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Abstract

A new crate-based front-end system has been built featuring low cost, compact packaging, fast readout, command capability, 16 bit digitization, and a high degree of redundancy. The crate can contain a variety of instrumentation modules and is designed to be placed near the detector. Remote, special purpose processors direct the data readout. Channel-by-channel pedestal subtraction and threshold comparison in the crate allow the skipping of empty channels. The system is suitable for the readout of a very large number of channels.

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CDF FRONT END ELECTRONICS: THE RABBIT SYSTEM

1. Introduction and Design Philosophy

The RABBIT (Redundant Analog Bus-Based Information Transfer) system is the front-end portion of the data acquisition system presently used by both the Collider Detector Facility (CDF) and Experiment E-706 at Fermilab. For CDF there are presently 100,000 individual signal sources consisting of photomultiplier tubes; strip, wire, and pad chambers; drift chambers; drift chambers with current division readout; and silicon strip detectors. Of these, the RABBIT system includes 60,000 individual channels in 129 crates[1].

A very large detector offers the opportunity to design a consistent, optimized system with the prospect that the engineering costs can be small compared to those of production. The new system can then be less expensive than one assembled from modules already existing but which may not be optimally matched to the requirements. While packaging in FASTBUS was considered, the required dynamic range could not be achieved in a system with cohabiting digital circuitry. This paper outlines some of the experience with the design and operation of this large and very wide dynamic range front-end electronic system.

The CDF detector operates in the main ring tunnel at Fermilab where access is not possible during machine operation. It was essential to design the electronics so that all normal operations such as pedestal subtraction, calibration, and diagnosis of improperly functioning modules could be accomplished without the necessity for physical contact.

The over-riding design specification was that the system should be able to read many calorimeter channels within one to two milliseconds for which the ratio of full scale signal to calibration signal would be of the order of one thousand to one. It was further desired that the calibration signal be measurable to an accuracy of 1%. Thus the system needed to perform over a 100,000 to one dynamic range.

In a previous paper the approach and philosophy for the design of this detector was outlined in some detail[2]. For the most part, this approach was followed within the CDF Particle

Instrumentation Group. With over 200 collaborators and five or six major electronic design groups working on various parts of the detector it was a challenge to maintain a consistent approach. One major decision was to reduce cable length and thus the possibility of noise pickup by amplifying and digitizing near the detector and, except for trigger data, to bring only digital signals to the control room. This dictated that the electronics be made as reliable as possible.

2. System Description

2.1. Overview

The components of the RABBIT system are: (1) the RABBIT crates; (2) the system modules; (3) front-end instrumentation modules which reside in the crate; and (4) the special purpose processors which direct readout.

A block diagram of the CDF readout system is shown in Fig. 1. The RABBIT crates are shown as double lines to indicate the dual bus capability. Modules which provide a system function are shown above the dual bus, and instrumentation modules are below. Instrumentation modules convert the quantities to be measured (e. g. charge or time) into DC voltage levels which can be multiplexed onto either top or bottom bus for digitization by the corresponding EWE (Event Write Encoder) module. Each EWE is controlled by an MX Scanner-Processor via a high-speed multi-drop bus called the UBUS. Each MX has two independent UBUS drivers and each UBUS can be connected to four EWE modules. The MX communicates to Fastbus through an MEP (Multiple Event Port) which provides the standard Fastbus slave interface.

During the recent CDF engineering run, there were 42 installed MX's. Each handled between 900 and 1700 channels, depending on detector arrangement and anticipated channel occupancy. The final system configuration will contain 57-65 MX's with about 1300 channels maximum per MX. The MX's are discussed in section 2. 4.

To date, more than 15 different kinds of RABBIT modules have been made in production quantities, for an approximate total of 3000 modules. These include system and instrumentation modules for a wide variety of detectors. Also included are modules used for scintillator calorimetry, gas calorimetry, drift tubes for shower localization, drift tubes for muon detection, and liquid argon calorimeters[3-7]. In addition, there exist a variety of utility modules designed to aid prototyping and testing. Table 1 gives a brief description of most of these modules. Some are described in more detail below.

