Monitoring and Controlling Particle Beams in Real Time

Application Note

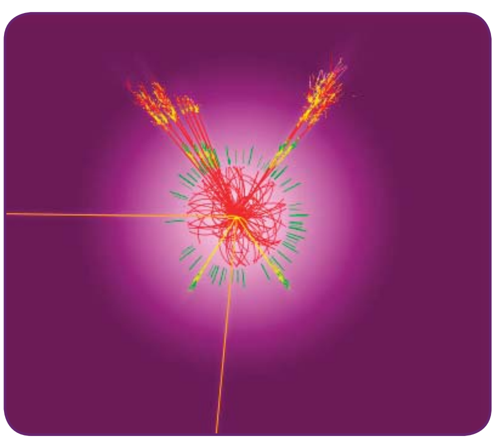
High-performance digitizers enhance beam quality in advanced applications

High-energy particle accelerators are helping researchers investigate the nature of matter and the origins of the universe. Typical experiments involve carefully controlled collisions between either intersecting particle beams or a particle beam and an atomic-scale target. Subsequent analysis of the results may reveal new insights about the building blocks of matter and the forces that hold them together, answer questions about particles and dark matter, and provide clues about the formation of the universe more than 13 billion years ago.

Creating particle collisions at nanometer scale and with picoseconds of duration requires extreme precision in spatial and temporal control. At facilities such as the European Organization for Nuclear Research, more commonly known as CERN, and the Australian Synchrotron, high-performance Agilent Acqiris digitizers are helping researchers achieve the levels of precision and control they need to perform more and better experiments in less time. Key attributes of the Agilent digitizers include high measurement throughput, very short "dead time" between acquisitions, excellent measurement fidelity, compact size and cost-effectiveness.

The remainder of this note describes the creation of high-energy particle beams, the control of particle beams inside CERN's Large Hadron Collider (LHC), and the control of electron beams that produce high-intensity light in the Australian Synchrotron.[1] A variety of additional references are included at the end of the note: These will help you learn more about these organizations, their facilities, the history of synchrotrons, and more.

1. *Hadrons are protons and neutrons.*



In use around the world Agilent Acqiris digitizers are contributing to research in many types of accelerator applications.

Particle accelerators

- CERN (Switzerland)
- Fermi Lab (US)

Synchrotron light sources

- Australian Synchrotron (Australia)
- SOLEIL (France)
- DIAMOND (UK)
- ESRF (France)
- KEK (Japan)
- Brookhaven National Laboratory (US)
- SPring-8 (Japan)
- SLAC (US)
- DESY (Germany)

Heavy ion accelerators

- GANIL (France)
- GSI (Germany)
- Brookhaven National Laboratory (US)

Agilent Technologies

Generating high-energy particle beams

Particle accelerators provide sharp contrasts in scale. For example, the LHC at CERN is 27 km (16.7 miles) in circumference; however, particle beams are characterized in terms of nanometers and picoseconds.

There are two types of accelerators. Linear accelerators or "linacs" operate in a straight line and, due to size constraints, have limited power. Synchrotrons are circular and have multiple stages. Currently, the highest power accelerators are synchrotrons.

To illustrate the structure of a synchrotron, Figure 1 shows a simplified diagram of the LHC. Listed in order of operation, here is a quick summary of the acronyms shown in the figure:

- Linac 2: The linear accelerator for protons
- PSB: Proton Synchrotron Booster
- PS: Proton Synchrotron
- SPS: Super Proton Synchrotron
- LHC: Large Hadron Collider

The process starts in Linac 2, which generates 50-MeV protons that are fed into the PSB. There, the protons are boosted to 1.7 GeV before being injected into the PS. The PS accelerates the protons to 26 GeV before sending them to the SPS, which raises the energy level to 450 GeV. Over a period of about 20 minutes the protons are injected into the main ring of the LHC. In this final stage bunches of protons are accumulated, accelerated to a peak energy of 7 TeV, and then circulated as two separate beams traveling in opposite directions for 10 to 24 hours. Collisions can be created at four separate intersections located around the LHC.

