HIGH DYNAMIC RANGE DIAMOND DETECTOR READOUT SYSTEM FOR THE CERN'S BEAM WIRE SCANNERS UPGRADE PROGRAM

J.L. Sirvent#, B. Dehning, J. Emery, CERN, Geneva, Switzerland
A. Dieguez, Universitat de Barcelona, Barcelona, Spain

Abstract

A secondary particle shower acquisition system is under design for the upgrade of CERN's beam wire scanners. The system needs to be capable of performing bunch by bunch synchronous measurements with an integration time of 25 ns and to cope with signal variations of up to 6 orders of magnitude. The whole dynamic range should be covered by the acquisition system with a single configuration and should have no tuneable parameters. The secondary particles are detected using a polycrystalline diamond detector with the signal digitization performed nearby with a custom front-end system, designed to resist a total ionising radiation dose up to 1 kGy in 10 years. The digital data transmission, front-end synchronization and control are performed through a bidirectional optical link operating at 4.8 Gbps using CERN's GBT protocol. For the digitization, two radiation tolerant integrator ASICs (ICECAL and QIE10) are under study.

INTRODUCTION

A beam wire scan is an interceptive method for transverse beam profile measurements. The working principle of wire scanners consists on the passage of a very thin carbon wire (~30um) through the particle beam. The secondary particle shower generated by the beam/wire interaction, is detected outside of the beam pipe and transformed into an electrical current proportional to the loss intensity. The beam profile is reconstructed by plotting the loss intensity versus the wire position. Using the measurements from these devices the beam is determined, allowing calculation of the beam emittance, an important parameter for optimising collider's luminosity.

The Beam Wire Scanners Upgrade Program

The CERN accelerator complex currently has 32 installed beam wire scanner systems of different architectures located along the injector chain and in the Large Hadron Collider (LHC) itself. In terms of mechanics, these systems share some common characteristics, such as the transfer of the motor movement from air to vacuum through bellows. These bellows have a limited lifetime and have compromised accelerator operation in the past trough the appearance of vacuum leaks. In addition, the use of complex mechanics leads to mechanical play that reduces the systems accuracy and hence measurement performance. The current scan speeds are also limited and do not allow the measurement of high intensity beams due to wire sublimation [1].

The development of a new scanner type is motivated by all the above mentioned issues and the need to measure smaller beam sizes at higher beam intensities in the future. The basic concept is to combine a high scan velocity, nominally $20ms^{-1}$ to avoid wire damage, with an accurate and direct wire position determination avoiding bellows and any lever arm mechanism. The specified beam profile measurement accuracy is set to 2µm. The upgraded system, common for the CERN PSB, PS, SPS and LHC, is therefore based on an in-vacuum motor rotor, with the stator outside, avoiding the use of bellows, and incorporating an optical position sensor for accurate position determination [2] (see Figure 1).

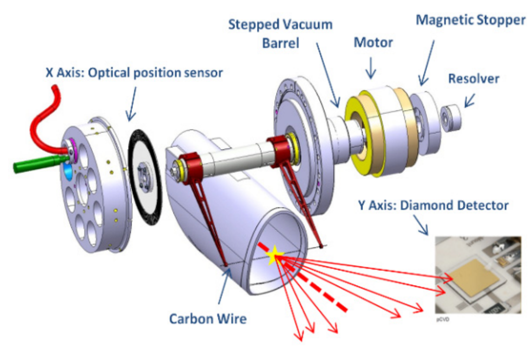

Figure 1: Upgraded Beam Wire Scanner Design.

Secondary Shower Acquisition System Upgrade

Presently, the secondary particle showers from operational beam wire scanners are detected by a scintillator. The light produced transits a wheel of selectable optical filters, after, it is detected using a photo multiplier tube (PMT) that transforms the optical signal into a current. A current-to-voltage, transimpedance, amplifier is used to drive this signal over CK50 coaxial cables of up to 250m, to surface buildings where the digitization is performed. To reach a suitable resolution, this architecture obliges the accelerator operators to set-up the system, selecting a suitable combination of PMT gain and optical filter, according to the beam characteristics. On these systems the dynamic range is limited by the pre-amplifier, sometimes the Gaussian tails of the beam profile are too much shadowed by noise, and in some cases PMT saturation effect can lead to incorrect measurements [3].

