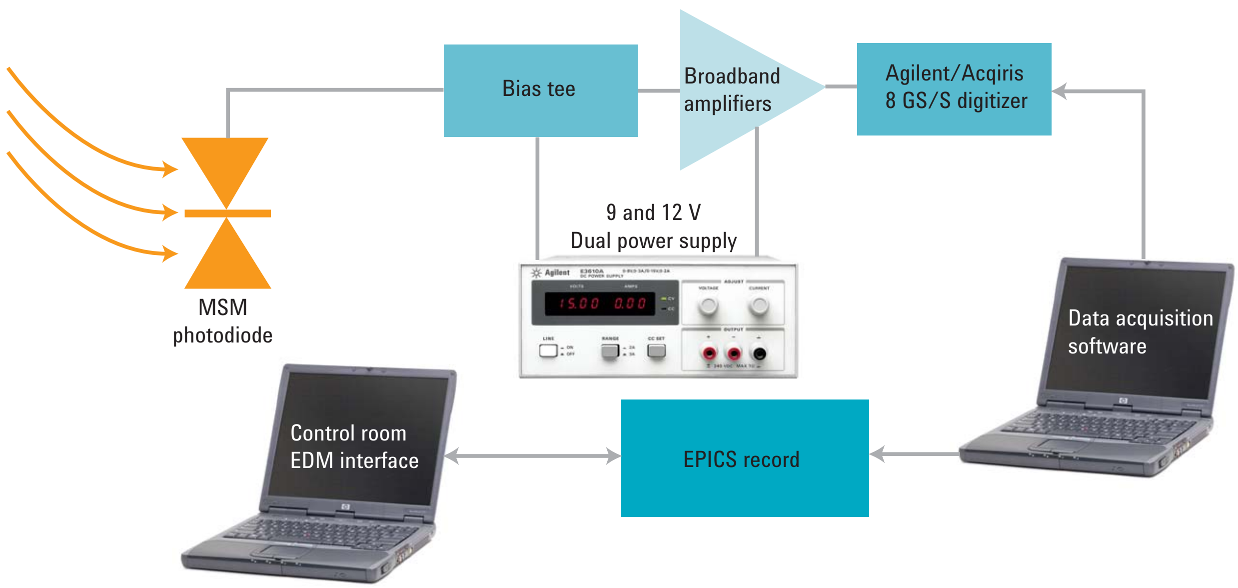

Fig. 1. Experimental setup for the measurement of the fill-pattern. Visible synchrotron radiation from the optical chicane is incident on the Metal-Silicon-Metal (MSM) Photodiode, which is biased to 9 V by the bias tee. Induced current from the incident light is amplified by 20 dB, and then digitized. The data acquisition software acquires the waveform and separates the signal into intensity values for each RF bucket, which is relayed to the control room though an EPICS interface. An EPICS interface also allows remote control of the acquisition system.

3. Results

Several measurements of the fill-pattern were made to study the performance of the FPM, and the results were Time (ns) Normalized Intensity Fill Pattern Measurement compared with those using the existing method of fill-pattern measurement, the capacitive strip detector.

3.1. Controlled Loss Of Beam

To test the sensitivity of the FPM relative to the existing strip detector, a current of 50 mA was injected into the storage ring, and a scraper was used to reduce the stored current gradually over a period of 12 minutes. During this process, the fill-pattern was measured simultaneously with the strip detector and the FPM. The fill pattern measurements are shown in Figure 3. Superior performance of the FPM is confirmed in Figure 3(b) where at currents below 5 mA, the strip detector signal disappears into noise while the beam profile is still clearly resolved with the FPM.

3.2. Single-Bunch Injection Measurements

To implement a top-up mode, the FPM must be able to measure the fill pattern with a resolution of an individual bunch. A single RF bucket was filled using a single-bunch injection mode at 0.05 mA per shot, and the output from the FPM was logged. As Figure 4(a) shows, a single shot as small as 0.05 mA could be detected by the photodiode before registering in any of the existing current detectors. Such sensitivity will allow finer control over the selection of injection currents used in the dynamic top-up protocol.