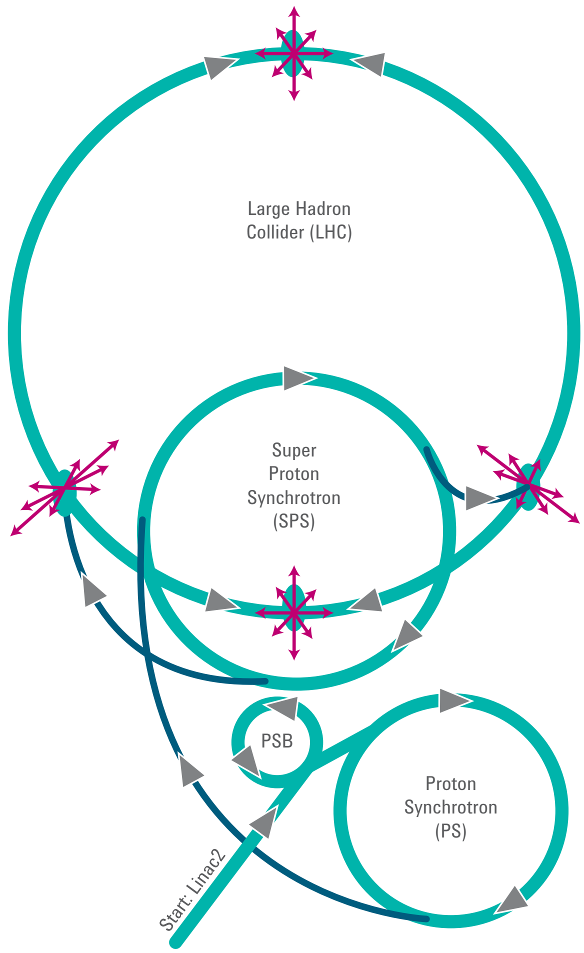


Figure 1. Simplified diagram of the LHC multi-stage synchrotrons as used to accelerate protons

Protons are accumulated, accelerated to a peak energy of 7 TeV, and circulated as two separate beams traveling in opposite directions

Generating high-energy particle beams, continued

In the LHC, each beam travels within a beam pipe that is evacuated to form an ultrahigh vacuum (Figure 2). The beam is guided around the circular synchrotron by a strong magnetic field created with superconducting magnets. The magnets are cooled to –271 °C, which is achieved with a distribution system that sends liquid helium to multiple sections of the accelerator. There are three types of magnets: 1,232 15-m dipole magnet are used to bend the beams; 392 quadrupole magnets, 5 to 7 m long, focus the beams; and prior to each collision a third set of magnets is used to concentrate the particles and increase the chances of collisions.

Within these massive machines, particle beams are not generated as a continuous stream. Instead, particles such as protons are formed into "bunches" that have durations (or "widths") measured in picoseconds. Bunching is intrinsic to the physics of using RF accelerating fields to achieve high gradients of acceleration within the synchrotron. The bunches, which may contain several billion protons, travel at velocities approaching the speed of light. Depending on the circumference of a circular accelerator, the duration of each full transit ranges from a few hundred nanoseconds to tens of microseconds.

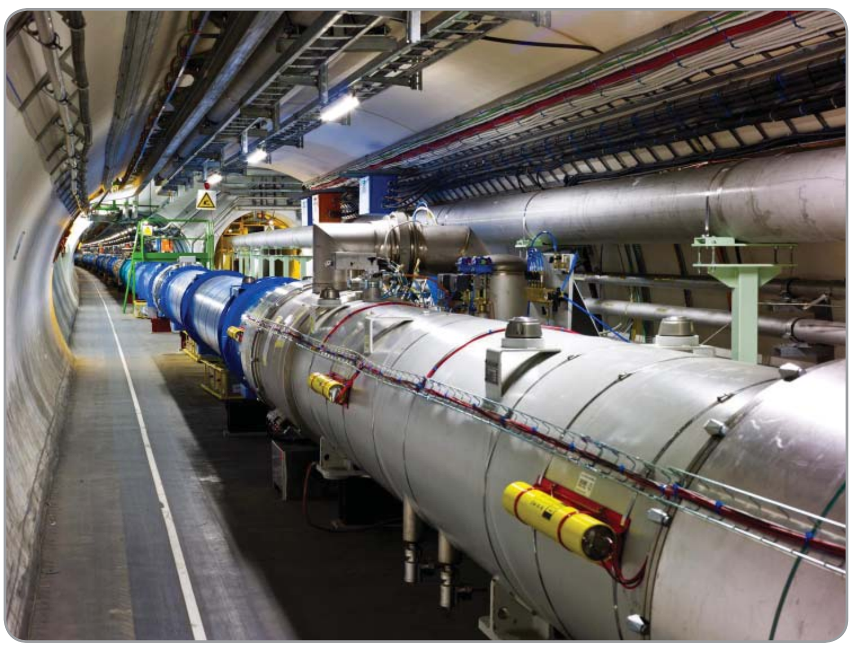


Figure 2. A section of the LHC within its tunnel.

Measuring and monitoring

Viewed from another perspective, particle accelerators themselves are giant scientific instruments. They include numerous subsystems, ranging from the interconnected array of small, medium and large accelerators all the way down to photo-detector diodes. Clusters of traditional test equipment are used to measure, monitor and control the quality of particle beams. One key measure of beam quality is its focus: Tightly focused beams help ensure higher rates of collisions and interactions.