The upgraded secondary shower acquisition system aims to use 500um thick polycrystalline chemical vapour deposition (pCVD) diamond as detector. This requires new acquisition electronics which need to cover the high dynamic range of the diamond detector without tuneable parameters, while also providing very low noise

jsirvent@cern.ch

ISBN 978-3-95450-176-2

measurements. The design of such system must be compatible with any CERN accelerator and beam wire scanner location.

DIAMOND DETECTORS AS BEAM PROFILE MONITORS

Diamond detectors are solid state ionization chambers. When applying a bias voltage on its electrodes, the passage of charged particles through the diamond bulk generate a current on the detector proportional to the deposited energy, and therefore to the number of particles that cross the material. These detectors have been deeply studied and characterized in terms of temporal resolution, radiation hardness and linearity by the RD42 collaboration at CERN [4], and successfully implemented as beam loss monitors [5].

Analogue Front-End Tests with Alpha Particles

An analog front-end was prepared and tested with an alpha source (^{241}Am). In order to drive the signal along 50 Ohm coaxial cables, the current signal from the detector is transformed into a voltage by a fast transimpedance amplifier, based on the THS3001 high slew rate operational amplifier. Input and output impedances are matched to 50 Ohm as shown in Figure 4.

The signal from the amplifier, produced by alpha particles crossing the detector, was sampled with a LeCroy oscilloscope at 5GSps with 50 Ohm input impedance. With the pCVD diamond detector biased at -700V, the front-end produced pulses of 4.5mV of amplitude with an approximate duration of 8ns (FWHM) and a little undershoot. The small undershoot due to the amplifier response was recovered in around 13ns, as shown in Figure 2. This is more than adequate to reach the 25ns resolution with no signal pile-up.

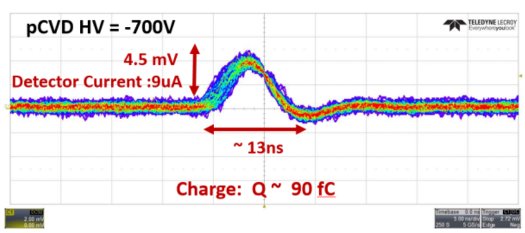

Figure 2: Signal from pCVD Diamond Detector after a transimpedance amplifier based on THS3001.

The charge created in the detector by a single alpha particle is around 90fC, and can be determined by integrating the detector current over the pulse duration. The detector current with this configuration can be easily calculated using the transimpedance amplifier transfer function, as shown on equation 1:

$$I_d(A) = 2V_o / Rf \tag{1}$$

Where I_d is the detector current, V_o is the signal amplitude in 50 Ohm and R_f is the feedback resistor used on the amplifier (1KOhm in this test).

Tests with Beam Wire Scanners

The analog front-end has been installed in the Long Straight Section 5 (LSS5) of the SPS accelerator, at approximately 1.6m from an operational linear wire scanner (BWS51731), and just in front of the original scintillation detector. See Figure 3.

Figure 3: Test Set-up on the SPS accelerator.

Measurements from the analogue front-end were recorded with an oscilloscope on the surface, using 80m of CK50 coaxial cable for signal transmission. A simplified electrical model of the set-up is shown on Figure 4.

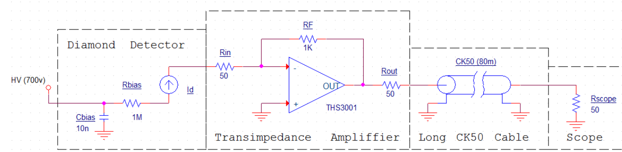

Figure 4: Simplified set-up for evaluating a pCVD diamond detector for beam profile monitoring.

The linear beam wire scanner mechanics in the SPS have a scan speed limited to 1ms^{-1}. To avoid wire sublimation, the beam used on the machine for these tests was an LHC pilot beam. The test conditions are summarized in Table 1.

