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Injection Efficiency Monitor for the Australian Synchrotron

A. Cole[1], M. J. Boland[12,a], E. D. van Garderen[2], A. Rhyder[2], and R. P. Rassool[1]

[1] School of Physics, The University of Melbourne, VIC 3010, Australia.
[2] Australian Synchrotron, Clayton, VIC 3168, Australia.

Abstract. The Australian Synchrotron AS is moving towards a continuous injection mode called top-up. During top-up the linac and booster synchrotron injection system will be in continuous operation rather than used every eight hours the way they are used at present. In order to monitor the performance of the injection system a real-time injection efficiency monitoring system has been developed. The system consists of several Fast Current Transformers [1] and matching digitisers [2] and is designed to count every beam pulse and measure the transmission efficiency through the whole accelerator complex. After calibrating the system using a properly matched Faraday Cup at the electron gun, a transmission efficiency is then calculated at each stage of transferring the beam from 90 keV out of the gun to 3 GeV in the storage ring. The system is used to optimise the injection process in order to maximise the injection efficiency and as an early warning system when equipment starts to fail and the injection efficiency decreases.

1 Introduction

One of the goals of the accelerator systems at the Australian Synchrotron (AS) is to efficiently deliver beam into the storage ring to maximise the beam delivered to the beamline users. Inefficiencies in the acceleration process are a quick and easy diagnostic to the correct operation of the accelerator system and often offer the first signs of an impending failure or breakdown. In addition the AS is moving to continuous *top-up* operations in 2012 which puts addition performance requirements on the systems. Presently the storage ring is filled two times per day where each injection lasts approximately 100 seconds, where charge is delivered into the storage ring at a rate of 1 Hz. This process allows adequate time for an operator to make adjustments to non-automated systems to compensate for drifts in equipment due to for example temperature changes or electrical noise. During a top-up injection only one shot of charge are injected into the storage ring every few minutes. This top-up process ensures there is a near constant current in the storage ring and a near constant brightness is delivered to the photon beamlines. However, this requires the accelerator systems to work first time and every time in a kind of transient mode, there is little or no time for fast pulsed magnets to stabilise or for a feedback process to regulate the system. In addition, during top-up mode only non-destructive diagnostics can easily be used to monitor the beam, making it difficult to make precision measurements of the beam position, charge and profile.

Given the constraints mentioned above, a system was developed to non-destructively and in real-time measure the transmission of the beam through all the accelerator systems, effectively tracking the amount of charge delivered from the electron gun to the storage ring. Fig. 1 shows an overview of the accelerator complex with the following injection efficiency measurements:

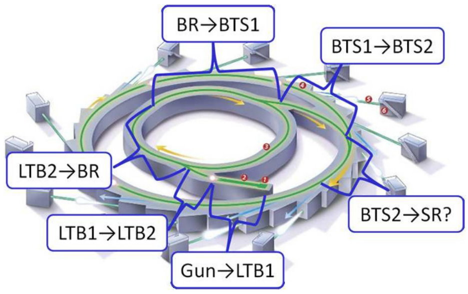

Fig. 1. Overview of the efficiency measurements at the AS accelerator complex.

- Gun → LTB1: from the electron gun at 90 keV through the linac and to the start of the Linac-to-Booster (LTB) transfer line at 100 MeV;
- LTB1 → LTB2: from the start of the LTB to the end of the LTB;
- LTB2 → BR: from the LTB into the Booster Ring (BR);
- BR first turn to BR last turn;
- BR → BTS1: from the last turn in the BR at 3 GeV to the start of the Booster-to-Storage Ring (BTS) transfer line;
- BTS1 → BTS2; from the start of the BTS to the end of the BTS;
- BTS2→ SR; from the end of the BTS to the Storage Ring (SR).

2 Beam Current Monitors

There are a number of ways to measure the beam current depending on the particle energy and time structure. At the AS the particles are all relativistic electrons, except at the electron gun where the initial charge of the low energy electrons can be precisely measured. The beams are all

[a] e-mail: mboland@unimelb.edu.au

pulsed starting with the grid on the gun which generates the 500 MHz bunch structure that is carried through the accelerator complex. There is some micro-bunching in the linac at 3 GHz but that can be ignored for the purposed of the injection efficiency measurement system. This simplifies the choice of measurement devices as there are not requirements for DC beams and the three types of current measurement systems are described in the sub-sections that follow with more details provided in Ref. [3].