Within a typical synchrotron or linac, the monitoring equipment includes two essential elements: a detector and a digitizer. The detector senses attributes such as the light intensity or energy level produced by individual bunches. A digitizer connected to the sensor converts an analog output from the detector into a digital representation that can be rapidly quantified, analyzed and used to provide feedback to beam control personnel. In some cases a PC is mounted in the instrument cage to provide initial processing before sending intermediate results across the local area network (LAN).

Bunches contain several billion protons and travel at velocities approaching the speed of light

Controlling particle beams in the LHC

With a circumference of 27 km, the LHC is the world's largest particle accelerator and collider. It is also the most powerful: It surpassed the previous record of 1 TeV in November 2009 and is designed to produce 7 TeV when it achieves full power in 2010.

Researchers will use the LHC to investigate a variety of questions in the field of high-energy physics: Why do particles have mass? What are the origins of the universe? What are the origins of dark matter?

As described earlier, the LHC is not an isolated machine. It is fed by four other accelerators, working in synchrony: In order, the Linac 2, PSB, PS and SPS accelerators successively boost the energy level of the protons that are eventually injected into the LHC.

Controlling the injector chain

All of these are under the control of the CERN Control Centre (CCC), which oversees operation of all eight accelerators that are part of the laboratory. The CCC consolidates all eight control rooms under one roof (Figure 3). It also manages the cryogenic and technical infrastructures for the lab. As an example, the cryogenics infrastructure controls cooling of the 1,600 superconducting magnets spaced throughout the LHC. When the LHC is running at full capacity, measured data and related simulations are expected to produce data in excess of 15 petabytes (PB) per year within the LHC Computing Grid. [1]

1. 1 PB equals 10^{15} bytes

Passing in succession from Linac 2 to PSB to PS to SPS to the LHC, protons are accelerated and formed into a pair of beams that travel in opposite directions within the LHC. Each beam consists of about 2,808 "bunches," each of which contains up to 100 billion protons. Bunches travel at 99.9999991% of the speed of light—and at that rate one transit of the 27-km LHC takes about 90 µs.

Figure 3. Inside the main control room of the CCC.
Photo courtesy of CERN. © Copyright CERN Geneva.

LHC is the world's largest particle accelerator with a circumference of 27 km

The performance of the LHC depends on the performance of the injector chain. Along that chain, the Open Analogue Signal Information System (OASIS) acquires and displays analog signals in the acceleration domain. The signals come from every CERN accelerator and are sampled using various types of digitizers.

The digitizers are co-located with front-end computers (FEC) that perform first-level processing. This preserves bandwidth when the acquired data is sent through an Ethernet network for display on a workstation running a dedicated virtual oscilloscope (Vscope) application (Figure 4).

Vscope is a software oscilloscope that takes data from various types of digitizers and displays all waveforms as if they came from the same type of hardware module. Through this scheme, CCC personnel can perform side-by-side comparisons of multiple signals from throughout the injector chain. The OASIS architecture aligns the signals to ensure meaningful comparisons by synchronizing acquisition settings across all of the hardware digitizers.

Capturing challenging signals

More than 2,000 individual signals are available to the operators and physicists who use OASIS. They are looking for a variety of indicators from the LHC and its injector chain: instabilities in the proton bunches; quality of the beams; current in the fast-pulsing magnets ("kickers"); phase relationships between the kickers; and the state of the RF signals in the accelerating cavities. All of these characteristics help determine if conditions are optimum for whichever experiments are scheduled for a given shift.

With proton bunches traveling near the speed of light, measurement speed is critical and digitizers must have very short dead time between measurements. This is one of the key reasons CERN is using more than 70 Agilent Acqiris digitizers within the OASIS system. Those digitizers are installed with all CERN accelerators.

Specifically, CERN is using one or more units of eight different Agilent Acqiris models. These range from 500 MSa/s to 8 GSa/s with 8- or 10-bit resolution on one, two or four channels (see sidebar). All are in the CompactPCI form factor and are installed in cPCI crates along with an FEC.

These high-performance digitizers are used to perform wideband beam monitoring and monitor forward and reverse RF signals in the accelerator cavities. In a literal sense, the beam-monitoring measurements are made possible by Agilent U1064A digitizers, which provide sufficient speed and bandwidth to capture the signals of interest. In the RF measurements, Agilent digitizers measure direct and reflected energy and thereby help determine the final energy provided to the beam during each revolution around the accelerator.