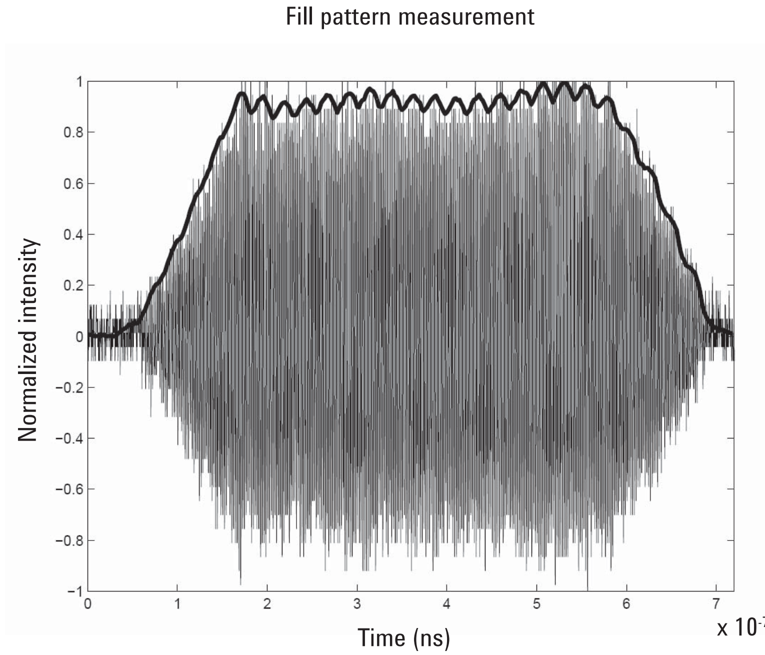

Figure 2. The fill pattern measurement made using the capacitive strip-detector (thin oscillating line), compared with results from the FPM (thick line).

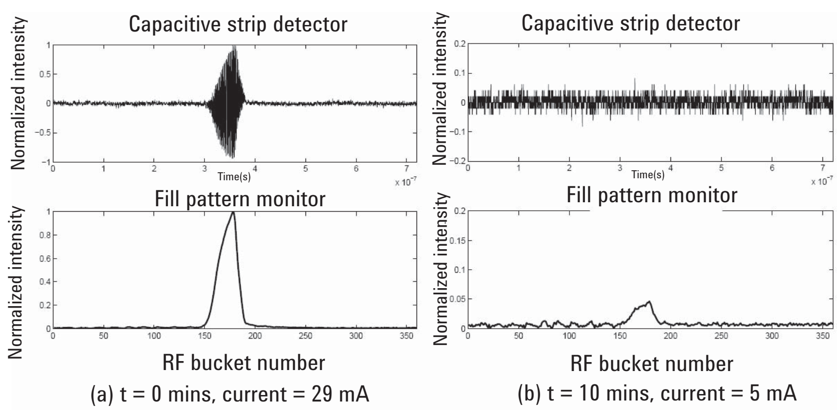

Figure 3. Measurements of the fill-pattern during controlled loss of beam. The upper graph was obtained with the capacitive strip detector, and the lower graph using the FPM. Figure 3(b) shows the response of both detectors at a beam intensity where the strip detector shows only noise. This low remnant fill-pattern was still measurable using the FPM.

After the single shot injection was completed, a small bunch was measured in the bucket preceding the target. To verify this signal was real and not a result of split binning, a measurement was taken on a streak camera located in the optical diagnostic hutch.

The results are shown in Figure 5, the streak camera also measuring the smaller bunch. When each of the peaks are fitted to a Gaussian and integrated, they have an integrated intensity ratio of 2.9 matching the ratio between the two bunch currents measured by the FPM.