Table 1: Testing Conditions

Attribute	Value
Scan Speed	1 ms^{-1}
Carbon Wire Diameter	30 um
SPS User	LHC Pilot
Bunches in the SPS Ring	1
Protons per bunch	1e^{10} protons
Bunch Length (4 Sigma)	4 ns
SPS Revolution Period	23 us
Energy	450 GeV

During the test, the bunch clock as well as the turn clock were sampled and used as a timing reference for the data processing. A Matlab script was used to perform a digital bunch integral with a duration of 25ns on every turn. The detector signal is shown in blue and the integrals as green markers on F5 top. The scan speed information, taken from the database, is then used to change the x-axis from the temporal to the spatial domain. Once this is done, a Gaussian fit is performed to

ISBN 978-3-95450-176-2

determine transversal bunch size (middle chart). For comparison, the profile measured with the operational system is shown in the bottom plot of Figure 5.

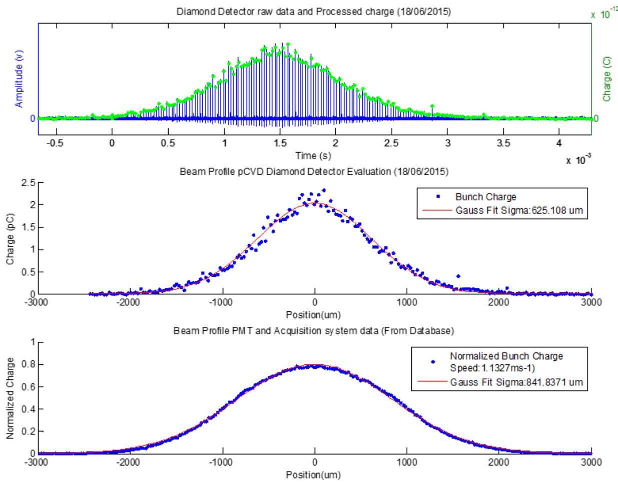

Figure 5: Signal amplitude of secondary shower intensities as a function of time and position. Top: pCVD Diamond detector measurements versus time. Middle: pCVD diamond detector integrals versus position. Bottom: Scintillator/PMT detector measurements versus position.

A couple of interesting effects can be observed comparing the middle and bottom plots of Figure 5:

- ***Spread of detector signals***: The measured signals on both detectors (pCVD and scintillator/PMT) are parameterized with a Gaussian distribution. It can be observed that the residuals variation is larger for the pCVD compared to the scintillator/PMT assembly. The higher variation shown by the diamond detector signal could be a statistical effect related to the random distribution of the secondary particle cone produced by beam-wire interaction, and the small size of the detector ($1cm^2$). With the scintillator covering a larger area, the effect of particle number fluctuation in the final signal is much lower compared to the pCVD detector.
- ***Profile width determination:*** The sigma values of the Gaussian parametrization for the pCVD detector is a 27% smaller than for scintillator/PMT setup. The reason of such beam profile difference remains unknown, and further studies are needed to understand this effect.

In total, 9 scans were done. A summary of the profile parameters are shown on Table 2, including the least-squares error (SSE) of both fits once normalized for comparison.

Table 2: Profile Measurements Summary

System	Mean Sigma	Std. Dev	SSE
Diamond	613.0 um	12.4 um	0.233
Scintillator	839.7 um	1.9 um	0.072

Although the sources of such differences remain unclear, they do not seem to be related to an effect of the electronics or the processing algorithm. To study such effects, a different set-up is scheduled to be installed at the same location with two diamond detectors placed above and below the beam pipe.

SECONDARY SHOWER ACQUISITION SYSTEM ARCHITECTURE

The implemented system architecture is shown in Figure 6. A previous article describes the motivation behind the architecture choice [6]. A custom radiation tolerant front-end will be placed in the tunnel at ~10m from the diamond detector. The front-end will perform charge integrations at 40MHz, synchronous with the beam and with a very high dynamic range. The digital data will be sent through a dual single mode optical fibre using CERN's GBT protocol at 4.8Gbps to the back-end electronics [7]. The front-end synchronization, data transmission and control is performed through the optical link. For the back-end system, the CERN custom designed VME FMC Carrier board (VFC) will be used to manage the data processing and storage. On the VFC, one Small Form-Factor Pluggable (SFP+) transceiver is needed per system, allowing up to 4 front-ends to be controlled with a single VFC.