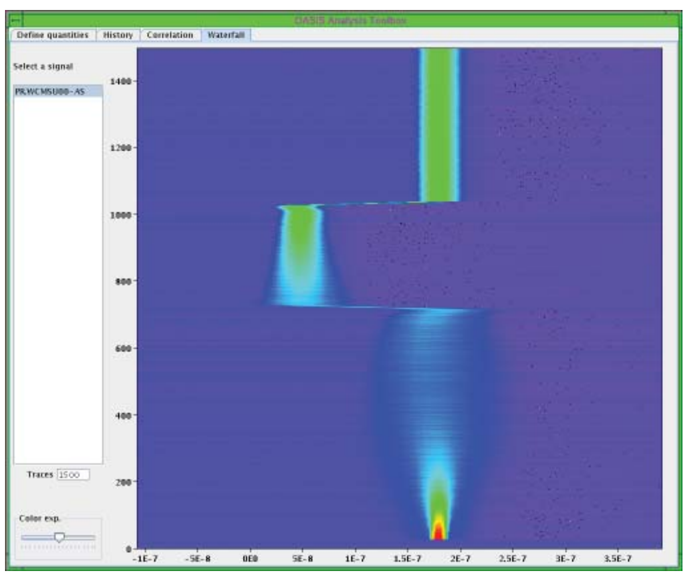


Figure 4. An OASIS Vscope screen showing an example bunch rotation similar to that seen in the LHC beam.

Image courtesy of CERN. © Copyright CERN Geneva.

More than 70 Agilent digitizers are installed across all of CERN's accelerators

The digitizers have also been used during investigations of neutron capture transmutation processes, which can be used to convert long-half-life radioactive substances into materials that decay more rapidly. The precision of these experiments depends on the resolution of the neutron energies that can be observed. Using a novel experimental arrangement that includes a bank of 70 Agilent Acqiris digitizer acquisition channels, the researchers have pushed the limits of previous experiments and are now able to observe neutron interactions with more detail and greater accuracy over a broader energy range.

Researchers have pushed the limits of previous experiments because they can observe neutron interactions with more detail

Looking ahead

As the LHC ramps up to its full 7 TeV power and begins a new era of physics research, Agilent Acqiris digitizers will be there as CCC personnel use the OASIS system to monitor the state of the interconnected accelerators. They can do so confidently, knowing the digitizers' very short deadtime between measurements will keep pace with proton bunches moving at nearly the speed of light as they circulate inside the LHC.

Agilent digitizers at CERN

Listed numerically by model number, the following high-speed cPCI digitizers are among those being used to feed signals to the OASIS system:

- U1063A: Four channels, 8 bits, 0.5 to 1 GSa/s
- U1064A: Four channels, 8 bits, 1 to 4 GSa/s
- U1065A: Four channels, 10 bits, 2 to 8 GSa/s

Controlling electron beams in the Australian Synchrotron

Synchrotron light sources accelerate electrons to produce synchrotron radiation that spreads across the electromagnetic spectrum, from infrared to visible light to X-rays. The resulting photon beams produce a brightness level more than one million times that of the sun. This intense light is used to perform imaging experiments via spectroscopy or diffraction in materials science, biology and medicine at millimeter, micrometer, nanometer and sub-nanometer scales.

Today, three generations of light sources are in use around the world; a fourth generation is under development. Each type provides different forms of radiation that are well suited to various types of experiments and investigation. In short, the successive generations have been capable of producing higher energy radiation (shorter wavelengths) and greater brilliance. At the risk of oversimplifying, the net result has been ongoing improvement in the capability to produce measurements with greater resolution in less time.

The Australian Synchrotron is a third-generation light source. It operates at 3.0 GeV with an expected electron bunch width of 20 ps. The storage ring's harmonic number is 360 and its period of revolution is 720.5 ns (Figures 5 and 6).

Figure 5. An aerial view of the Australian Synchrotron in Melbourne

To ensure a high-quality beam, the synchrotron uses a technique called fill-pattern monitoring (FPM) to measure real-time intensity distribution of electron bunches in the storage ring. Knowledge of the electron fill-pattern profile is important for experiments that require precise spatial and temporal control. For experiments that are spatially and temporally sensitive, a source with a known temporal-intensity profile makes it possible to analyze the effects of the radiation source on the results.

The standard measurement approach uses a pickup-type monitor. One example is a detector that uses a capacitive strip to measure the voltage induced by the bunches as they pass through the accelerator's vacuum chamber.

An alternative approach is to detect and measure the optical synchrotron radiation generated by each bunch. This requires an ultra-fast optical diode and a high-performance digitizer to perform direct measurements of emitted radiation intensity. Working with Agilent, the Australian Synchrotron team developed this type of detector and, as described below, demonstrated its ability to provide bunch-by-bunch resolution.

