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Possible Spin-Offs from LHC Physics Experiments for Beam Instrumentation

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This paper aims to introduce some of the new technology and materials used in the construction of the LHC physics experiments into the domain of the beam instrumentalist. The development of radiation hard fibre-optic technology, for example, can equally well be applied to beam instrumentation systems for the direct transmission of analogue or digital signals from high to low radiation environments. Many electronics techniques such as a system developed for the fast integration of photomultiplier signals could also prove very useful in the construction of new beam diagnostic instruments for bunch-to-bunch measurements. Other topics covered will include a fast beam synchronous timing system based on laser technology and a look at pixel detectors as a possible replacement for CCD cameras in imaging applications.

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POSSIBLE SPIN-OFFS FROM LHC PHYSICS EXPERIMENTS FOR BEAM INSTRUMENTATION

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Abstract

This paper aims to introduce some of the new technology and materials used in the construction of the LHC physics experiments into the domain of the beam instrumentalist. The development of radiation hard fibre-optic technology, for example, can equally well be applied to beam instrumentation systems for the direct transmission of analogue or digital signals from high to low radiation environments. Many electronics techniques such as a system developed for the fast integration of photomultiplier signals could also prove very useful in the construction of new beam diagnostic instruments for bunch-to-bunch measurements. Other topics covered will include a fast beam synchronous timing system based on laser technology and a look at pixel detectors as a possible replacement for CCD cameras in imaging applications.

1 INTRODUCTION

The Accelerator and High Energy Physics (HEP) Experiment domains of large laboratories are often separated, with very little interaction taking place between the two. Accelerators are generally maintained by on-site staff, while the HEP Experiments are designed and built by a multitude of world-wide institutions. This makes it difficult to exchange ideas and foresee common applications for any development work. However, many of the new techniques investigated by the HEP Experiments can equally well be applied to beam instrumentation. With the ever-increasing demands on beam diagnostics requiring new and innovative solutions, coupled with decreasing staff numbers, such collaborations can prove to be very useful. In the following sections I will highlight a few techniques derived from the LHC Physics Experiments that are already being investigated for beam instrumentation purposes.

2 RADIATION HARD FIBRE-OPTIC TECHNOLOGY

Acquiring data in the front-end systems of HEP experiments necessitates the use of radiation resistant electronics. The detector itself is also crowded with equipment, severely limiting the amount of space available. Hence, in order to minimise the amount of electronics located in these high radiation regions, the LHC experiments have been investigating ways to transmit the data as soon as possible to the outside world. Described in this section is a way in which analogue signals can be extracted with limited very-front-end electronics.

2.1 CMS Analogue Signal Transmission

The CMS tracker is comprised of pixel, silicon and gas microstrip detectors, located in the centre of the experiment, right next to the beam pipe [1,2]. The silicon and gas microstrip detectors are read-out by charge sensitive amplifiers. The resulting signal, from some 12 million detector channels, has to be transmitted to the counting room on the outside of the CMS detector. The requirements for this link is as follows:

- Full scale dynamic range ~ 200:1 (46dB)
- < 2% deviation from linearity
- Overall rms link noise < 0.2% of full scale.
- Operation in magnetic field of up to 4T
- ~10kGy/year integrated radiation dose and 10^{13} (1Mev neutron equivalent)/cm^2 hadronic fluence.

The solution adopted by the CMS tracker team[1] makes use of analogue fibre-optic transmission [3,4]. A 1310nm, edge emitting, MQW semiconductor laser diode is directly modulated by a transconductance amplifier, with the light produced passing into a single-mode optical fibre. This fibre, some 150m in length, carries the analogue signal to the digitisers in the counting room, where it is converted back into an electrical signal by PIN photodiodes. Using this technique, the requested linearity was obtained, with a link noise of less than 0.2%. The overall bandwidth was limited by the laser driver to 172MHz.

Since radiation hardness was of great concern, many tests were carried out on the influence of radiation on the laser characteristics [5,6,7] and on the fibre-optic cable [8]. In conclusion, it was found that a variety of commercially available 1310nm lasers and single-mode fibres could meet the stringent radiation requirements for operation in the CMS tracker environment.