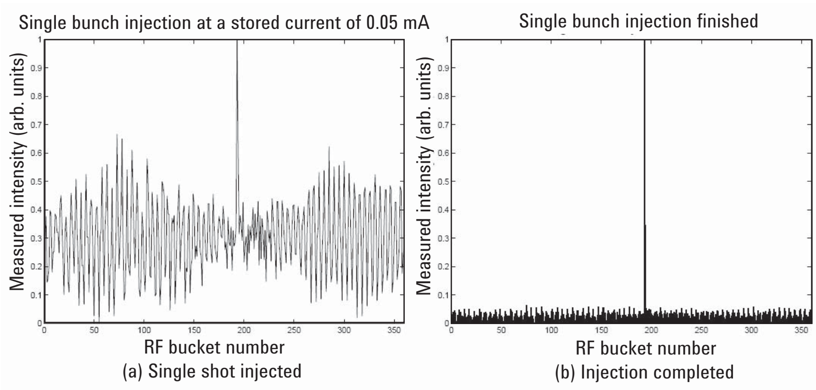

Figure 4. Single bunch injection tests. Figure 4(a) shows the first shot into the storage ring of the injection test as detected by the FPM. Figure 4(b) shows the finished injection test, with all of the injected current stored in the correct RF bucket.

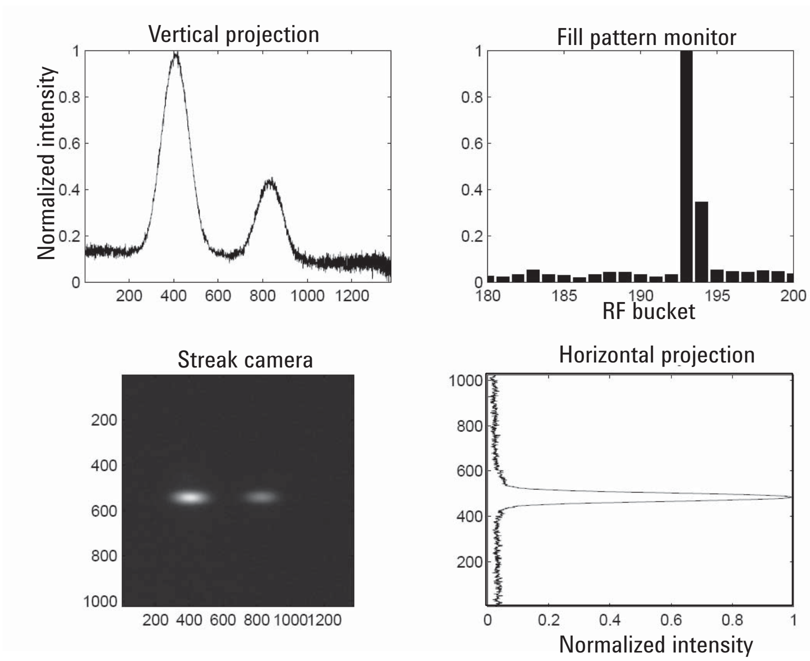

Figure 5. A comparison between measurements from the streak camera and the FPM. The ratio between the integrated intensity of the peaks were measured to be 2.9 for both the streak camera and FPM.

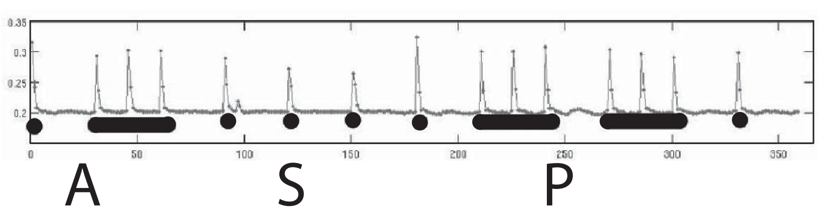

Fig. 6. "ASP" Morse code message. The morse code was used as a novel test of the injection systems ability to place current into arbitrary RF buckets.

