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**Optimization of the Pulse Arrival Time
Determination in the Zeus Central Tracking
Detector FADC system**

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1 Abstract

The constant fraction discriminator algorithm for finding the arrival time of pulses from a drift chamber is outlined. Using a Monte-Carlo simulation the effect of noise and pulse rise time on the timing resolution is studied. A simple correction to this algorithm, which reduces the effect of non-linearities in the pulse rising edge is described. The effect of the correction on the Zeus central tracking detector, instrumented with an eight-bit flash analogue to digital converter system is studied. Using calibration pulses the timing resolution of the system is measured to be 0.021 ± 0.003 digitizing periods, which is in agreement with 0.024 ± 0.001 predicted by the Monte-Carlo simulation. Without the correction the resolution is 0.17 ± 0.02 digitizing periods. The optimum risetime for the ZEUS system is estimated from this model. The model is applicable to other systems which require accurate timing of pulses and have a relatively constant pulse shape.

2 Introduction

The Zeus experiment has been installed and taking data at the Hadron Elektron Ring Anlage (HERA) at DESY since May 1992. An important component of Zeus is the Central Track Detector [1] (CTD). The CTD is a cylindrical drift chamber approximately 2m in length and 1.5m in diameter. It is located within a superconducting magnet providing a uniform axial field of 1.43T. The design spatial resolution is $120\mu\text{m}$. There are more than 24,000 wires in the CTD of which 4608 are sense wires [2]. The CTD electronics are described in detail elsewhere [3]; in this paper we will be concerned with the Flash Analogue to Digital Converter (FADC) system and its use determining drift times and pulse heights.

3 The FADC system

The FADC system digitizes incoming data at a rate of 104 MHz with an accuracy of 8 bits. These data are stored in a digital pipeline until the trigger system makes a decision. Among the challenges faced are the volume of data involved (413 GBytes/sec from the CTD before the first level of triggering, approximately 250 MBytes/sec afterwards) and the high rate of triggers (in the region of 1kHz at the first level). To reduce the data volume as soon as possible in the read-out chain the FADC samples are scanned for pulses and the pulses parameterized by Digital Signal Processors (DSPs) on the same circuit board as the FADCs. These search for pulses and then determine drift times and pulse sizes. Each DSP processes the data from sixteen wires. The DSPs can also write out the unprocessed data, thus allowing the performance of the DSP to be monitored.

4 Pulse Arrival Time Determination

The drift velocity in the chamber is about $50\mu\text{m}/\text{ns}$. Thus to achieve the design resolution the pulses must be measured to 2.4ns or better. Since the digitizing period is 9.6ns the drift time must be measured to better than a quarter of this. A simple threshold algorithm would, at best, give us a timing resolution of $9.6\text{ns}/\sqrt{12}$, i.e. 2.8ns , corresponding to a spatial resolution of $140\mu\text{m}$. It follows that to reach the design resolution we use a pulse timing algorithm which interpolates within a digitizing period. Work done using a test chamber at the Rutherford Appleton Laboratory [4] concluded that the optimum method of finding the arrival time of a pulse was the constant fraction discriminator (CFD) algorithm.

Figure 1: Sketch of the rising edge of a chamber pulse. The quantities used by the CFD are indicated.

The DSP packs the drift time data very densely to keep the data volumes to a minimum. The constraints on the data volumes mean that the drift times are only stored to a precision of a quarter of a digitizing bin. This leads to a timing resolution of $2.4/\sqrt{12}ns$, ie. $0.7ns$ corresponding to a spatial resolution of $40\mu m$, which is adequate.

4.1 The constant fraction discriminator algorithm

To determine the pulse arrival times the DSP searches through the data looking for signals above a threshold value. Provided the signal at some point exceeds the threshold the algorithm finds the maximum signal and then looks in the preceeding bins for the minimum. The constant fraction discriminator threshold, C_{ft} , is then defined as

$$C_{ft} = C_f(S_{max} - S_{min}) \quad (1)$$

S_{max} is the maximum signal and S_{min} is the minimum signal at the start of the rising edge (see Fig. 1). C_f is the “constant fraction”. For CTD pulses the optimum value of C_f has been found to be 0.16 [4].