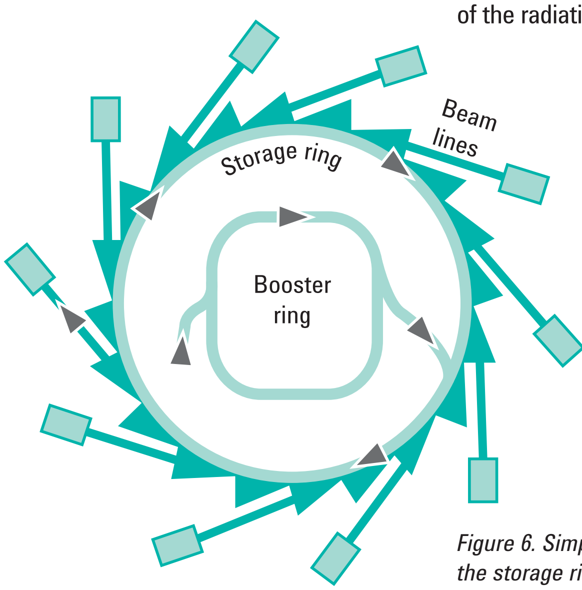


Figure 6. Simplified diagram of the Australian Synchrotron: the booster ring (inner) feeds the storage ring (outer) and beamlines (branches from storage ring) house experiments

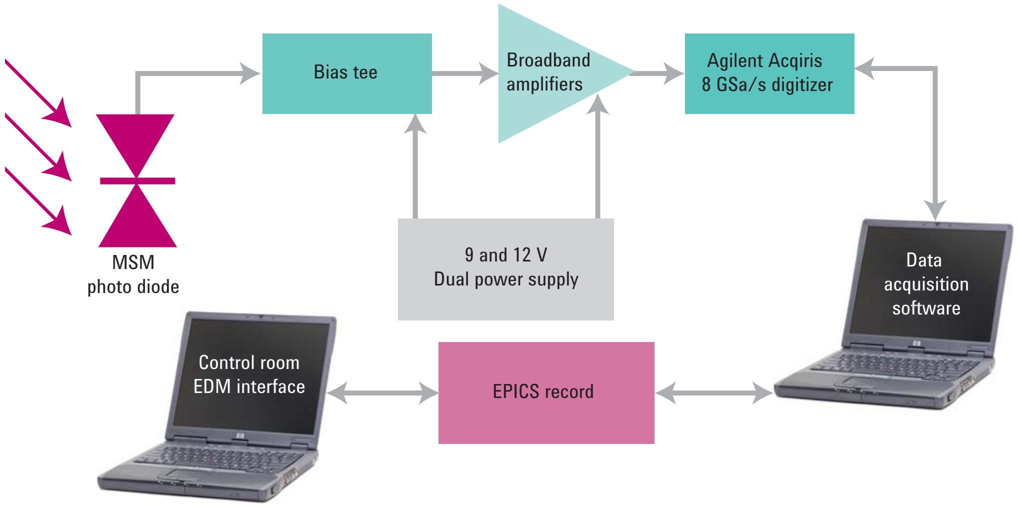


Figure 7. Experimental setup for measurement of fill pattern

Testing the alternate approach

To validate the diode/digitizer detector, the synchrotron team performed a variety of tests and compared the results to those of the pickup-based approach. As summarized below, the results compared very favorably. For a detailed description of the tests and results, please refer to Measurement of the Real-Time Fill Pattern at the Australian Synchrotron (Agilent publication 5989-7558EN).

In the tests, the diode/digitizer-based FPM was used to measure the fill pattern of the electron beam circulating in the storage ring. The ability to perform dynamic control lends itself to "beam top-up" modes. These modes enable, when needed, computer-controlled injection of additional electrons into the storage ring to compensate for losses, or to create custom fill patterns to meet the requirements of specific experiments. A dynamic beam top-up mode is appealing because it provides a stable beam intensity, which reduces thermal strain on optical components and provides predictable synchrotron radiation for experiments.

Sketching the experimental setup

A key feature of the Australian Synchrotron is a dedicated optical diagnostic beamline. It consists of an optical chicane, a focusing lens that forms a 1:1 primary image of the beam, and an optical bench that includes all of the diagnostic instruments. During testing, this assembly was used to align the diagnostic beam onto the small active area (0.04 cm2) of the ultra-fast metal-silicon-metal (MSM) optical diode (30 ps rise time). 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 made it necessary to amplify the induced photocurrent. A series of broadband amplifiers provided 20 dB of gain and the resulting signal was digitized using an Agilent Acqiris U1065A 8 GSa/s CompactPCI card mounted in a cPCI crate (Figure 7). 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 matches the orbit frequency of stored electron beam.