Front-End Design

For the detector readout, two integrator ASIC candidates are being evaluated, ICECAL [8], and QIE10 [9]. Their main specifications are summarized on Table 3.

Table 3: Diamond Detector Readout ASIC Candidates

Feature	QIE10	ICECAL
Dynamic Range	3.2fC-340pC (1e5)	4fC-16pC (1e3)
Integration Window	25ns (40Mhz)	
Channels per ASIC	1	3
Input Impedance	50 Ohms	
Dead-timeless	Yes	
Number of Bits	8	12 *
Quantification Error	~1%	<<1% *
Linearity Error	~1% (Log)	<1% *
TDC Capability	Yes	No
Max TID	~0.5kGy *	***
ASIC Technology	AMS SiGe BICMOS 0.35um	
Designer Entity	Fermilab	U. Barcelona

* ADC Dependent
** Early characterization, further tests will be done
*** Not yet characterized.

ISBN 978-3-95450-176-2

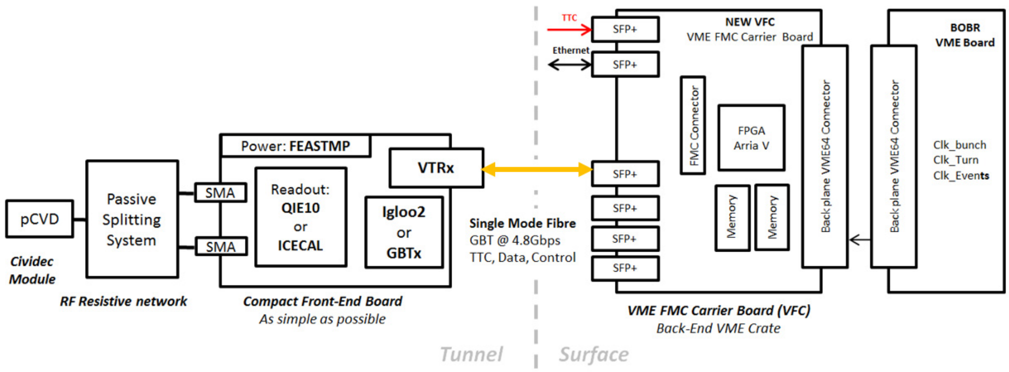

Figure 6: Upgraded secondary shower acquisition system architecture.

For fast evaluation, not only under laboratory conditions but also for tunnel operation, the digital front-end was designed in a modular way. The Igloo2 UMd Mezzanine from the CERN CMS collaboration [10] is used as a digital motherboard, responsible for driving the optical link. This board features an Igloo2 Flash-based FPGA with the GBT protocol implemented on its firmware and a versatile link transceiver (VTRx).

Independent mezzanine boards for each of the two readout ASIC candidates were designed to be attached to the motherboard through a SAMTEC connector. The two front-end versions are shown in Figure 7. All the components used on these boards have already been characterized under radiation by collaborators.

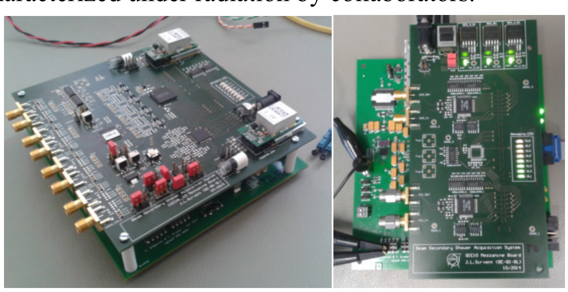

Figure 7: F.E. versions (Left: ICECAL, Right: QIE10).

In order to reach the 1e6 dynamic range of the specifications, the signal from the diamond detector will be split into several channels with different gain/attenuation. These signals will be sampled in parallel on the front-end and processed in parallel on the back-end to reconstruct the beam profile.