The algorithm then searches through the pulse looking for the first sample on the rising edge of the pulse which exceeds C_{ft} , denoted i . The arrival time, in units of the digitizing period, is defined as

Figure 2: Histogram of the fractional part of the pulse arrival time returned by the CFD.

$$T = (i - 1) + \frac{C_{ft} - S_{i-1}}{S_i - S_{i-1}} \quad (2)$$

where S_i is the value of the i^{th} FADC sample, and S_{i-1} is the value of the preceeding sample.

4.2 Observed timing distributions

Figure 2 shows the fractional part of the arrival time distribution, calculated to arbitrary precision (i.e. $T \text{ Modulo } 1$). Instead of the flat distribution which would be expected the data shows a peak.

The shape of the distribution can be understood if the two extreme cases are considered. With a very short rise time S_{i-1} will always be 0 and S_i will be equal to the pulse size so ΔT will always be 0.16. In the limit of long rise times the interpolation will give a good estimate of the arrival time and ΔT over many events will be a uniformly distributed between 0 and 1. The rise times of pulses from the Zeus CTD lie between these two extremes.

5 Simulation of arrival time distributions

The non-uniform distribution of ΔT leads to a systematic error in the observed drift times. It is important to correct for this and this must be done in a simple way since the correction has to be done at the DSP level where processing time is limited. The arrival time distribution has been investigated using Monte Carlo simulation of the CTD pulses.

Pulses were simulated using a function consisting of three components, a constant pedestal value, a rising edge and a falling edge. The rising edge was modelled by a sigmoid, that is a cubic polynomial with coefficients adjusted to give a gradient of zero at the beginning and end.

Figure 3: Scatter plot of the fractional part of the time reconstructed by the CFD versus the actual pulse arrival time.

The falling edge was modelled by the sum of two exponentials with different time constants. The heights of the simulated pulses were distributed according to a Landau distribution with the most probable pulse height and the width of the distribution chosen to match the pulse height distribution in cosmic ray data taken with the CTD. Noise was simulated by adding a random number to each sample of the simulated pulse. The noise signal was simulated by the Fourier transform of a spectrum with constant amplitude but random phase. Both the rise time and the noise amplitude were varied in order to study their effects on the resolution.

Pulses were generated with random start times and analysed using the standard Zeus analysis framework [5]. Figure 3 shows the fractional part of the generated time versus the fractional part of the reconstructed time. The fact that the reconstructed time is a monotonic function of the generated time implies that we can make a correction to the drift time based on the reconstructed time. In addition it is possible to derive this correction from the distribution of reconstructed drift times rather than having to know the shape of each pulse.

Let ΔT and ΔT_{rec} be the fractional parts of the true and reconstructed pulse arrival time respectively. If the pulse shape is constant and there is no noise present then the time reconstructed by the CFD is a function of the actual arrival time: $\Delta T = f(\Delta T_{rec})$. If $f(T)$ is a monotonic function, as indicated by Fig. 3, then $f(\Delta T_{rec})$ is given by

$$f(\Delta T_{rec}) = \int_0^{\Delta T_{rec}} \rho_{rec}(t) dt \quad (3)$$

where ρ_{rec} is the distribution of ΔT_{rec} , the fractional part of the reconstructed arrival time, as shown in figure 2 .

To implement this correction at the DSP level the drift time is calculated to 1/128 of a digitizing period and mapped onto the appropriate 2.4ns bins.

Figure 4: The spread of calibration pulse arrival times from one wire relative to the mean for the cell. Solid line shows the distribution with correction, dotted line without

5.1 Tests with calibration pulses

In order to measure the timing resolution of the FADC system, and the effect of the correction on the resolution, the CTD calibration system was used. Each cell of the CTD is equipped with a calibration source which is used to inject signals into the pre-amplifiers of the eight sense wires in a drift cell. Thus the times at which the calibration pulses reach the FADC channel for each wire are fixed relative to each other. However, the finite resolution of the system means that the *measured* times will vary relative to each other. Within a cell the mean arrival time of the pulses on all the wires was calculated for each calibration pulse. This mean was subtracted from the arrival time for each of the wires. This difference was histogrammed for many calibration pulses. Its width is an indication of the accuracy with which the pulse arrival time was measured. Figure 4 shows the distribution with and without the correction described in the previous section. The timing accuracy is calculated from the RMS of the distribution. Without the correction the accuracy is 0.17 ± 0.005 digitizing periods, with the correction the accuracy is 0.021 ± 0.003 digitizing periods. For pulses of the same (fixed) amplitude and rise time the Monte-Carlo simulation predicts an accuracy of 0.024 ± 0.001 after the correction, in good agreement with the measurement. Errors quoted are statistical only.