2.2. Front-end Discussion

2.2.1. The RABBIT Crate

The RABBIT crate[8] is a custom-designed enclosure for housing and powering the front-end instrumentation modules and various system modules. It consists of a dual bus backplane, mechanical support pieces, and card guides. The outside dimensions of the crate are 18. 5 inches high by 17. 25 inches wide by 13. 75 inches deep. There are slots for 25 modules in the crate. Card dimensions are 16. 875 inches tall by 12. 75 inches deep, or 5 by 6 Americard Units (the size of an American Credit Card). Card to card spacing is 0. 65 inches. A card can accommodate up to 64 directly addressable channels. The card height is sufficient for connectors for both readout buses as well as the signal inputs from the detector, which come directly through pins in the backplane. This design permits the signal lines to be permanently attached to the back of the crate and frees the front edge of the card for trigger output connectors.

Of the 25 card positions in the crate, three have permanently assigned functions. The two leftmost positions are assigned to the EWE modules, the crate controller-digitizers. The BAT (Before After Timer), which generates various gate timing signals, occupies the rightmost position. These signals are transmitted across the backplane, and are available at all slot positions. The EWEs and BAT act as terminations for the backplane signals. Because readout speed and gate timing are important parameters, the addressing and timing signals are transmitted across the backplane as ECL levels. The EWEs terminate the timing signals from the BAT, and the BAT terminates address lines, which are driven by the EWEs.

The backplane contains two nearly identical readout and control buses, each controlled by a separate EWE. Each bus contains module address lines, sub-address lines, a pair of analog lines, and a full set of power supply lines. A EWE can address any module in the crate except the other EWE, and can communicate digitally in either direction with the selected module. Each bus also has a pair of analog lines, across which the selected channel on the addressed module can multiplex differential DC levels to the EWE for digitization.

Crates are powered by dual sets of modular, 400 Hz, 3 phase, linear power supplies. The 400 Hz power is provided by motor-generators. Each set of supplies powers one of the dual buses in the crate. On the RABBIT modules, the corresponding voltages are connected by a Shottky diode OR. In the event of a failure within one of the two sets of supplies, modules continue to receive power from the other set.

Each power supply set consists of two separate modules which provide the six standard RABBIT voltage levels. The standard levels are +/- 5. 5, +/- 8, and +/- 15. 5 volts. An individual module occupies 210 cubic inches, weighs 10 pounds, and has bayonet mounting with snap-in connectors to permit easy changing. Each supply set has a 680 watt capacity and is designed to operate at 65 to 70 percent efficiency. The policy is to limit the total crate power load to approximately 70% of the rating of a single set. During normal operation, therefore, each set of the redundant pair operates at only about 35% of its rated load, so that the mean time between failures should be high. No effort has been made to balance the loads.

This system has several noteworthy features. Reliability was a primary concern in the design of this system, since it was anticipated that there would be extended periods during which the detector and the front-end systems would be inaccessible. If one of the EWEs in a crate malfunctions or if one of the crate power supplies fails, there is a very good chance that the crate can continue to operate due to the high degree of redundancy in the system. Another feature is the potential for increased readout speed. The time required to read out a crate can be reduced by almost a factor of two by utilizing the two EWEs in parallel. This becomes important as the luminosity and event rate increase.

More than 300 RABBIT crates have been produced to date. The material cost of a crate is approximately $1000. Power supplies now number in excess of 300 sets, and cost approximately $450 each, or $900 per set. Both the crates and the full complement of power supplies are being produced by commercial vendors in production quantities.

2.2.2. System Modules

Over 600 system modules of five types have been produced. The most important of these are described in this section. Table 1A is a list of the system modules. Where possible, Table 1 refers to module types by the three letter, capitalized names which are stored on the modules in PROM and which can be read out along with the module's serial number and version code. Modules without PROM identification are indicated by names printed in lower-case .

The measurement method upon which the RABBIT System is based involves sampling two voltage levels for each event; one to establish a reference level and another for the measured quantity. For the CDF charge-integrating amplifiers (QVC's), this is done by sampling the integrator output just before the interaction and again after the signal has settled to its final value. For fixed target applications, each integrator is followed by an analog delay element, the output of which is sampled before and after the signal exits the delay line, thereby providing the delay necessary to make a trigger decision. Time to voltage converters (TVC's) usually involve the switching of a precision current source onto an integrating capacitor to produce a voltage ramp which starts when an input signal is detected. The TVC's have a common stop which switches off the current source, so that the capacitor voltage remains constant afterward. In this case, the signal is the capacitor voltage, and the reference is a voltage which is equal to the voltage present before the ramp began. The difference between the two measurements increases linearly with the length of the time interval between the detector input and the stop signal.