3.3. Morse Code Test

Top-up operations require the system to be able to inject electrons into arbitrary RF buckets in the storage ring. To test the ability of the injection system thoroughly, a novel test was conducted to place a Morse-encoded message into the beam. Using one filled bunch for "dot" and 3 filled bunches for "dash", the message "ASP" was successfully placed into the stored beam, as shown in Figure 6.

4. Top-Up Mode

An expectation of third-generation light sources is a low emission electron beam providing brilliant synchrotron radiation. Low emmitance combined with a high brilliance requires a large stored charge per bunch which lowers the beam lifetime. This lower lifetime results negatively affects the total photon flux during the experimental time for beamline users.

A method for compensating for the lowered beam lifetime is to periodically inject electrons into the storage ring. The real-time nature of the data provided by the FPM allows for bucket-resolution intensity targeted injections.

Top-up mode operation requires both the accurate real-time data provided by the FPM as well as the ability of the Australian Synchrotron injection[3] and timing[2] systems to inject selected individual buckets in order to provide an even filling of the beam. An evenly filled beam reduces temperature fluctuations in optical components[4], as well as providing users with a constant intensity radiation source for experiments.

In top-up mode the FPM monitors the relative emitted light intensity of stored electrons in successive buckets in real-time. When the stored current drops below a predeter-mined value, electrons are injected into the least-filled buck-ets. As each target bucket is filled, the next low-intensity bucket is identified for further top up. As Figure 7 shows, during a shift dedicated to top-up mode the stored current was maintained at a threshold current of 100 mA using this dynamic injection targeting protocol.

To study the automated top-up mode, the storage ring was injected to 60 mA using a pattern fill. Due to limitations in the temporary timing system used during the test, the injector was set to use only every fourth bucket so that the effective fill-pattern was 90 buckets of the available 360.

Electrons were injected into the storage ring. The dashed curve in Figure 8 shows the result of an attempted pattern fill of 308 filled buckets, with a gap of 52 empty buckets. This graph also shows the problem with standard "pattern fill" injection: the fill-pattern is not as square as required, and the electron intensity of the filled buckets varies significantly due to an uneven current distribution from the electron gun. This crude pattern can be dynamically corrected using a feedback system based on data from the FPM.

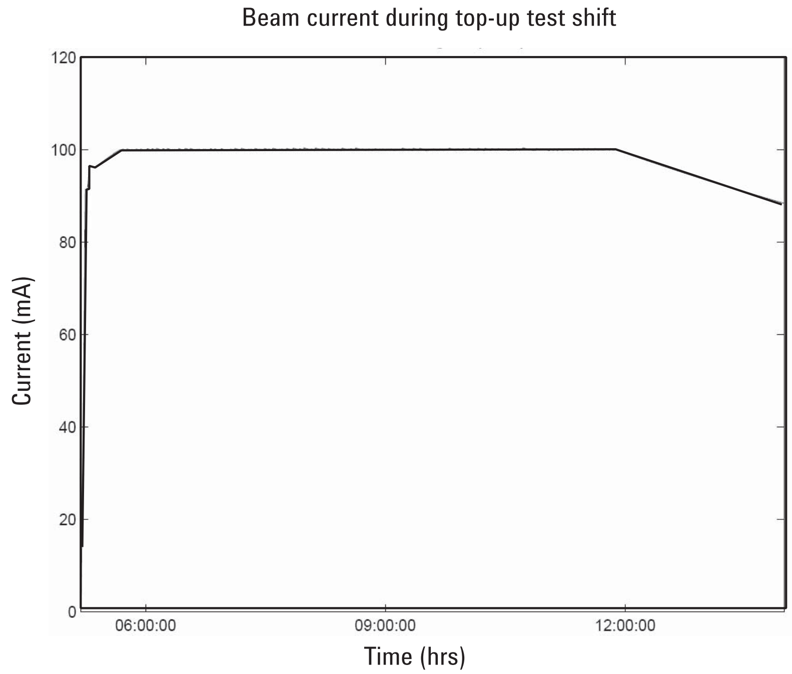

Figure 7. The stored beam current over time during an 8 hour top-up test shift. At 12:00 hours, the protocol was disabled and the beam allowed to decay normally.