2.1 Faraday Cup

A Faraday Cup (FC) is a conducting metal device insulated from the surrounding vacuum chamber used to capture all the charge from an impinging beam. The charge is then drained across a 50 Ohm resistor to measure the induced voltage as shown schematically in Fig. 2. This method of measuring a beam charge is destructive to the beam, is accurate to approximately 1% and can only be used in specific situations. The accurate use of a FC is limited to low energy beams where the charged particles can be assumed to be fully stopped by the cup. A retractable FC is used at the AS at the exit point of the 90 keV electron gun and was used to calibrate the signals from the Wall Current Monitor (see Sec. 2.2).

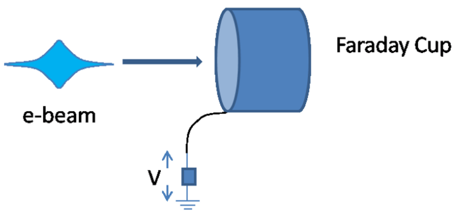

Fig. 2. Schematic of a FC for measuring beam current.

2.2 Wall Current Monitor

The Wall Current Monitor (WCM) is a device in-line with the beam pipe that has an insulating break in the vacuum chamber so as to divert the image currents across a resistor. The induced voltage can then be measured on a fast digitiser and is proportional to the charge in the beam. At the AS the WCM is adjacent to the FC but has the advantage of being non-destructive. Once calibrated against the FC, the WCM can be used to continuously measure the charge that is coming from the 90 keV electron gun during normal operation.

2.3 Fast Current Transformer

A Fast Current Transformer (FCT) consists of a ring shaped metal core through which the beam passes and can be considered as a one turn primary winding, see Fig. 4. The secondary winding is a wire coil around the core, analogous to a conventional step-up transformer. The beam current is indicatively coupled to the secondary winding, inducing a voltage that is proportional to the beam current. Ampere's law guarantees that the current measurement is the same independent of the position of the beam as it passes through the hole in the core.

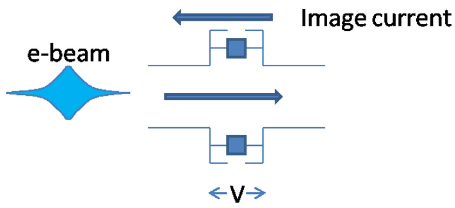

Fig. 3. Schematic of a WCM.

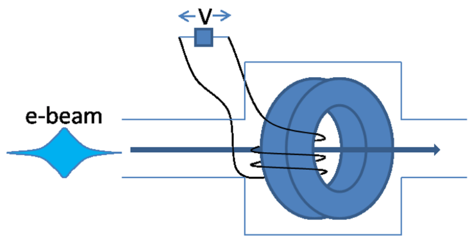

Fig. 4. Schematic of an FCT.

3 Beam Structure

The AS electron gun can deliver at 1 Hz either a 1 ns long single bunch of electrons with up to 0.7 nC of charge or a bunch train of up to 75 bunches with a 2 ns spacing and up to a total charge of up to 7 nC. The pre-bunching is achieved at the cathode with a biased grid that has a 500 MHz modulation applied during emission. The 500 MHz modulation is to match the RF acceleration frequency in the booster synchrotron and the storage ring. The beam is micro-bunched in the linac at 3 GHz, however the bandwidth of the measurement devices are not able to measure this high frequency and the micro-bunches are rapidly recombined once the beam enters the booster, so this effect is ignored in the efficiency measurement system.

The time structure of the beam as measured on the Wall Current Monitor at the electron gun is shown in Fig. 5 for single bunch mode and in Fig. 6 for multi-bunch mode. Both sets of data were taken on a 4 GHz bandwidth analogue front end scope and can clearly resolve the individual bunches in the bunch train as seen from the zoomed plot in Fig. 7.

4 Low Bandwidth Digitiser Measurement

The measurements presented in Fig. 5 and Fig. 6 were taken with a high bandwidth analogue front end scope fed by a 16 port multiplexer into the 4 input channels. With this configuration only one of four signals can be viewed at a time and therefore the transmission through the full accelerator complex could not be achieved in one shot on a real-time basis. A system was devised to deploy many low bandwidth digitisers to all the current measurement

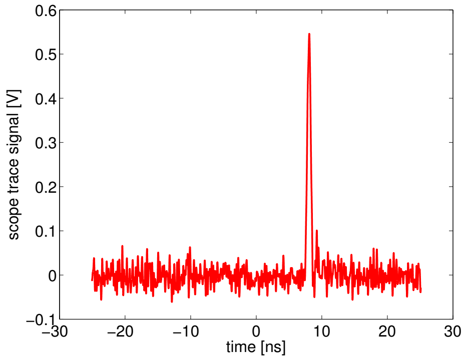

Fig. 5. Single bunch mode WCM data.