5.2 Pulse shape

The process of calculating the correction to the arrival time described above assumes that the pulse shape is independent of both pulse size and arrival time. This assumption is supported by a study of cosmic ray data. The average number of bins on the rising edge for cosmic ray data is plotted as function of drift time and pulse size in figure 5. The average number of bins on the rising edge is essentially constant for all drift times and pulse sizes. This is because,

Figure 5: Mean number of bins on rising edge as a function of drift time and pulse height

for clean pulses, the pulse shape is largely determined by the bandwidth of the analogue electronics which instrument the sense wires. For very large pulses the FADC saturates and the CFD returns an inaccurate result. However, these pulses are flagged as saturated in the DSP output and a correction can be applied based on the number of FADC samples during which the pulse was saturated, since for a constant pulse shape this number is proportional to the actual analogue pulse height.

6 The effect of rise-time on resolution

A rise time of much less than one digitizing period would limit the resolution of the CTD to 2.8ns. At long rise times noise and the finite resolution of the FADC system would degrade the resolution. The optimum rise time is thus a function of the noise in the system and the rate at which the signals are digitized. Using the simulated pulses described above and different noise amplitudes the optimum rise time for a given system can be determined.

Figure 6 shows the timing resolution as a function of rise time for the CFD algorithm with the arrival time calculated to arbitrary precision. In Fig 6a no correction has been applied, in Fig 6b the correction described above has been applied. The rise time is defined as the time taken for the pulse to rise from 10% to 90% of its maximum value. At very small rise times the timing resolution is $\approx 1/\sqrt{12}$ of a bin as would be expected. The resolution improves as the rise time increases, but is limited by noise above a certain risetime. The RMS of the noise signal is given in least significant bits (LSBs) of the FADC system, full scale is 256 LSB.

Figure 7 shows the resolution as a function of rise time. The level of noise was chosen to match those observed in the CTD, that is, a noise RMS of 1.2 LSB. The pulse size distribution was modelled with a Landau distribution with most probable height of 15 LSB and a width

Figure 6: Timing resolution as a function of rise time for different noise amplitudes. *a)* uncorrected and *b)* corrected. The different symbols indicate the RMS noise amplitude.

of 60 LSB which matches CTD cosmic ray data. In figure 7a the arrival time is calculated to arbitrary accuracy, in figure 7b the time is rounded to the nearest quarter of a digitizing period (2.4ns).

From these plots we can see that the optimum rise time for the Zeus CTD system is $1.4 + 0.6 - 0.2$ digitizing periods, compared with the measured mean rise time of 1.75 ± 0.3 digitizing periods, as estimated from the mean number of samples on pulse rising edges for cosmic ray data.

7 Conclusion

We have studied the use of the CFD algorithm in the Zeus CTD. The calculated arrival times using this algorithm are not uniformly distributed but the relation between the two is monotonic and allows us to make a simple correction in the on-board processors. In the CTD the pulse shape is relatively constant, since the shape of the majority of pulses is determined by the readout electronics rather than the ionization statistics in the chamber.

Using calibration pulses the accuracy of the pulse arrival time measurement is estimated to be 0.021 ± 0.003 digitizing periods. We have used a Monte Carlo simulation to study the effect of rise time and noise levels on the timing resolution of this system and found that the optimum rise time for the level of the noise in the CTD is $1.4 + 0.6 - 0.2$ digitizing periods. This compares well with the measured rise time of 1.75 ± 0.3 digitizing periods. This technique should also be applicable to other systems where the pulse shape relatively constant.

Figure 7: Timing resolution as a function of rise time for corrected and uncorrected t_{rec} . a) unrounded , b) rounded.

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