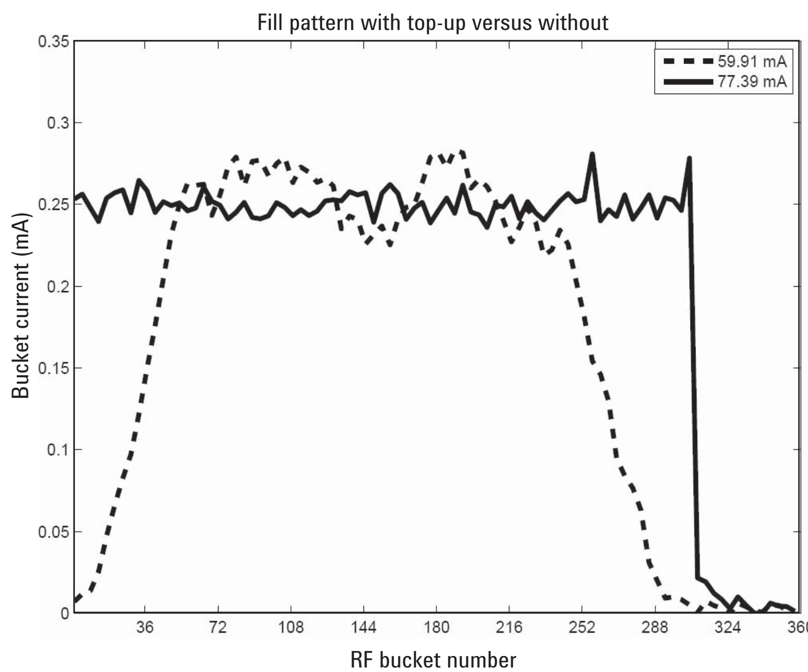

Figure 8. Initial fill-pattern before top-up, compared with the final fill-pattern after top-up. The legend refers to total stored beam current. While the initial fill shows poor differentiation between empty and filled buckets, after top-up the intended pattern is quite clear.

As the beam current drops below a preset threshold (77.3 mA during this experiment), the injection procedure outlined above allows the fill-pattern to be corrected, and the current increased to the predetermined threshold level. A small deadband of 5 mA prevents non-stop injection. The solid curve in Figure 8 shows the final fill-pattern after using the top-up algorithm. As the difference between filled buckets become smaller, the fill-pattern can be further squared off by altering the LINAC grid potential to reduce the injection current.[5]

The standard deviation of the filled buckets, shown in Figure 9, drops dramatically as the top-up procedure continues, showing the impact dynamic top-up has on the original fill.

One method of determining the "flatness" of a given fill-pattern is to create a histogram of the intensity values, as shown in Figure 10. If the fill-pattern is not flat (for example the pre-top up fill-pattern shown in Figure 8), the histogram will exhibit a continuum of intensity values ranging from empty to filled, with a shape dependant on the slope of the measured fill-pattern. As the intensity profile becomes flatter, the values will tend to converge into two groups, shown in Figure 10(b). The center of each of the two groups represents the ideal values for a flat fill-pattern, so the standard deviation of each of the groups gives a measurement of how "flat" the intensity profile is. Top-up mode protocol has been successfully demonstrated at the Australian Synchrotron using the real-time intensity data provided by the Fill Pattern Monitor. The FPM has proven itself to be a reliable method to dynamically maintain the storage ring fill pattern.