In an effort to minimize calibration errors, maximize precision, and reduce cost, noise, and complexity, the system was designed so that no digitizations occur on the amplifier boards themselves. Instead, the signal and reference levels are simultaneously multiplexed over one of the two backplane analog buses to the corresponding EWE where the ADC digitizes the difference between the two levels. Since the dual samples are carried through the system as a differential pair, any noise pickup tends to appear as common-mode noise on the differential pair and thus cancels in the difference circuitry just prior to conversion. Because there is only one difference circuit per EWE, substantial effort can be made to adjust the components so that common mode levels cancel to great precision.

The EWE thus has two functions in the system. First, It acts as the controller for the crate; that is, it receives instructions from the programmable MX and performs the corresponding module and channel addressing as well as any required digital communication with registers on front-end modules. As part of this function, it also sends digitized data upon request to the MX.

The second function of the EWE is to perform the analog-to-digital conversion of the differential voltages that are multiplexed to it across the backplane. In the simplest mode of operating, the MX would instruct a EWE to address and digitize each channel in the crate in a sequence determined by the MX programming. However, in a crate containing many channels of which only ten percent contain interesting signals, the resulting readout time would be dominated by the digitization of pedestals. In addition, each pedestal is unique because no effort is made to equalize the baseline voltages of the many output stages; consequently, taking data in this mode would require an extensive off-line pedestal data base and much off-line processing to subtract pedestals from the recorded values. Therefore, the ADC section of the EWE was designed to perform channel-by-channel pedestal subtraction before readout and to test a signal before conversion to determine whether it is above a software settable threshold. If the signal is over threshold, the analog to digital conversion is made and the result is read out by the MX. If the differential voltage received from a selected channel is under threshold, that channel is skipped, and the MX goes on to query the next channel. It is feasible to implement this expensive ADC process because there is only one ADC per crate per bus.

The ADC used in the present EWE design is a 16 bit, linear, successive approximation device with a 17 microsecond conversion time. An additional three microseconds is allowed for settling and threshold comparison. The threshold comparison can be made to a precision of about 0. 1% of full scale. A variety of gains, thresholds, polarities, and offsets can be selected to configure the ADC process as desired. The ADC linearity is better than 0. 01% of full scale. Temperature dependence is less than 1 count per degree C variation.

The various backplane timing signals are generated by the BAT module. A timing cycle is initiated on receipt of a front panel signal from the trigger system, and the generated timing signals are transmitted over the RABBIT backplane to the various front-end modules in the crate. These signals control the gating operation of the sample-and-hold switches of the charge-integrating amplifiers, and the start-stop and reset functions of the TVC channels. Provision has been made for the implementation of up to five different gate timing signals, which can be preset in hardware as needed for specific detectors. For fixed target applications, a version of the BAT has been made in which some of the gate timings are programmable. In both versions, the BAT additionally generates a precision fixed reference voltage and a programmable reference voltage and special timing signal for use with on-board charge injection pulsers and TVC test circuitry. The BAT also provides readout channels for monitoring the temperature and the power supply voltages in the crate.

2.3. Instrumentation Modules

Table 1B lists the instrumentation modules produced to date. There are more than 2700 modules of 11 types. This section describes three of these modules which are important components of the CDF central calorimeter readout system.

2.3.1. The Photomultiplier QVC

The Photomultiplier QVC (PMA) is a 12 channel charge-integrating amplifier module[9] for use in the photomultiplier system for CDF. It was designed to measure average energy depositions in a calorimeter tower to an accuracy of better than 1% over the range 300 MeV to 375 GeV. This requires that the electronics have a dynamic range of approximately 100,000. The design includes an additional amplification stage to accurately measure the energy loss of minimum ionizing particles in the 0. 5 MeV to 5. 0 MeV range, thereby requiring the equivalent of 20 bits of dynamic range with 16 bits of resolution.

Each phototube channel on the module consists of a charge sensitive amplifier, sample-and-hold circuitry implementing the dual sample scheme, X1 and X16 amplification stages, and two sets of redundant analog multiplexers for sending the sampled differential analog voltage levels to either EWE for digitization. In addition, each channel has a fast analog output which sends pulse height information to the CDF trigger system[10]. The module also has two on-board calibration systems which monitor the gain of both the electronics and the calorimeter.

