p-CARBON CNI POLARIMETERS AT BNL: THE FASTEST PHYSICS SETUP IN THE WORLD

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Recent years of polarized proton running at BNL proved the efficiency of the idea of using the analyzing power of pC elastic scattering in the CNI region for proton beam polarimetry. Excellent performance of the polarimeters at both RHIC and AGS allowed fast and detailed beam polarization studies including polarization loss during the accelerator ramp, profile measurements and effects of spin rotators. Based on the latest achievements of digital electronics the DAQ system uses signal waveform processing in FPGA crystals and allows on-the-flight selection of up to 500 million elastic pC events per second with no dead time. Principles of operation of the polarimeters and of the DAQ system are presented together with selected performance examples.

The research program with polarized protons at BNL collider-accelerator complex demanded a fast and cost effective tool for beam polarization measurements in a wide energy range with a few percent accuracy. In 1999 the experiment E950[1] at AGS proved the general possibility to use pC elastic scattering in the CNI region for proton polarization measurements and evaluated the analyzing power of the process. The process appeared very promising because of the small energy dependence of A_N predicted by theory[2] and nearly fixed 90^o recoil kinematics in the whole energy range. Yet the small value of the analyzing power of several percent requires huge statistics of about $2 \cdot 10^7$ for a single polarization measurement. Fortunately the large cross section of the process allows the collection of such statistics in seconds, but at the event rate of millions per second. In addition to rate issue, recoil carbon identification is necessary for background suppression along with the measurement of the transferred momentum because of strong $-t$ dependence of A_N. Moreover, a system dead time, if correlated with the polarization sign change, can produce uncontrollable false asymmetries. Thus the most critical part of the setup is a very fast (dead-timeless) DAQ system meeting the above requirements.

Such a system was built based on the fast waveform digitizer[3] (WFD) modules recently developed at Yale University. Signals from Si strip detectors are preamplified, transferred and shaped to obtain short (40 ns FW) pulses with the amplitude proportional to the charge, deposited in the detector. The pulse shapes are then digitized at the equivalent frequency of 420 MHz and analyzed inside the modules, providing the recoil carbon deposited energy and time of flight. The events are then filtered through lookup tables (LUT), checking the kinematic correspondence between the obtained values for carbon identification. The selected events are used to increment scalers and histograms in the modules, and can be stored in the on-board memory. The main advantage of such an approach is that there is no data transfer to the host computer during a data taking run, which makes the system really dead-timeless. The analyzing part is capable of processing of one event per RHIC bunch crossing period (110 ns) resulting in maximum of $\approx 10^7\,\mathrm{s}^{-1}$ events per channel.

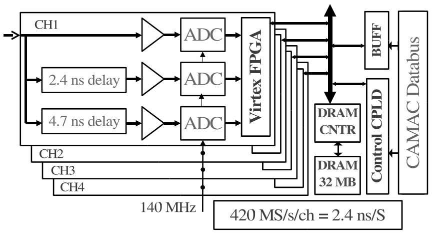


Figure 1. Block diagram of the WFD module.

The WFD is a CAMAC module hosting 4 independent channels (Figure. 1) with common storage SDRAM (64 Mbyte) and CAMAC control circuity. In each channel the input signal is split into three, two of which are delayed 1/3 and 2/3 of the ADC digitization period. Three 8-bit ADCs synchronously start conversions at 140 MHz resulting in triple equivalent digitization frequency. All the waveform analysis is done inside the Virtex-E Xilinx FPGA[4] chip at 70 MHz clock frequency. The analysis algorithm is rather specific since it has to process every 6 waveform points in parallel (the FPGA clock is only 1/6 of the digitization frequency). The block diagram of the analyzing circuits in the FPGA is shown in Figure. 2. The input signal passes through a digital filter for noise reduction and partial