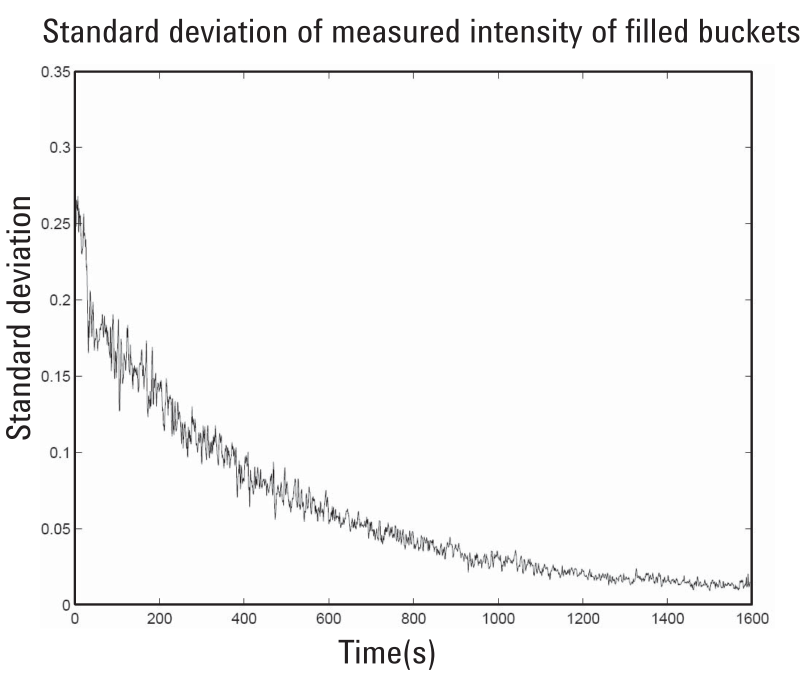

Figure 9. The standard deviation of the measured intensity of the filled buckets versus elapsed time during top-up operations. The drop in the deviation is the result of a more even filling pattern.

5. Summary

This paper reports on the design, construction and use of a device that measures the real-time fill-pattern of the storage ring at the Australian Synchrotron. Using an ultra-fast diode combined with suitable electronics, a measurement of the fill-pattern with a resolution of one RF bucket was obtained in real-time. A series of controlled tests and complementary measurements confirmed the reliability of the system. The relative bucket intensities allowed implementation of an automated top-up protocol. This use of the FPM is now an integral part of the control system software at the Australian Synchrotron[6].

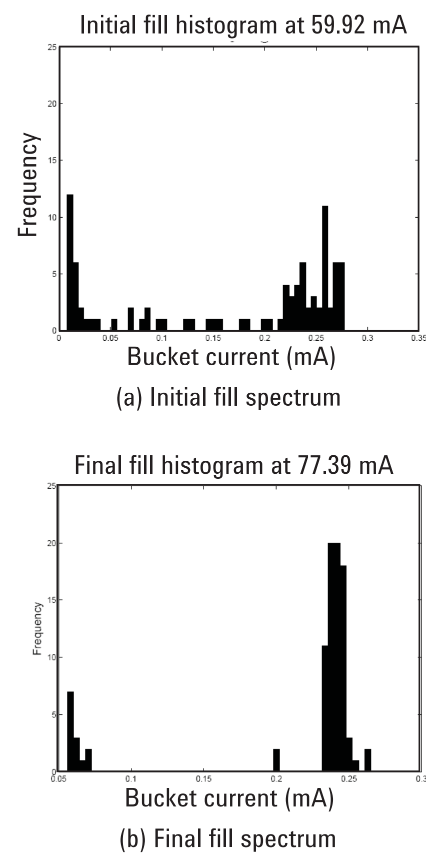

Fig. 10. The difference in the spectrum between the initial fill and the final fill. The clustering of the values around two central points denotes the "ideal" current levels for both the empty and filled buckets.

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