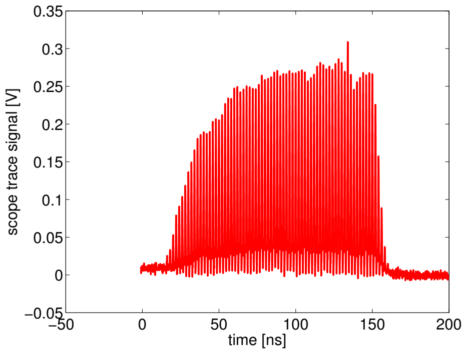

Fig. 6. Multi-bunch mode WCM data.

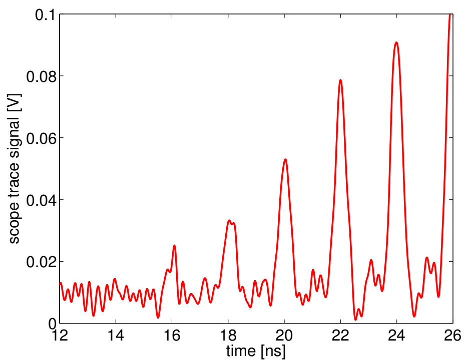

Fig. 7. Muli-bunch mode WCM data zoomed to show individual bunches.

devices to capture each signal in one shot for each injection cycle to provide real-time measurements of the injection efficiencies.

To achieve this it was first necessary to determine if the signals from the current measurement devices could accurately be read and calibrated with a low bandwidth analogue front end digitiser. In Fig. 8 the 1 GHz bandwidth multi-bunch mode data is shown while Fig 9 shows data measured with a 200 MHz analogue front end bandwidth digitiser during the same run and plotted on the same scale. The first thing to note is that the rise time of the signal is much reduced as expected and the peak values as a consequence are lower than in the high bandwidth measurements. However, when the cable attenuation factors are taken into account and the voltage signal from the bunch

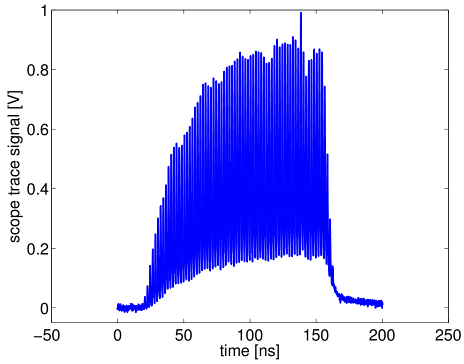

Fig. 8. Multi-bunch FCT data captured with 1 GHz analogue bandwith digitiser.

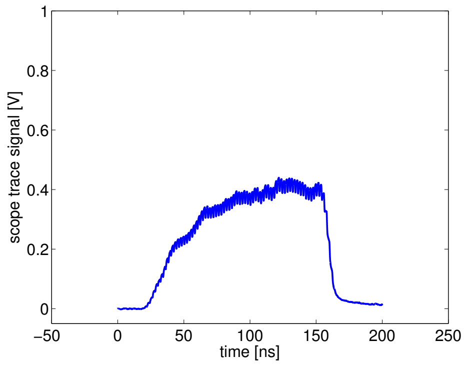

Fig. 9. Multi-bunch FCT data captured with 200 MHz analogue bandwith digitiser, same run as Fig. 8.

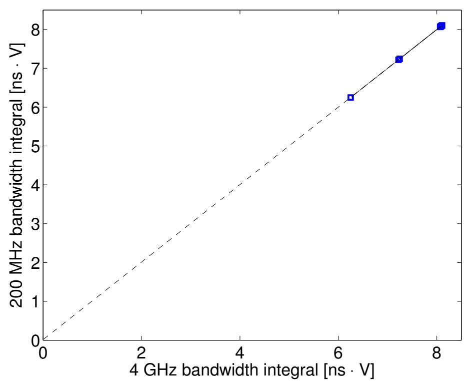

Fig. 10. Comparison of integrated multi-bunch FCT data

train is integrated, the high and low bandwidth signals are in good agreement, as shown in Fig. 10.

Furthermore, since we aim to measure the efficiency from one point to another, some systematic errors cancel out when a ratio of the initial and final charge measurements is taken. This relaxes the measurement requirements from an accurate absolute beam charge to a stable relative beam charge measurement. This type of efficiency measurement is sufficient to accurately diagnose the accelerator performance during top-up in real-time.