FPM configuration, control and data displays were provided remotely through an Experimental Physics and Industrial Control System (EPICS) interface. The EPICS software environment, which is used to develop and implement distributed control systems, is based on a client/server model and uses publish/subscribe communication. Because it creates TCP/IP messages every time a variable is changed, EPICS is unable to keep pace with the raw data flowing from the FPM. To overcome this issue, an embedded PC housed in the crate was used to perform preliminary local analysis of the digitized data.

Summarizing the results

The team used several measurements of fill pattern to study the performance of the FPM. To allow meaningful comparisons with measurements obtained with the capacitive-strip recorder, the results were time-normalized.

Two control-related tests were performed. One simulated controlled loss of the beam, which tested FPM sensitivity. The other gauged FPM resolution by measuring single-bunch injections. In both cases the FPM outperformed the strip recorder. During beam-loss testing, the FPM provided more precise characterization of the fill pattern (Figure 8) and better sensitivity as beam power decreased (Figure 9).

During single-bunch injection testing, a single RF bucket was filled using a single-bunch injection mode at 0.05 mA per shot. A comparison of the injection into the storage ring and the post-injection energy confirmed precise injection into a single RF bucket (Figure 10). This level of sensitivity will allow finer control over the selection of injection currents used in the dynamic top-up protocol.

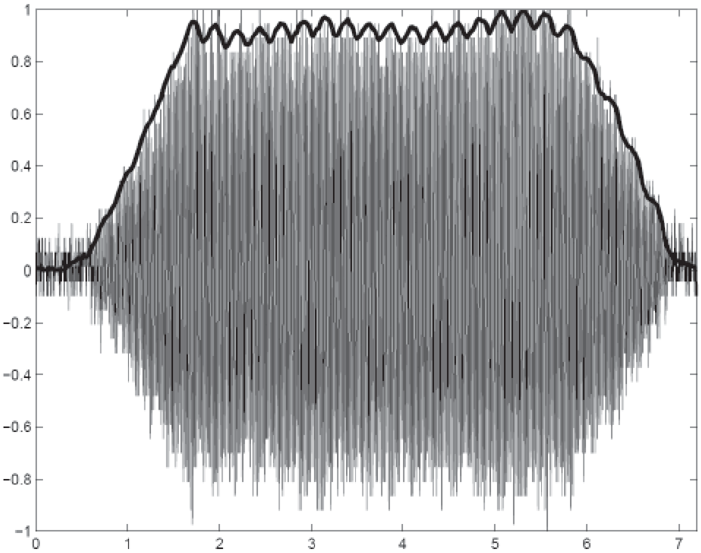


Figure 8. Comparison of fill-pattern measurements made with the capacitive-strip recorder (thin oscillating lines) and the FHP (thick line)

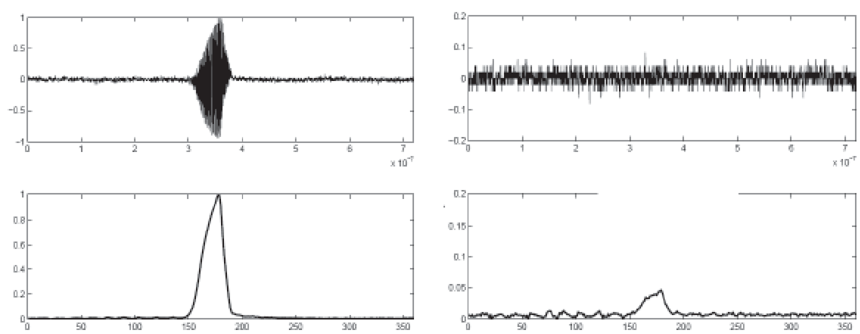


Figure 9. Comparison of fill-pattern measurements made during controlled loss of beam. The lower-right trace shows that the FHP was able to measure a lower-level remnant fill pattern.