QIE10 Front-End Version Studies

A full prototype set-up was used for the first measurements with the QIE10 front-end. Due to unavailability of the CERN-VFC board at the time of the tests, an Igloo2 development kit was used as back-end system. For complete operation, an SMA to SFP+ module and a custom clock conditioning circuit, including programmable delay lines, were attached to this kit.

On this prototype system, the front-end is continuously sampling and sending data to the back-end system in synchronism with the accelerator bunch clock. When the back-end receives a trigger signal, the optical link data is temporally stored on a 512MB LPDDR memory using 64 bits words. The 64 bits data frames contain: bunch ID, Turn ID, data and status bits. A PC connected to the back-end system, through UART and with a custom user application, provides feedback on the optical link status, allows the user to perform the control of the front-end over the link and recovers the data from the LPDDR memory for analysis. This application also controls a Keithley 6430 sub-FemtoAmp current source through a general purpose instrumentation bus (GPIB). The complete set-up for laboratory tests is shown in Figure 8.

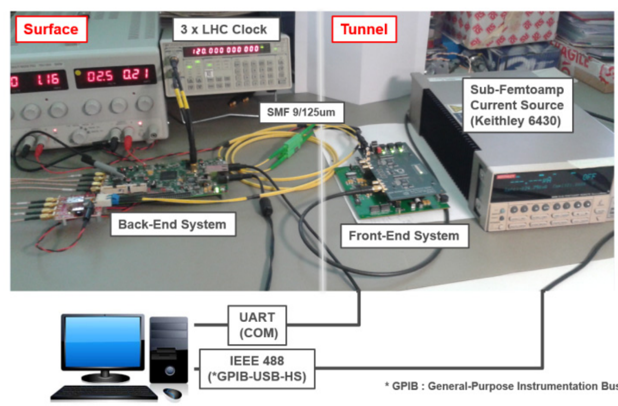

Figure 8: Laboratory tests set-up.

QIE10 is a charge integrator and digitalization ASIC able to cover a dynamic range of 1e5 with 8 bits encoding. Its logarithmic charge encoding algorithm contains 16 sensitivity levels, which are divided in 4 ranges. Its 8 bits digital data format contains 6 bits for mantissa and 2 for range. The QIE10 uses 4 different internal capacitors, highlighter later as CIDx in different colours, to achieve integrations every 25ns, with each integrator channel requiring 100ns to process its 25ns integral. In order to check the QIE10 response, logarithmic sweeps were performed with the Keithley current source. Temporal windows of 25us (1000 samples at 40 MHz) were taken for each current increment, then, the value of each CID was averaged. The data measured was compared with the ASIC nominal logarithmic parametrisation to check any possible deviation, as shown in Figure 9.

ISBN 978-3-95450-176-2

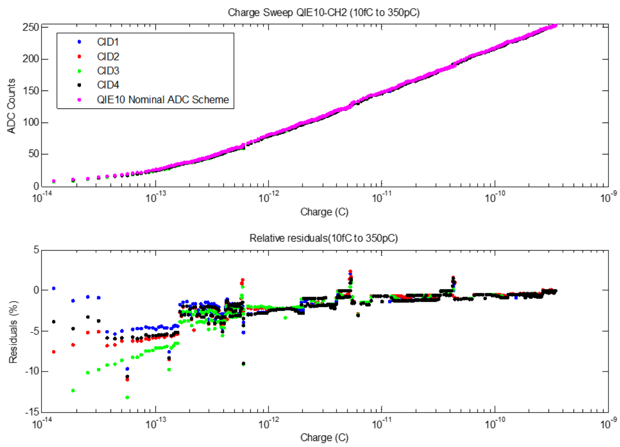

Figure 9: QIE10 response to a logarithmic current sweep (top) and relative residuals from nominal response (bottom).

The top plot of Figure 9 shows the QIE10 ADC values which represent the input charge, while the lower plot shows the residual error. Clearly visible is the logarithmic behaviour of the QIE10 and the 4 ranges in which the ASIC splits its dynamic range (seen as little spikes in the residual error). The measured values in our prototypes show a good agreement with respect to the ASIC nominal ADC response, remaining below 5% of difference, except for a small part of the first range. All the integrator capacitors (CIDs) show a similar response.