2.2 Example Application for Beam Instrumentation

This type of fibre-optic transmission is already being investigated for possible use in beam instrumentation. In

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[1] http://cms-tk-opto.web.cern.ch/cms-tk-opto/default.htm

the original design of the LHC beam position system it was envisaged that all of the front-end electronics would remain in the tunnel. It soon became apparent, however, that qualifying all components for a high radiation environment would prove to be very difficult. Hence an alternative solution was sought.

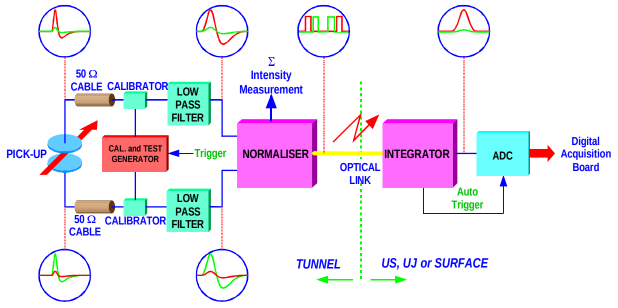

Figure 1: The LHC beam position measurement system

A schematic of the new system is shown in Fig. 1. The acquisition is based on a wide band time normaliser [9], which encodes position as a pulse modulation. This pulse modulated signal, originally transported electrically between the normaliser and integrator, will now be transmitted from one to the other using a 2km fibre-optic link. Only the very front-end analogue electronics and the radiation-hard laser transmitter will remain in the tunnel, with the integrator, ADC and subsequent digital electronics installed in surface buildings.

Figure 2: Output response of the LHC beam position monitor fibre-optic link.

Fig. 2 shows the final ECL output pulses (rectangles) as a function of the PIN photodiode amplitude response. The position is encoded in the time between the two falling edges (10ns ± 1.5ns). It was not possible to accurately measure the overall jitter in the link, since it was less than the 11ps jitter of the oscilloscope itself. To give some idea of its influence, a 15ps jitter would introduce noise into the system at the 1% level. This system is being tested at CERN this year and, if successful, will be adopted for the LHC beam position measurement system.

3 FAST TIMING SYSTEMS

Most beam instrumentation relies on an accurate timing system. This is particularly true for applications requiring bunch-to-bunch measurements. In this section I will describe the timing system developed for the LHC Experiments, which has now also been adopted to provide the fast timing signals for the LHC beam instrumentation.

3.1 *The Timing, Trigger and Control System for the LHC*

The Timing, Trigger and Control (TTC) system [10] for the LHC Experiments is being developed as part of the CERN-RD12 Project[2], which was initially a common project for ALICE, ATLAS, CMS and LHCb. The usefulness of the system has now become apparent for many other users, transforming the project into an LHC Common Project financed by both the CERN Experiment and Accelerator sectors.

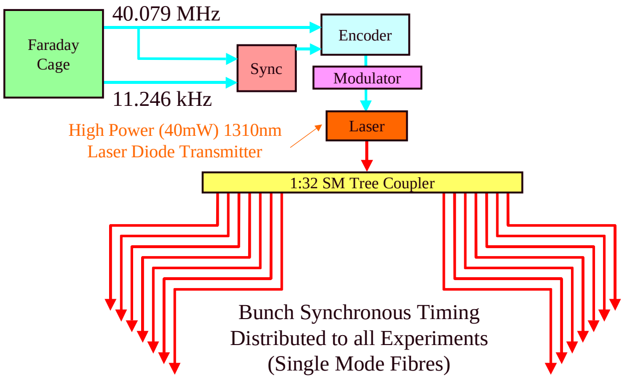

Figure 3: Schematic of the TTC distribution chain.

The TTC system is designed to provide bunch synchronous timing, a level-1 trigger (or revolution frequency for beam instrumentation), and the ability to send broadcast and individually-addressed control signals to front-end equipment. A schematic of the TTC distribution chain is shown in Fig. 3.