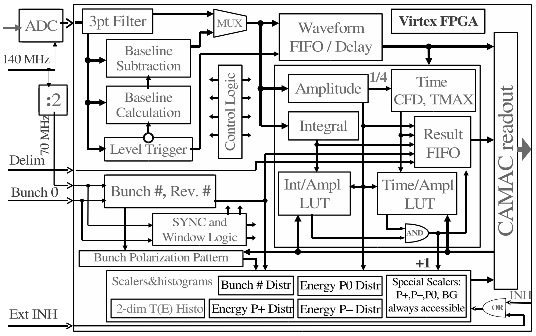
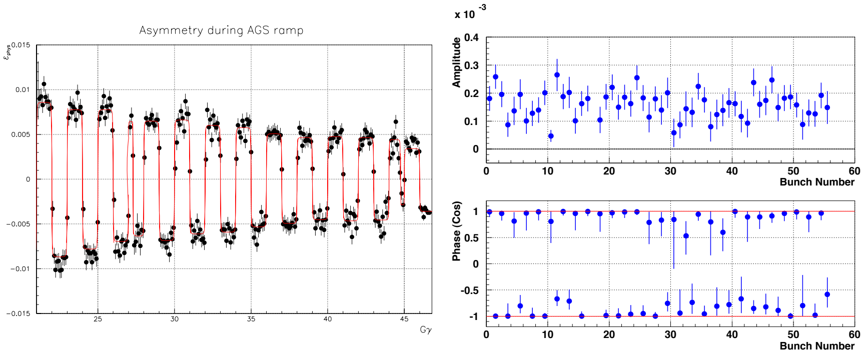


Figure 2. Simplified block diagram of one WFD channel.

compensation for different amplifications of delayed sub-channels. A level trigger is used to determine the presence of a significant signal in a particular bunch crossing period, and if the signal is not detected, the ADC values are used for the baseline calculations. The baseline is determined individually for all three sub-channels to compensate for different amplifier offsets and is averaged over the 16 latest bunch crossing periods with no significant signal. The baseline is then subtracted and the signal is stored in a FIFO, from which it can be directly read out as a waveform or taken for further analysis. The analysis is of the conveyor type and takes up to 5 stages, each stage corresponding to a sequential bunch crossing. On the first stage the whole waveform is used to define the signal amplitude (maximum), integral and time at maximum. The second stage implements 1/4 constant fraction discriminator (CFD) based on the amplitude value defined at the first stage. The CFD time and amplitude is then used to filter the event through a LUT, which is preprogrammed to account for energy-TOF correlation, specific for carbon nuclei. Another LUT is used to compare the amplitude and integral values, which deviate from proportionality in case of two particles arriving within one bunch crossing. If both LUTs report positive result, all signal parameters are stored in the result FIFO and used to fill the on-board histograms. The FPGA keeps track of the bunch and revolution numbers, as well as of the bunch polarization pattern, which allows a variety of histograms including distributions of the energy (polarization sorted) and bunch number and 2D time-amplitude histograms. Their contents can be read out after the data taking and is sufficient for beam polarization determination. Yet for better understanding and debugging purposes the signal parameters from the result FIFO can be transferred to the on-board storage memory, limiting the maximum event rate to $3 \cdot 10^6\,\mathrm{s}^{-1}$ per channel.

With the carbon event rate up to $10^6\,\mathrm{s}^{-1}$ and 20–60 s target-in-the-beam time for a typical $2 \cdot 10^7$ events polarization measurement, about a thousand regular measurements were done at RHIC in proton run-2004. The extremely flexible and powerful design due to the application of the FPGA allows a variety of specific beam studies in RHIC and the AGS including polarization loss on the ramp (Figure 3a), polarization profile and bunch by bunch polarization measurements (Figure 3b). Good spin physics is also done with the polarimeters including measurements of the $-t$ dependence of the pC analyzing power at different energies (see[5]). The shape of the dependence reveals the non-vanishing contribution of the hadronic spin flip amplitude to the process. Thus the pC CNI polarimeters at BNL collider complex with the dead-timeless DAQ system based on the WFD proved to be a real success during the latest years.



a) b)

Figure 3. Polarimeter performance examples: a) raw asymmetry during the AGS acceleration ramp, spin flips every $G\gamma = 1$ and at depolarizing resonances, beam energy is $E_{beam} = 0.524 \cdot G\gamma$; b) bunch by bunch raw asymmetry (upper) and spin orientation (lower) from a single typical measurement, RHIC, 55 bunch mode.

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