The check of the 16 sensitivity levels (4 per range) are shown in Fig. 10, with the charge versus mantissa value plotted. The slope of the linear fits performed in each sub-range shows the sensitivity levels.

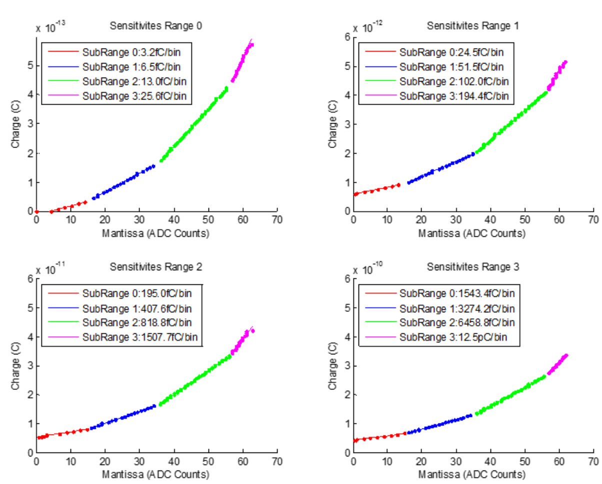

Figure 10: QIE10 Sensitivity levels.

Both of the QIE10 ASICs contained on the front-end board show a similar behaviour, the data collected during these studies will be used later for calibration. The tests have shown that the complete front-end performs according to specification, which qualifies the electronics in terms of functionality and accuracy for installation in the SPS tunnel for further testing.

CONCLUSION

Diamond detectors have been shown to be a promising solution for secondary particle detection in combination with wire scanners to determine the transverse beam size. Further investigations are required to understand the 27% difference of the beam profile measured with such detectors with respect to the standard scintillator/PMT system. The larger fluctuation of the diamond based system will be addressed with a second test set-up using more detectors.

The digital readout electronics system has been fully tested under laboratory conditions demonstrating the specified performance of the QIE10 readout ASIC. The measured signals are showing a remaining systematic error of maximum 5% respect to the nominal ASIC response. The QIE10 front-end will be installed in the SPS tunnel and its performance tested under operational conditions.

REFERENCES

[1] M. Sapinski et al., Carbon fiber damage in particle beam, Proc. of HB2010, Morschach, Switzerland, pp. 231-234, (2010). http://jacow.org/.

[2] J. Emery et al., "A fast and accurate wire scanner instrument for the CERN accelerators to cope with high environmental constraints and increasing availability demand", Proc. of IEEE Multi-conference on Systems and Control, Antibes, France (2014)

[3] M. Kuhn et al., Investigations of the LHC emittance blow-up during the 2012 proton run, Proc of IPAC2013, Shangai, China, pp. 1394-1396, (2013), http://jacow.org/.

[4] CERN RD-42 collaboration. "CVD diamond radiation detector development". http://rd42.web.cern.ch/rd42/.

[5] E. Griesmayer et al., A fast CVD diamond beam loss monitor for LHC, Proc. of DIPAC2011, Hamburg, Germany, pp. 143-145, (2011), http://jacow.org/.

[6] J.L. Sirvent et al., “Secondary particle acquisition system for the CERN beam wire scanners upgrade”. Journal of Instrumentation, 10, C04021 (2015).

[7] The GBT Project, "Radiation Hard Optical Link". https://espace.cern.ch/GBT-Project/

[8] E. Picatoste et al., “Low noise 4-channel front end ASIC with on-chip DDL for the Upgrade of the LHCb Calorimeter”. Journal of Instrumentation, 10, C04017 (2015).

[9] A. Baumbaugh et al., “QIE10: a new front-end custom integrated circuit for high-rate experiments”. Journal of Instrumentation, 9, C01062 (2014).

[10] S. Goadhouse, et al., “The CMS HCAL FEE Control Module” TWEPP14, Aix-en-Provence, France. September 2014.

ISBN 978-3-95450-176-2