The 11.246kHz LHC revolution frequency and the 40.08MHz LHC bunch frequency are derived from the 400MHz RF acceleration frequency. These are used via a PLL to provide the 160.32MHz clock required for the 160.32MBaud biphase mark encoding shown in Fig. 4. Encoding at four times the bunch frequency allows two data streams (Channels A and B) to be sent in addition to this frequency. Channel A is used to provide the revolution frequency (for beam instrumentation) or the

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[2] http://ttc.web.cern.ch/TTC/intro.html

level-1 trigger (for the experiments), while Channel B can be used to encode formatted commands and data. These messages can be used to synchronise acquisitions on a given turn and to send data such as the current beam type, energy, intensity etc. to the front-end controllers. All this is carried out using the TTCvi encoding VME interface [11].

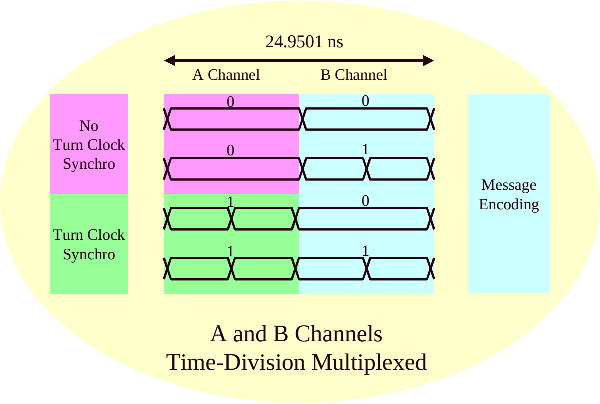

Figure 4: TTC encoding

Once encoded, the signal will be transmitted via a high power (40mW) 1310nm diode laser, though single-mode fibre optic cables to all the LHC access points. At each point, the signal will be redistributed via multi-mode fibres either to the experiments, where it is re-encoded with experiment specific information, or to the beam instrumentation.

A radiation hard receiver ASIC, the TTCrx [12], will be used to decode the transmitted data. Each receiver chip can be individually addressed and has programmable coarse and fine delays to adjust for bunch time-of-flight and varying fibre lengths around the ring. The overall jitter at the output of the TTCrx is ~100ps.

The TTC system provides a ‘ready made’ solution for the fast timing requirements of the LHC beam instrumentation. In addition, the ability to encode messages will provide users with the possibility of receiving relevant machine parameters in their front-end systems. Another advantage is the fact that the receiver chip is radiation hard, so allowing its use inside the tunnel. The TTC system has therefore been adopted to provide all beam synchronous timing for the LHC.

4 ELECTRONIC CHIP DESIGN

The fact that HEP experiments are at the forefront of technology, combined with the stringent space requirements inside the detectors themselves, often leads to the design of specialised ASICs on which many complex functions are integrated. One example of such an ASIC, the TTCrx, was described in the previous section. Here we will look at a further example with a more general functionality, which could prove very useful for several beam instrumentation applications.

4.1 Fast Integration ASICs

The LHCb experiment[3] is equipped with three types of calorimeter [13]. The pre-shower and scintillator pad detector contain some 12000 channels in total, with each channel constructed of coils of optical fibre embedded in a scintillator material. Their function is to separate electrons and pions or photons and minimum ionising particles (MIPs), for the level-0 trigger of the experiment. This is followed by the 6000 channel, lead/scintillator electron calorimeter, and the 1500 channel, steel/scintillator hadron calorimeter. The light from all these scintillators will be detected using photomultiplier tubes.

Each photomultiplier signal has to be integrated at a rate of 40MHz, requiring a very fast integrator. Two separate developments are being undertaken by the LHCb collaboration to achieve such performance. The Laboratoire de Physique Corpusculaire (Université Blaise Pascal, Clermont-Ferrand, France) is developing a multiplexed differential integrator, capable of providing 10-bit resolution after digitisation at 40MHz [14]. This is intended for use with the pre-shower calorimeter, to produce the level 0 trigger. For the electron and hadronic calorimeters, the Laboratoire de l’Accélérateur Linéaire (Orsay, France) is producing an integrator with a 12-bit resolution that works at 20MHz [15]. It is this second integrator that I will describe in more detail in this section.