The charge-integrating amplifier is a discrete component, cascode type amplifier[11-18]. It consists of a low-noise JFET input transistor, followed by a common base stage and two emitter-follower output drivers. The amplifier has an open loop gain of approximately 5000 and a gain-bandwidth product adjusted to approximately 10 MHz so that the dynamic input impedance of the integrator matches the 50 ohm impedance of the signal cable. The integrating capacitor is a 300 pF, 1% NPO type ceramic with a 30 ppm/degree C temperature coefficient. The performance characteristics of the PMA are summarized in Table 2.

The PMA has two on-board calibration systems. The first is a pulser which can inject charge into a selected amplifier. This circuitry provides a method of accurately monitoring the charge gain of the amplifier. The second system is the current channel readout for monitoring the calorimeter. Each amplifier has a readout channel that measures the average current flowing through the feedback resistor of the charge-integrating amplifier. The calorimeters are equipped with Cs^{137} sources which are attached to a wire which loops through the calorimeter. A motor moves the source through the calorimeter, irradiating each of the calorimeter towers in turn. This procedure injects a current of approximately 50 nA into the amplifier while the source traverses the calorimeter. The response of the current channel to a source of known strength provides a monitor of the calorimeter gain. Feedback resistors used in the amplifiers are 0. 1%, RN55C type metal film with 50 ppm/degree C temperature coefficient. The charge pulser and the current readout monitor the gain variation of the overall system to an accuracy approaching 0. 1%.

The PMA circuit board is a standard two-sided board made entirely of commonly available components . Production cost for a single board is $500, including test and calibration. This translates to $40 per amplifier or $13 per readout channel.

2.3.2. The Photomultiplier TVC

The Photomultiplier TVC (PMT) module contains eight common-stop TVC's. The individual starts are the amplified and discriminated sums of two phototube dynode outputs. Discriminator threshold is approximately 1 millivolt (sum of the two inputs). Full scale range is 3 microseconds and the response is linear. Individual and OR'ed timing signals are available at the front panel.

In laboratory bench tests, the response lies within 0. 5 nanosecond of the best straight line for the first 600 nanoseconds of the 3 microsecond range. Intrinsic timing jitter is approximately 200 picoseconds and temperature coefficients are typically 100 picoseconds per degree C.

2.3.3. The Muon QVC/TVC

The Muon QVC/TVC (MAT) module contains eight identical sections, each servicing the two ends of a charge-division drift tube operating in limited streamer mode. Each section contains two charge-integrating amplifiers for charge division position measurement along the wire and one TVC for drift time measurement of position transverse to the wire. Full scale for the integrators and the TVC are 250 pC and 3 microseconds respectively. Response is linear for both charge and time. In laboratory bench tests, intrinsic integrator noise is less than 20 fC and intrinsic TVC jitter is typically 0. 5 nanosecond. The common stop TVC is started by a low level discriminator which sums the outputs from the wire ends. TTL timing signals from the TVC's and certain analog sums from the integrators are available on the front panel connectors for trigger purposes.

In cosmic ray tests with drift tube detectors[3], the system achieved 3 millimeter spatial resolution along a 5 meter wire length and 200 micron position resolution across the 8 centimeter wide drift cell.

2.4. Mx Description

2.4.1. The MX

The MX is a high speed special purpose processor[19] for acquiring data from the CDF detector as instrumented by the RABBIT System. It is designed entirely in ECL with approximately 900 IC's. The MX is a programmable device with an arithmetic processor containing a high speed ALU and multiplier. The RAM resident program controls the acquisition of data from the Rabbit crates, applies channel dependent correction constants, and stores the corrected data in event buffers. The CDF Data Acquisition System permits multiple buffer operation with a maximum of four buffers. The MEP interface routes the data to the device responsible for assembling the events. The MEP also monitors the status of each MX buffer and prohibits access to specific buffers if they are in use or need to be emptied. Error conditions detected by the MX during readout are reported to the MEP as well.

The mechanical package is a 27" x 57" aluminum frame which holds six large multi-layer printed circuit boards with wire-wrap interconnects between boards. There are about 700 inter-board connections and a total of 3900 wires, most of which implement modifications that improve performance and functionality. The panels hang on ball-bearing slides mounted in 80" high relay racks. A rack can contain up to eight MX's. Each MX is powered by two 5 volt, 65 amp, 400 Hz power supplies of the same design as those used to power Rabbit crates. The supplies are mounted in the MX rack, in a 4 x 4 array behind the MX's . Rack cooling is provided by twelve 230 CFM fans, of which three cool the power supplies and nine cool the MX's. A single MX dissipates 430 watts and a fully loaded rack dissipates 6500 watts. Temperature measurements in the lab with unrestricted air flow out of the top of the rack with an inlet temperature of 24 degrees C show an input to output temperature differential of 10 degrees C. In operation at the experiment, the temperature differential was 17 degrees C and the inlet temp was 19 degrees C. The hottest IC in the MX is a 5 watt ALU where the normal operating temperature was 59 degrees C.

2.4.2. The Memories

The MX has 80 Kbytes of RAM storage for data correction and program constants, instructions for controlling the EWE, and buffers for up to four events. The program storage memory is configured as 2k words by 64 bits to accommodate the 64 bit instruction word. There are three memories of 4k words by 16 bits each for storing various constants, including the data correction constants for each channel and the logical channel identifiers that identify the physical channels in order to facilitate off-line analysis. The Rabbit crates are controlled from a memory that is 8k words by 24 bits. This memory is a list of 24 bit words containing control bits and channel addresses to be down-loaded to the EWE registers via the UBUS. The EWEs respond to a requested operation with data and status. The data comprising an event are stored in a 4k word by 32 bit memory divided into four 1024 word event-buffers. The data words and the channel identifiers are both 16 bits in length; nevertheless, each buffer can conceivably contain up to 1800 data channels, because consecutive channels in the readout stream can be clustered in groups of up to seven channels so as to suppress unnecessary identifiers. Five Index Registers are available for use as pointers to aid in accessing the various memories.

2.4.3. The Arithmetic Pipeline

The arithmetic pipeline accesses data from the three constants memories simultaneously in one instruction, allowing an operation of the type D=A+B*C to be performed every 100 ns. In the above expression, the A, B, and C represent data from the memories that hold the program and data correction constants. The B operand can also be a data word from a Rabbit crate, thereby permitting linear corrections to be applied to data. With a second such operation, quadratic data corrections can also be performed. There are a total of 16 inputs available which include all of the registers and memories in the MX as well as the data from the EWE's and information from Fastbus. The result may be stored in any memory or index register in the MX.

2.4.4. MX Instructions

There are 22 basic MX instructions presently implemented. These are configured into 25 instruction types by the MX assembler and include simple memory to memory calculations, loop control, subroutine organization through call and return instructions, and various EWE control instructions (see instruction list in Table 3). Execution times vary from 100 to 200 ns. An instruction which uses data from memory and has a result not needed by the next instruction and which is subsequently stored in memory requires 100 ns. If the result is needed by the next instruction, the execution time increases to 150 to 200 ns, depending upon instruction type. Multiply instructions require the longest time. Branch instructions permit 64 different branching conditions and require 200 ns to branch and 150 ns for the decision not to branch. In addition to the standard Call and Return, instructions have been implemented for Do Loop control and context switching. The later is especially useful for handling multiple independent processes such as the simultaneous control of several EWEs. There are five instructions for controlling EWEs. These instructions cause the EWE's control registers to be loaded from a list stored in the MX containing one entry per EWE register to be loaded.

2.4.5. Rabbit Control

The MX communicates with a EWE via the UBUS, a bi-directional, differential ECL, multi-drop, twisted-pair cable which has a maximum length of 250 ft. It is possible to address up to four crates on either of the MX's two U-BUS ports. The EWE responds to the MX as a slave, performing a specified function upon command. Non-handshake protocol is employed using a 250 ns wide strobe to clock data into the EWE. The cable protocol includes 16 bi-directional data lines, five address lines, and three control lines. The five MX instructions for controlling a EWE treat the EWE as a set of registers to be loaded. When loading is complete, the MX program can perform other operations while the EWE executes the function specified in its registers.

2.5. MX Associated Software

Several specialized software tools have been developed to support the MX scanner and its use in the CDF experiment. An assembler and MX initialization facility were developed in order to facilitate the initialization of each MX with the program and data required to perform its functions. This investment has proved to be very worthwhile in that it is relatively easy for any experimenter with programming experience to learn how to write MX programs.

2.5.1. MX Assembly Language

The MX assembly language, called ASM/MX, features a friendly, BASIC-like syntax while providing control of the MX at the register level. At the same time, ASM/MX is a much more structured language than standard assemblers. These qualities make MX programs easy to write and maintain. An ASM/MX program consists of independent functions with local variables. Local variables allow the programmer to make changes to a function without having to check the rest of the program for side effects. Global variables are available to all functions and facilitate the sharing of information between functions. In addition, there exist "Named Storage Modules" which act like Fortran common blocks and are available to functions which explicitly ask for access. Variables are declared at the beginning of each function so that the programmer always knows where a given variable is defined. Functions can be referred to by name in any routine by the CALL statement whereas branch labels are always local to the function in which they are declared and can be used by the IF and GOTO statements only. Each function is guaranteed to have only one entry point so that changes to a function will affect only that function, rather than the whole program. This provides additional structure for the program.

It is useful to note some of the syntax features of ASM/MX. An attempt has been made to have the syntax resemble the mnemonic statements normally used in higher level languages. All statements begin with a meaningful keyword, such as LOAD, IF, GOTO, or WAIT. ASM/MX facilitates the programmer's use of the MX's features by providing a syntax which resembles ordinary algebraic expressions instead of the LDAX, ROR, STX type syntax commonly found in assemblers. Memory references resemble references to arrays in high level languages. Fig. 2 shows a short listing generated by the ASM/MX assembler. The assembler annotates each instruction with the memory location it will occupy and the execution time for each instruction, assuming the nominal 25 ns clock. The generated instruction code is shown in hexadecimal at the bottom of the figure, along with a breakdown of the instruction fields. Roughly 7500 lines of MX code have been written to date to support data acquisition. In addition, another 37,000 lines of code have been written for diagnostics purposes, illustrating the ease of use of MX assembly language as well as the assembler.

2.5.2. MX Initialization Program

The MX Initialization Program (Linker/MX) has the task of generating and down-loading the various programs and data lists required by the MX for data acquisition and calibration functions. This program is referred to as the linker because it joins data from several data files, including the code file generated by the assembler and information from several CDF specific databases. The linker is driven by the Rabbit Database. This facility gives the linker a list of Rabbit channels for each MX and the read-out order. Each channel is associated with a channel type. The linker uses the channel and run types together to select a "channel template" which tells the linker how to read out this channel. This mechanism allows the readout method for each channel to be modified without having to recompile the linker itself.

The MX resident program is driven by a set of lists which are loaded into the MX by the Linker/MX program. One list sets up the physical channel address, pedestal subtraction, threshold value, and several read-out options for each Rabbit channel. The list of logical channel ID's is used to translate from the physical channel address for each channel to a logical channel address. The list of "bank headers" is used by the program in formatting the data generated by the MX. Linear and quadratic correction constants are used in order to correct the data arithmetically after it has been digitized. Calibrations determine the pedestal, gain, and linearity of each Rabbit channel and of the ADC in the Ewe.

2.5.3. Utilities

The MX has no control panel. During normal operation, the user is separated from the MX and Rabbit crates by several layers of software. In view of this, two diagnostics systems have been written to provide direct access to the MX and RABBIT hardware. The first, Control, serves as a test bed for new diagnostics features and was developed in parallel with the MX prototyping phase. Moxi is the name of the second generation MX control facility and unlike Control is based on the standard CDF user interface facility (UIPACK). All CDF diagnostics and user software is required to conform to this standard user interface. To date, there have been written approximately 20,400 lines of code for Control and 8300 lines of code for MOXI, reflecting the fact that MOXI makes use of the standard UIPACK routines.

Both Control and Moxi can start or stop the MX clock and load its memories with instructions and/or data. It is also possible for the user to perform MX and RABBIT crate diagnostics directly from the host computer. Since these utilities bypass the "booking" procedure used by the system to assure exclusive access to a hardware module, they can be used to spy upon an MX which is in use by the data-taking system. This is useful if the MX is found in some error state or some failure is suspected. Moxi allows the user to choose between menu oriented and command oriented user interfaces with a choice of mnemonic command names such as LOAD, SET, READ and WRITE. Registers and memories are referred to by name such as PC and UM, rather than machine addresses, as in the Control program. The user can also stop the MX clock at any point with break-points, or step through a program one instruction at a time. Moxi executes a user defined list of read and write operations whenever a break-point or trace-point is encountered. Trace-points are like break-points, except that they do not interrupt the execution of the MX program.

3. Operational Experience

3.1. Performance of the System in the CDF Detector

The recent CDF engineering run gave good opportunity for testing the RABBIT system on a large scale with many readout channels and in combination with the rest of the data acquisition system[20]. The stability of the system for analog channels can be seen in Fig. 3 which shows the difference between pedestals for the Central Muon Chamber System[4] as seen over a one month period. Fig. 4 also shows the distribution of pedestal widths for the phototube channels in the Central Electromagnetic Calorimeter[5] taken during the run, illustrating the low noise of the system. In general, pedestals were found to be extremely stable, although the system allowed for frequent calibration of pedestals.

An example of the performance of the TDC channels is given in Fig. 5. The channels shown here were used for monitoring the time of arrival of particles in the Central Hadron Calorimetry Scintillator[6]. The mean of the distribution corresponds to the difference between the time of the crossing which resulted in the interaction and the time of arrival for resulting particles at the Central Hadron Calorimeter. The width of the distribution corresponds to the resolution in nanoseconds.

Finally, the stability of the amplifier gain is shown in Fig. 6. The distribution corresponds to the the differences in gain for 959 Phototube amplifier channels measured ten days apart for the Central Electromagnetic Calorimeter[5]. The gains are determined by means of the charge injection calibration, where the amplifier response is measured as a function of pulse height and fit to a straight line. This is done for all the amplifier channels and then monitored over the run. The gain stability is quite adequate as can be seen from the figure.

3.2. MX Operational Experience, Reliability

During the CDF engineering run, the scan times for a typical 20% occupancy event varied from 6 ms to 27 ms and averaged about 13 ms. Many factors played in slowing the scan time from the design goal of 2 ms. The central detector was running with about half the ultimate number of

MX's. Also, the RABBIT crates contained only one EWE; upgrading to 2 EWE's per crate should additionally speed up the readout by a factor of two. Finally, in order to obtain the best possible measurements from the EWE, large software delays were inserted into the MX algorithm. The interactions between MX and EWE are now better understood, and the new MX algorithm will be faster and more efficient. The expected scan time for the the next run is 2 to 3 msec, assuming 1000 to 1600 channels per MX and 10% to 20% occupancy.

It is difficult to determine the reliability of the MX , because of the close coupling between it and the overall operation of the system . It was often the case that no failure could be discovered in MX's which were replaced and reported as defective. During the run it was discovered that a class of errors which had been attributed to MX failures were instead caused by Fastbus network failures. The error reporting system could not distinguish the two error types. This class of errors accounted for 25% of the errors reported during the run.

3.3. Operational Experience of Changing Modules During the Run

During the recent engineering run for CDF, there were no regularly scheduled days when the accelerator would be off allowing access for maintenance of the detector and front-end electronics. Lists of problems were accumulated and used to help assess the need for an access.

Before anything was done to a module, the problem was verified both to assure that it was real and to document the trouble for the eventual repair. Modules were replaced and tested one at a time to make certain that the problem was with the targeted module and that the replacement did not cause new problems. The tests were staged to first assure that the crate was alive using a stand-alone program, then the module's performance was checked. This was followed by checking the performance of the crate and finally running the new module with a portion of the data acquisition system. As major detector pieces became complete, a system calibration was done to obtain a set of constants for data correction. If these fell within allowable ranges, that portion of the system was said to be complete. Part of the system checkout involved a visual check of various LED indicators. Interestingly, this was the most expedient way of verifying that global timing signals had been reinstalled properly. The data clearly showed whether the connection had been properly made; however, the accesses were not always lengthy enough to allow for a calibration run.

During an access, a minimum of four people were required to change successfully more than a few modules and bring the system back into a state which was at least as good as existed before the access. The work in the collision hall required two people. One person was required to locate the bad module, get a lift into position, replace the module, and watch for signs of life when the tests which were performed in the control room were done. The other person was required to communicate with the control room about the tests and to keep diagnostic reports about the modules' problem, serial number, and location in addition to the serial number of the replacement module. This information was later entered in a database which, among other things, helped to identify chronically bad locations or modules. Testing of the module was done in the control room and also required two people. