OVERVIEW OF STANDARDS FOR BEAM INSTRUMENTATION AND CONTROL

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Abstract

This paper provides an overview of progress toward uniform standards in beam control methods and beam instrumentation at accelerator laboratories. Examples of growing standards among the accelerator community are given and the viability of global implementations is reviewed.

INTRODUCTION

Performances of an accelerator are strongly dependent on the beam parameters measurement accuracy and on the capability of controlling/stabilizing those parameters. Among others, the beam current, size or emittance, position or losses are parameters to be carefully measured and controlled.

Common methods have emerged to measure and control those key parameters in accelerator facilities.

Instrumentation and feedback algorithms also strongly rely on electronics performance. Since the number of electronic modules to be integrated in the accelerator control system is significant (several thousands), standard crates and modules are extensively used to ease acquisition electronics installation, configuration and maintenance.

If the choice of an electronic standard for a global implementation impacts several other accelerator services (radio-frequency, control, machine protection system), the scope of this paper is limited to instrumentation applications. Main electronic standards are reviewed with a selection of commonly used systems and methods for beam instrumentation and control.

BEAM INSTRUMENTATION AND CONTROL METHODS

Among the main beam instrumentation and control methods that are commonly used on accelerator facilities, a focus is made on beam current/charge, beam size and beam position parameters.

Beam Charge/Current

The control of the beam charge is based on the bunch charge measurement acquired shot by shot for linear machines, or on the total and the bunch by bunch current for circular machines, generally averaged over several turns.

Faraday Cup This interceptive device catches all the particles circulating in a linear accelerator. The resulting current, produced when discharging the cup, is directly related to the number of particles hitting the cup. Collected current is acquired with analog to digital converters (ADCs) with high bandwidth (~GHz) and high sampling-rate (~ GS/s) in particular in case of pulsed-beam charge measurement [1].

Current Transformers Those instruments based on the transformer principle [2] are declined in three main types:

- Fast Current Transformer (FCT) is a passive device delivering a high frequency signal that represents the bunch shape. High bandwidth/high sampling rate electronics is necessary for its acquisition (ADCs or oscilloscopes).
- Integrating Current Transformer (ICT) has a voluntary limited bandwidth to monitor the charge of low-repetition rate macropulses. Dedicated front-end electronic circuits sample and hold the bunch charge information for easy digitization.
- Direct-Current Current Transformer (DCCT or PCT) allows direct DC current measurement of a stored beam in a circular accelerator [3]. High resolution digitization is required in this case to allow high precision lifetime measurement, typically with 24 bits multimeters.

Commercially available current transformer devices [4] are widely spread in the accelerator community. They are composed of the sensor and associated front-end electronics. Remaining acquisition electronics for integration into the control system will be easily found in any electronic standard.

Pickup current Monitors Based on pickup beam position monitors (BPMs), it consists in high speed digitization of a BPM sum signal [5]. This is a relative bunch charge measurement and a good alternative to FCT to measure the bunch filling pattern on light sources.

Photodiodes Fast photodiodes collecting synchrotron radiation are also largely used to monitor the relative current in each individual bunch in circular light sources. Simplest implementation consists in high speed digitization (8 GS/s typically) of an Avalanche Photodiode (APD) output intercepting the visible light [6]. Fitting algorithm may be used to compensate for the lack of samples on each bunch.

Time resolved experiments on lights sources may be sensitive up to 109 purity (defined as the ratio between the number of electrons in a 'filled' high current bunch and in its 'empty' following bucket). To achieve such high dynamic range, the statistical Time Correlated Single Photon Counting (TCSPC) method is applied [7]. It consists in configuring the sensor (generally an X-ray APD) in a low pulse rate so that each photon has the same probability to be detected whatever the electron/bunch it originates. Then pulses are shaped by a constant fraction discriminator (to minimize the dependence of the rising edge position to the pulse amplitude) and a Time to Digi-

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tal Converter (TDC) sorts and counts the pulses depending on their arrival time with respect to the revolution clock with a typical resolution of few ps. If commercial all in one TCSPD standalone electronics modules exist, discriminators and TDC can be integrated individually in any electronic format.

Beam Size

The control of the beam size is critical to keep constant (at the maximum value) the luminosity (collider) or the flux (light sources). Prevalent diagnostic systems for beam size measurement can be divided in two categories: one dimensional sampling and two dimensional sampling.

One dimensional sampling Those instruments provide a beam profile measurement since they acquire projections only:

- Wire scanner is a thin wire that is moved across the beam. During the scan, both secondary emission and secondary high energy particle shower are produced. Generated current in the wire and detected particles (with a scintillator and photomultiplier) are related to the number of beam particles intercepted and a transverse profile can be determined. Both signals are digitized with ADCs. For high energetic beams, wire scan has to be fast enough (20 m/s) to avoid wire destruction. In this case acquisition electronics has to be synchronized with the wire motorization system [8].
- Ionization profile monitors: interaction between the beam and residual gas generates secondary particles (ions and electrons) with the same space distribution as the primary particles (beam). Secondary particles are accelerated (electrostatic field) and collected in one of the two transverse planes. Detection is done with electrodes and ADCs or multichannel plates associated to a screen and a camera [9].

Two dimensional sampling Those instruments provide an image in the transverse plane:

- Radiative screens: Different kinds of screens are used to image the beam: scintillating screens, Cerenkov radiators, Optical Transition Radiation (OTR) screens. In all cases, the image produced on the screen is acquired by a camera.
- Synchrotron light monitors: the photon beam emitted by synchrotron radiation has the same dimensional characteristics as the beam it originates. Then imaging the synchrotron light (by double slit interferometry on the visible light or with a pinhole camera in the X-ray range) with a camera allows to measure the beam transverse size.

The type of camera that is broadly used for beam imaging is charge couple device (CCD) camera with Gigabit Ethernet (GbE) connection which is now a standard easy to integrate into a control system.

The control of the beam size is generally a slow (~few seconds) process that relies on the beam size measurement and acts on dedicated magnets. Algorithm is in this case embedded in high level applications. Nevertheless, in synchrotron light sources, where one of the coupling variation sources is insertion devices, some experiments require faster switching configuration of those insertion devices [10]. This implies a high speed data processing that high level applications won't be able to guaranty in the future. Different implementations (with for example FPGAs to perform the image processing) will probably have to be considered in this case.

Beam Position

The beam position stability is a key parameter in all kind of accelerators: for colliders to maximize the interaction cross-section, for Free Electron Lasers (FEL) to maximize beam/photon cross section and consequently the lasing gain factor and for all light sources, to minimize the spot size seen by the experiments. Usual position/angle stability requirement is set at 10% of the beam size/divergence; nevertheless some experiments (crystallography, phase contrast imaging, or even coherent diffraction on light sources for example) are in fact even more sensitive.

Beam Position Monitors The different kinds of existing detectors (shoebox, striplines, buttons, and cavities) are always combined to electronics with:

- High level of complexity: combination of analog and digital processing, filtering, down-mixing mechanism, parallel treatment (up to 4 channels), automatic gain control for high dynamic range, high speed/high resolution digitization (typically ~100 MHz/14 bits ADCs), multiple data flow (single-pass, turn by turn, low latency short term averaged data for fast feedback application, long term averaged data for closed orbit monitoring).
- Synchronisation capabilities with respect to the machine triggers and reference clocks.
- High number of inputs/outputs (RF signals, timing, data distribution, interlock, post-mortem).
- Tight requirement on stability: the measurements should not be dependent to temperature variation. This is generally addressed by a permanent relative calibration mechanism (multiplexing scheme or pilot tone). The sensitivity of the electronics to electromagnetic perturbation (power supplies noise) is also a crucial point for the design.

Due to the complexity and tight requirements described above, electronic design of beam position monitors are rarely made of commercial off-the shelf (COTS) components to be integrated into modular electronic crates. Existing commercial products are standalone electronic modules integrated to the control system by GbE interface [11]. In house BPM electronics designs are also rarely fully integrated into standard modular crates, having at least the analog front-end out of the box. To improve the modularity, an interesting approach has been taken for the XFEL and SwissFEL BPM electronics: the same in-house designed Modular BPM Unit (MBU) crate and generic PSI ADC carrier (GPAC) are used for any kind of BPM (buttons or cavities) installed on those accelerators, only the RF front-end and ADC mezzanine boards are BPM specific [12]. This reduced considerably the integration, management and maintenance effort to be done.

Beam Position Feedbacks Automatic feedback systems are mandatory and broadly used to stabilize the beam orbit/trajectory and to dump the beam instabilities.

- Orbit feedback system is global, using all BPMs and all correctors of the machine. Its correction rate is generally up to 10 kHz. It relies on the BPM response matrix that relates corrector magnet kicks to beam displacement at BPM positions. Correction algorithm uses inverted response matrix to determine new corrector settings from orbit error. It requires a real time BPM data distribution and processing that are often performed by FPGAs with serial RocketIO links [13]. It can be implemented on COTS boards and crates but only serial high speed backplane communication links (PCIe for example) are capable of transmitting the large amount (~100 Mbits/s depending on the number of BPMs and correctors) of data (particularly useful for monitoring and archiving data at feedback sampling rate).
- Multibunch Feedback system is used to damp the beam instabilities in transverse or longitudinal planes. It measures individually the bunch position oscillation and counteracts it. An analog frontend is used to balance BPM button signals and to suppress closed orbit offset. Resulting signal is digitized at the RF frequency, processed (FPGA) and converted to analog to be sent to a power amplifier and the kicker (or RF cavity for the longitudinal feedback). Different kinds of implementation exist, some are fully integrated in standard crates (Elettra [14], SLS [15] in VME) whereas other are standalone (generally commercially available) modules: Spring-8 processor [16] (also used by TLS, KEK-Photon-Factory and SOLEIL), Libera Bunch-by-bunch by Instrumentation Technologies [11] (ESRF, Diamond, Alba, NSRRCC, CLS, ANKA, ALS) or iGp by Dimtel [17] (DAΦNE, KEK-Photon-Factory, ALS, DELTA, Indus-2, NSLSII, SPEAR3).

Others

Beam loss monitors Beam loss monitor acquisition is done either by digitizing (with ADCs) the signal coming from scintillator and PM, or with counter boards in case of coincidence pin-diode detectors for example.

Beam Halo monitors Beam Halo can be detected either with imaging technics (using cameras), either with high dynamic range wire scanner [18] (using 16 bits ADCs).

Photon BPM Based on secondary emission principle it consists in measuring 4 currents produced by blades or diamonds intercepting the beam halo. Usual 16 bits acquisition boards are used implemented either in standalone commercial electronics, either in standard crates after a dedicated electronics frontend.

ELECTRONIC STANDARDS

Electronic standards stand for modular electronic crates that define a mechanical shape, backplane connectors and protocols used for data transfer between the cards on the backplane bus. The crate provides the power-supply voltages for the cards to be inserted (12V, 5V, 3V…) and share the common resources: Central Processing Unit (CPU), Power Supply Unit (PSU), fans…

Modular electronic crates are widely used in large accelerator facilities. Indeed by lowering the number of different electronic module references, it eases a lot integration, maintenance, management and control. Working with a standard also gives the opportunity to have a wider user community (with other laboratories or industrials). This is mandatory for industry to be able to provide COTS products like CPU, PSU, ADCs or FPGA boards. Using electronic standards for global implementations improves the reliability and the modularity and has a direct (positive) impact on the mean time between failure (MTBF) and mean time to recover (MTTR) of the accelerator.

Nuclear Instrument Module (NIM)

NIM is the first and simplest electronic standard. It has been created in 1969 and defines:

- Mechanical dimension
- Backplane connectors used exclusively for power-supply and logic
- A negative current based logic (called fast logic standard)

This standard is now phased out and cannot be considered for new installations. Nevertheless it is still alive due to existing modules still in operation in laboratories. This can partly be explained by the well adapted logic definition for fast signals.

Versa Module Europa Bus (VME)

VME standard is born from the combination of the Versa-bus specification (initiated in 1979 by Motorola) and the Euro-card mechanical format. It has been officially standardized in 1987 as ANSI/IEEE 1014.

The standard defines a multi-processor bus with communication priority that is controlled by a so called arbiter module (occupying the slot 1). The communication scheme is asynchronous (not tied to the timing of a bus clock), provides DMA transfer and interruption mechanism. The maximum (parallel) bus speed is limited to 40 MB/s in its first definition but some more recent evolutions (VME64, VME64x, VME320) offer improved bus speed, up to 320 MB/s.

VME is developed and supported by the VME International Trade Association (VITA [19]). Its market is huge (far ahead other standards used for accelerator application) mainly due to its massive use in military and aerospace industries.

Main advantages of VME are its mechanical robustness and its wide range of COTS modules (ADC, TDC, FPGA boards) based on a very large community. Nevertheless, its future life-time is not clear and innovative products for accelerator applications may be difficult to source. Its old parallel bus definition does not allow very high data rate transfer, but this limitation is very often solved by the use of external multi-gigabit transceivers (MGT) for communication between modules.

Peripheral Component Interconnect (PCI) and compactPCI

PCI is the standard that defines the personal computer (PC) peripheral bus. It has been originally developed by Intel, and standardized in 1991. In contrast to VME, the PCI bus is synchronous, with data and addresses multiplexed on the same lines. The maximum bus speed goes from 132 MB/s (for 32 bits, 33 MHz version) to 528 MB/s (for 64 bits, 66 MHz version). The physical length of the bus is limited to 4 slots since electrical reflexions on unterminated lines are exploited to increase the wavefront voltage. Modules can be powered with 3.3 or 5V with keying connectors to prevent any wrong insertion.

CompactPCI is a declination of the standard for PCI-based industrial computers. The form factor is based on standard Eurocard dimension (like VME), and the bus length is extended to 8 available slots. The backplane connectors are more robust and are adapted for hot swapping possibilities (staged pins to apply power before bus signals at insertion). CompactPCI modules are very cost effective solutions, and allow to use mass market products with widely used and debugged drivers [20]. This standard should progressively be replaced by its new declination CompactPCI Serial in which the old parallel bus has been replaced by point to point links (allowing use of PCIe, SATA or USB protocols), nevertheless I/O boards under this new standard are still difficult to source.

Micro Telecommunication Computing Architecture (µTCA)

µTCA standard emerged from the ATCA (Advanced Telecommunication Computing Architecture) standard, established in 2002 by and for telecommunication industry. ATCA has improved crate management capabilities (hot-swapping, alarms, cooling regulation…), point to point serial lanes on the backplane for high speed data transfer (>400 MB/s on PCIe 4 lanes) and provides redundancy (at least for power-supply and fans).

µTCA standard allows direct connection of the advanced mezzanine card (AMC) to the backplane, suppressing de facto the large carrier board defined in ATCA. It has scalable form factor, from 5 single-size slots to 12 double-size slots [21]. The carrier hub (MCH) module is mandatory. This module takes care of the module management (cooling, power-supply, hot-swap, remote access, alarms…), has the switch functionality for PCIe and GbE communication on the backplane, and distributes the clocks. A central processing unit may be used for data concentration and additional processing, for data archiving on hard disk and for Ethernet connection to the control system.

In 2009, 6 laboratories (SLAC, DESY, FNAL, IHEP, IPFN and ITER) and 38 industrial have mounted the xTCA for Physics working group to adapt µTCA standard to physics applications. It specified the µTCA.4 standard, based on µTCA, with (among other) 2 new functionalities:

- Definition of the Rear Transition Module (RTM) and associated connector. This module allows the implementation of application specific I/Os and room for signal conditioning and conversion.
- Distribution on the backplane of timing signals like machine clock, triggers or interlocks.

µTCA.4 is a standard that is adapted for physics instrumentation with high baud rate real time data transfer on the backplane and timing signal distribution. It offers high analog signal processing possibilities. Its management capabilities and redundancy should give it a very good reliability. The drawback of this standard is at the moment its higher cost compared to cPCI and VME, and implementation is more complex. It might also be more difficult to find staff with the expertise to work on this standard since the community is still confidential.

Electronics Standards in Accelerator Laboratories

The three electronics standards that are currently the most widespread in accelerator laboratories are VME (from far the most popular), cPCI and µTCA (table 1.)

µTCA user community is not very large yet but is growing very quickly. The majority of new accelerator installations has (or is considering) chosen this standard for partial or global implementation (MAX-IV, PAL-XFEL, E-XFEL, FRIB, ESS, FAIR).

Global Implementation

Global implementation in accelerator laboratories with all the electronics following the same standard is pretty rare. Most of the time additional standalone electronics is used, mainly for BPM and bunch by bunch feedback systems. Those instruments have a high level of complexity, and need high performances (in terms of bandwidth, baud rate, noise…) that lead to a lack of COTS components under all available standards. Standalone electronics that can fit the needs of different accelerators have been developed.

The most recent µTCA.4 standard could answer part of those issues, proposing on its backplane timing signal distribution, low-noise/high bandwidth lanes, serial point to point high-speed protocols, and the possibility to have transition modules on the rear for application/accelerator specific signal conditioning and conversion. Nevertheless considering the higher cost of this standard it may be oversized for simpler applications.

Table 1: Standards in Instrumentation

Machine	Date of first operation or last major upgrade	VME	cPCI/PCI	ATCA /µTCA
Elettra	1993	X		
Bessy II	1995	X		
DELTA	1995	X		
SPring-8	1997	X		
SLS/HIPA/PROSCAN (PSI)	2001	X		
SPEAR3	2003	X		X
SOLEIL	2006		X	
DLS	2007	X		
FERMI	2010	X		X
SACLA	2011	X		
ALBA	2011		X	
PLS-II	2012	X		
NSLS-II	2015	X	X	
MAX-IV	2016		X	X
PAL-XFEL	2016	X		X
E-XFEL	2016			X
SwissFEL	2016	X		
FRIB	2016-2021			X
ESS	2019-2025			X
FAIR	2022			X

CONCLUSION

The use of standard electronics for data acquisition eases the integration, maintenance and management of the entire pool in accelerator laboratories where they are massively implemented. The three most popular standards are VME, cPCI and most recently µTCA. This last one is still in its growing phase (with maturity issues) but benefits from a large support from the accelerator community (µTCA.4). By addressing some of the limitations from other standards (timing signal, backplane communication speed) it could be a good candidate for global implementation in the future, nevertheless its cost and level of expertise needed for its implementation have to be taken into account.

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