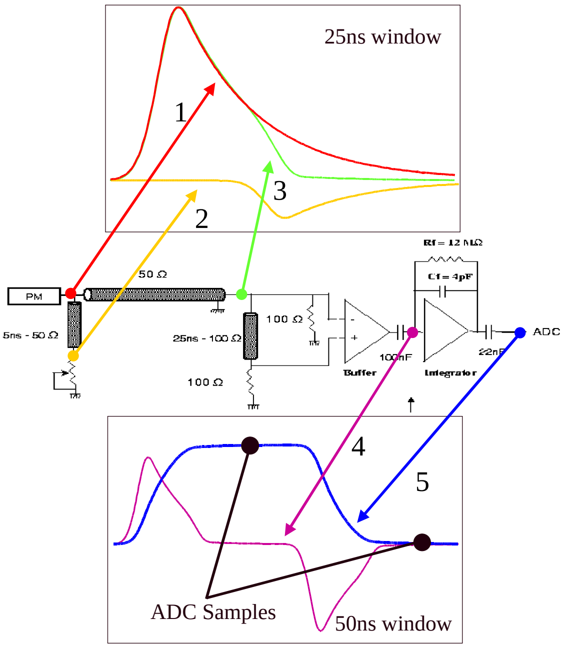

Figure 5: Schematic of the front-end electronics for the LHCb electron and hadronic calorimeters.

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[3] http://lhcb.web.cern.ch/lhcb/

The general layout of the front-end electronics is shown in Fig. 5. At the exit of the photomultiplier (trace 1), the signal needs to be shaped to avoid an electronic pile-up at the next bunch crossing after 25ns. This is done using a clipping circuit, which inverts and returns part of the signal (trace 2), to pull the photomultiplier signal to zero after ~10ns.

The integration repetition rate for such signals is limited by the finite discharge time of the integrating capacitor. One way to reduce this dead-time is by using two integrators and a multiplexor, allowing one to integrate while the other discharges. This is the technique being applied to the pre-shower calorimeter. However, the inevitable injection of charge from the discharge switches of such an integrator generates pedestals that can be sources of drifts at the 0.1% level. The alternative possibility, adopted for the electron and hadronic calorimeters, is to subtract the signal from itself in a linear way during the integration process. This is achieved by delaying half of the signal by 25ns before combining it with the original signal via a differential buffer. The buffer and the integrator are AC coupled to remove any DC offsets, so that the integrator finally sees a signal similar to that shown in trace 4. The 12-bit ADC samples the integrated signal (trace 5) at 40MHz with one sample for the signal and one for the background, giving a 20MHz overall signal integration rate.

Both the multiplexed and signal subtraction integrators have been developed as analogue ASICs, and are currently under test by the institutions involved.

4.2 Possible Applications for Beam Instrumentation

There are several possible candidates that spring immediately to mind, when looking for applications of such integrators in beam instrumentation. The most obvious is for the integration of similar photomultiplier signals, for example from beam loss monitors or from the multi-anode photomultipliers used for bunch-to-bunch beam size measurements. Another application, which is currently under investigation at CERN, is their use for the integration of fast BCT signals. The current method of providing bunch-to-bunch intensity measurements takes the difference of the peak and valley of the signal using two 40MHz ADCs. There are, however, several drawbacks to this technique, namely that it is very sensitive to bunch length variations and also to the bunch synchronous timing. A fast integrator would overcome both of these difficulties. Similar signals can also be obtained from luminosity monitors and numerous other instruments, which could all benefit from the development of such fast integrator ASICs for their signal treatment.

5 IMAGING

In this section I will describe the development of a hybrid pixel detector, an exciting spin-off from HEP experiments, which I am sure will find many applications in all kinds of imaging instrumentation.

5.1 Hybrid Pixel Detectors

Hybrid pixel detectors were first used successfully in the WA97 experiment at CERN [16] following the developments in the CERN-RD19 collaboration [17]. Since that time many particle physics experiments are developing sub-detectors based on this new technology, which can detect both particles and γ-radiation. The readout requirements for HEP detectors, however, differ from those for imaging. The detected signals are generally delayed and require an external trigger before recording one image. Moreover, the shape of the pixel is a narrow rectangle, favouring a high spatial resolution in one dimension, usually corresponding to the direction of the magnetic field in the experiment. The CERN-MEDIPIX project[4] was therefore launched as a spin-off from the CERN-RD19 collaboration, to apply such hybrid pixel technology specifically to imaging applications.