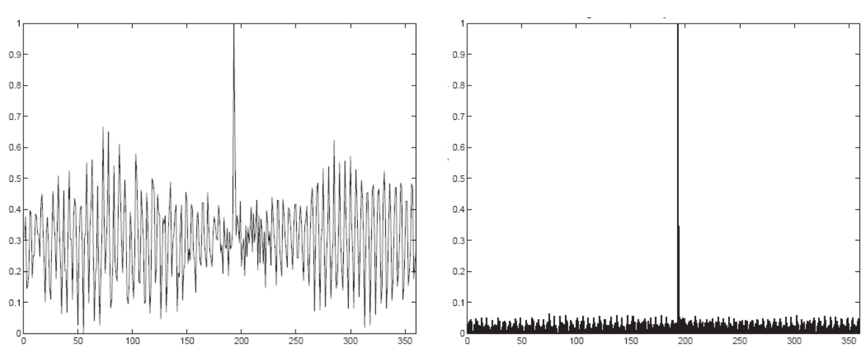


Figure 10. Comparison of first shot into storage ring (left) and finished injection test (right), showing all injected current in the correct RF bucket

A third test used a novel approach—the creation of a Morse code message—to test the precision of electron injection. Top-up operations require that the system be capable of injecting electrons into arbitrary RF buckets in the storage ring. Using one filled bunch for a "dot" and three filled bunches for a "dash," the message "ASP" (for Australian Synchrotron Project) was successfully placed into the stored beam (Figure 11).

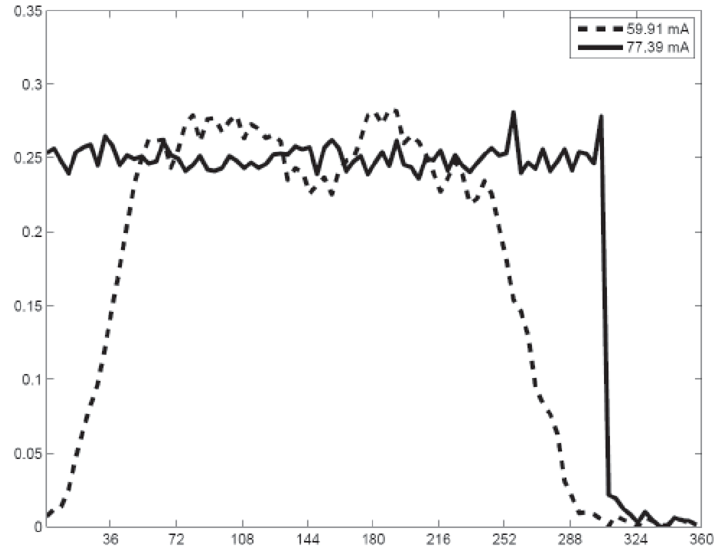


Figure 12. Precise top-up produces a square, even fill pattern that ensures a constant intensity radiation source for experiments

Evaluating the FPM

After the successful completion of those initial tests, additional testing was performed to evaluate the performance of the FPM during actual top-up operations. Third-generation light sources are expected to produce a low-emission electron beam with a high brilliance. This requires a large stored charge per bunch; however, this lowers the beam lifetime, which negatively affects the total photon flux during the time available for experiments.

The periodic injection of electrons into specific RF buckets in the storage ring can be used to compensate for the lowered beam lifetime. The real-time data provided by the FPM allows for bucket-level resolution during targeted injections. Testing showed that this capability enables the creation of an evenly filled beam, which exhibits a square shape (Figure 12). An evenly filled beam reduces temperature fluctuations in optical components and provides users with a constant-intensity radiation source for their experiments.

Further details are described in the Measurement of the Real-Time Fill Pattern application brief. In summary, the top-up mode protocol was successfully demonstrated using the real-time intensity data provided by the FPM. During testing the FPM proved itself to be a reliable way to dynamically maintain the storage ring fill pattern.

Going forward

The combination of an ultra-fast photo diode, suitable electronics and the Agilent Acqiris digitizer enables real-time measurements of fill patterns with a resolution of one RF bucket. This use of the FPM is now an integral part of the control system software at the Australian Synchrotron.

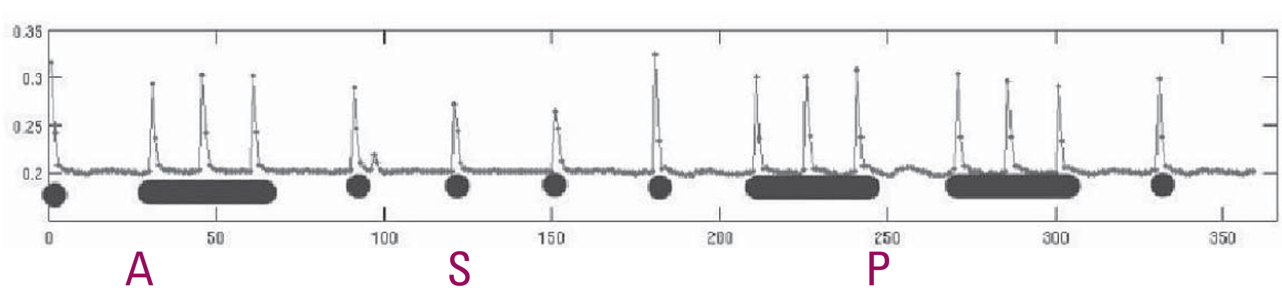


Figure 11. Morse code dots and dashes were formed by injecting electrons into arbitrary RF buckets