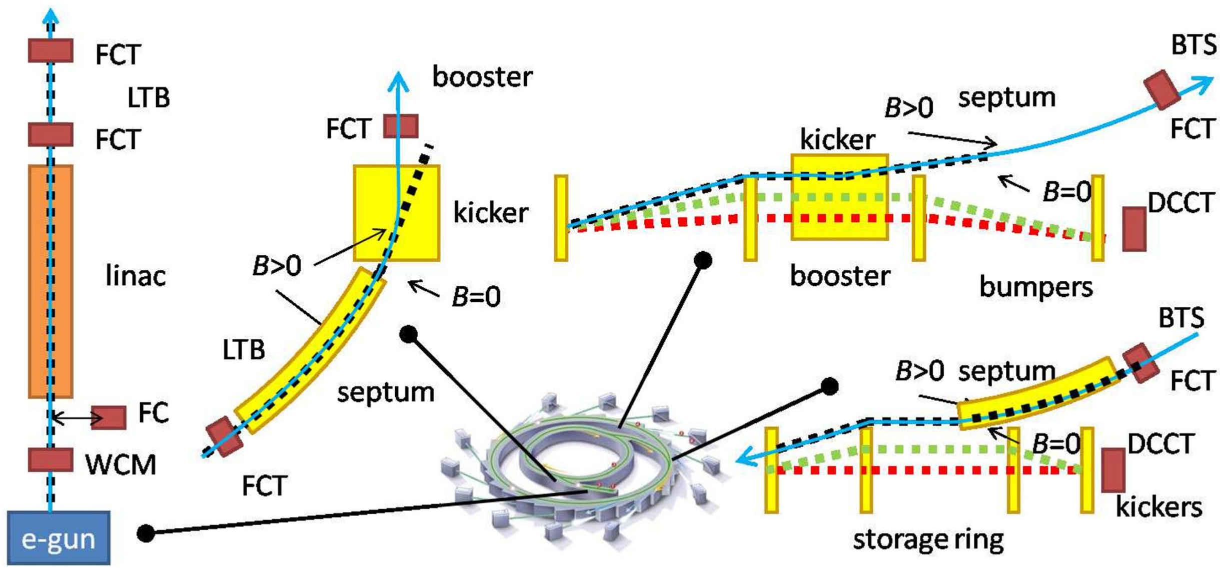

Fig. 11. Schematic of the injection process in the AS accelerator complex showing the relative positions of the current measurement devices used to measure the injection efficiency.

5 Beam Injection Process

The injection process is shown schematically in Fig. 11 highlighting the transport through the linac, into the booster, out of the booster and into the storage ring. The light blue line represents the injected beam path, while the dashed lines represent paths with the magnetic fields in intermediate positions.

In the linac the beam passes through static solenoid magnets and travelling wave RF fields, so the transmission efficiency is mainly controlled by the focussing strength and the RF phase. For injection and extraction from the booster and injection into the storage ring pulsed magnets are used to transmit the beam.

At the booster injection point the kicker has to fire to put the injected beam on axis and be completely de-energised less than 430 ns later when the beam completes the first orbit of the booster ring. A combination of the septum and kicker strengths provide the correct steering angle for the beam and the efficiency is mainly controlled by these magnet settings.

To extract the beam from the booster, a bump orbit that is slowly increased in amplituded is created on the millisecond time scale, the red and green dashed lines in Fig. 11 indicate the increasing strength with time. Four bumper magnets are used to control the offset and angle of the bump and when the beam is at the maximum offset a fast kick is applied to steer the beam into the septum magnet.

Similarly, to inject into the storage ring the stored beam is brought close to the injection septum magnet but in this case the bump orbit is generated using four fast kickers. The septum guides the injected beam in parallel to the stored beam and as the kickers are again reduced in strength both beams combine and damp down over many thousands of revolutions in the storage ring.

6 Results

The injection efficiency measurement system has been implemented and used during operations [4]. An event based timing system is used to precisely trigger the current measurements with ~100 picosecond jitter. The stability of the hardware trigger is critical since the electron gun pulse is separated from the booster extraction kick by more than 600 ms. During a test run the booster extraction efficiency was measured to be 94 ± 2% over a period of several hundred extraction cycles. Fluctuations of the pulsed magnets introduce some noise into the measurement which have produced non-physical results of > 100%. Signal processing hardware and software solutions are being examined to improve the reliability of the system before the start of top-up operations due to start in May 2012.

References

1. Bergoz Fast Current Transformer, Bergoz Instrumentation, http://www.bergoz.com.
2. Agilent U1082A Acqiris 8-bit High-Speed PCI, http://www.agilent.com.
3. Proceedings of CAS 2008, CERN Accelerator School: Beam Diagnostics, CERN Report CERN-2009-005 (CERN, Geneva 2009) 141.
4. E. van Garderen *et. al.*, Newly Installed Beam Diagnostics at the Australian Synchrotron, in Proceedings of DIPAC'11, Hamburg, 16-18 May 2011.