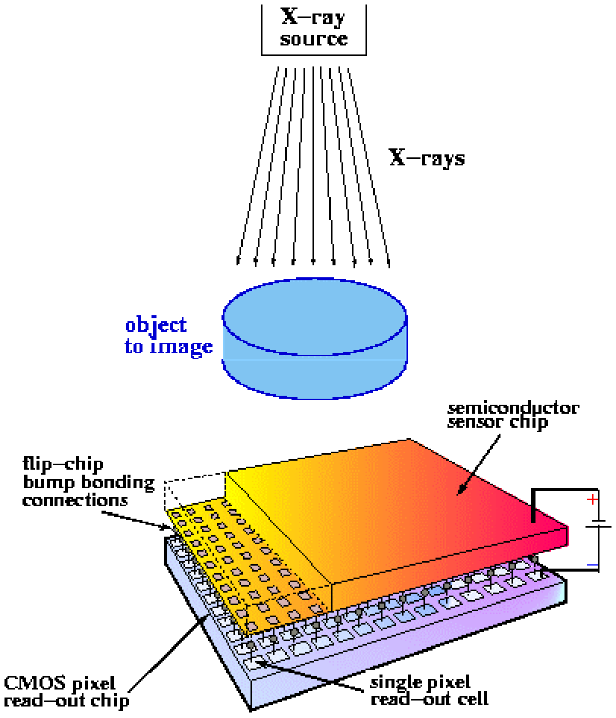

Figure 6: Hybrid pixel detector layout

Hybrid pixel detectors consist of one or several ASICs, each containing a 2-dimensional matrix of readout electronics which are bump-bonded to an equally segmented semiconductor detector (see Fig. 6). This has the advantage that the underlying readout electronics is

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[4] http://medipix.web.cern.ch/MEDIPIX/

independent of the choice of pixel detector. The material used (e.g. Si, GaAs, CdTe) can therefore be chosen according to the requirements of each individual application, depending on their response to a certain photon or particle energy range.

The Medipix1 chip consists of a 2D diode array of monolithic semiconductor containing 4096, 170μm square pixels, giving an active area of ~1.2 cm^2. This is bump-bonded to an equally segmented array of readout electronics. Each individual pixel has a read-out chip containing a pre-ampifier, comparator, global threshold setting, 3-bit threshold fine-tune (addressable on each pixel), elements for masking and testing, and a 15-bit counter giving a maximum count of 32768 photons per pixel. This means that in total each cell is made up of ~400 transistors.

In terms of its operation, the maximum count rate is 1MHz per pixel, with a dead-time between acquisitions of 384μs, which is the time taken by the 10MHz clock to read out a complete frame.

The advantage of such a system over conventional CCD imaging is the fact that it makes use of single photon counting as opposed to charge integration. This means that noise is suppressed and that detector leakage current and electronics mismatch can be compensated, leading to a dynamic range that is ultimately limited by the size of counter implemented behind each pixel. Its insensitivity to dark currents also allows for long exposure times under very low intensity illumination. The other great advantage is that the whole readout system is purely digital.

A second-generation chip, the Medipix2, is currently under development, and will contain 256 × 256 square pixels each 55μm^2 in size, giving a total active area ~2cm^2. On this new chip it will also be possible to select a window in energy over which the device is sensitive.

5.2 Possible Applications for Beam Instrumentation

It is clear that hybrid pixel detectors could very soon become real candidates as replacements for CCD cameras and other imaging detectors. In fact, the Medipix1 detector has already been tested on instruments in the experimental zones of several synchrotron light sources (see e.g. [20]). Studies are also in progress for their use in future projects such as DIAMOND and CLIC. The current detectors are probably not sufficiently radiation resistant for use in general accelerator environments. However, the fact that very radiation resistant examples exist for HEP applications, will hopefully mean that such models will, before long, be available as an alternative for CCD cameras for beam imaging applications.

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