Enabling advanced research

Agilent Acqiris digitizers are designed to meet the requirements of demanding applications in advanced research: particle or high-energy physics; nuclear physics; hydrodynamic testing; astrophysics; and plasma research. Five key attributes make our digitizers well-suited to these applications:

- The available channel densities provide more measurement capability in a smaller footprint.
- Multiple channels across multiple modules can be synchronized using the Acqiris AS bus system.
- High measurement throughput allows high trigger rates and therefore the ability to capture more measurement events.
- High precision and excellent accuracy ensure correct results from fewer measurements.
- Turnkey software plus support for multiple operating systems and programming environments enables faster system integration.

Whatever the application, Agilent's high-speed data converters help you see things other digitizers may miss.

Additional resources

- CERN: http://public.web.cern.ch/public/
- Australian Synchrotron: www.synchrotron.org.au
- LHC: http://public.web.cern.ch/public/en/LHC/LHC-en.html
- Project OASIS: www.project-oasis.web.cern.ch/project-oasis
- EPICS: www.aps.anl.gov/epics/
- History of synchrotron radiation sources (Lawrence Berkeley Lab): http://xdb.lbl.gov/Section2/Sec_2-2.html

Related information

Application Notes and Articles

- *Measurement of the Real-Time Fill Pattern at the Australian Synchrotron*, Agilent publication 5989-7558EN http://cp.literature.agilent.com/litweb/pdf/5989-7558EN.pdf
- *Digitizers Become an Integral Part in the Quest for Nuclear Waste Elimination*, Agilent publication 5989-7562EN http://cp.literature.agilent.com/litweb/pdf/5989-7562EN.pdf

Product Brochures

- *Agilent U1063A: Acqiris 8-bit high-speed cPCI digitizers*, Agilent publication 5989-7470EN http://cp.literature.agilent.com/litweb/pdf/5989-7470EN.pdf
- *Agilent U1064A: Acqiris 8-bit high-speed cPCI digitizers*, Agilent publication 5989-7444EN http://cp.literature.agilent.com/litweb/pdf/5989-7444EN.pdf
- *Agilent U1065A: Acqiris 10-bit high-speed cPCI digitizers*, Agilent publication 5989-7443EN http://cp.literature.agilent.com/litweb/pdf/5989-7443EN.pdf

On the Web

- www.agilent.com/find/u1063a
- www.agilent.com/find/u1064a
- www.agilent.com/find/u1065a

Acknowledgements

Agilent extends its thanks to the authors of the application brief *Measurement of the Real-Time Fill Pattern at the Australian Synchrotron*

D.J. Peake and R.P. Rassool
School of Physics, The University of Melbourne
Melbourne, Victoria, 3010, Australia

M.J. Boland, R. Dowd, G.S. LeBlanc, M.J. Spencer and Y-R.E. Tan
Accelerator Physics Group, The Australian Synchrotron
Clayton, Victoria, 3168, Australia

Whatever the application, Agilent's high-speed data converters help you see things other digitizers may miss

www.agilent.com
www.agilent.com/find/digitizers

Agilent Acqiris Product Information

USA	**(800) 829-4444**
Asia-Pacific	**61 3 9210 2890**
Europe	**41 (22) 884 32 90**

Additional Agilent Contact Information

Americas

Canada	(877) 894 4414
Latin America	305 269 7500
United States	(800) 829 4444

Asia Pacific

Australia	1 800 629 485
China	800 810 0189
Hong Kong	800 938 693
India	1 800 112 929
Japan	0120 (421) 345
Korea	080 769 0800
Malaysia	1 800 888 848
Singapore	1 800 375 8100
Taiwan	0800 047 866
Thailand	1 800 226 008

Europe & Middle East

Austria	43 (0) 1 360 277 1571
Belgium	32 (0) 2 404 93 40
Denmark	45 70 13 15 15
Finland	358 (0) 10 855 2100
France	0825 010 700*
	*0.125 €/minute
Germany	49 (0) 7031 464 6333
Ireland	1890 924 204
Israel	972-3-9288-504/544
Italy	39 02 92 60 8484
Netherlands	31 (0) 20 547 2111
Spain	34 (91) 631 3300
Sweden	0200-88 22 55
Switzerland	0800 80 53 53
United Kingdom	44 (0) 118 9276201

Other European Countries:
www.agilent.com/find/contactus

Revised: October 1, 2009

Printed in USA, January 4, 2010
5990-5154EN

Agilent Technologies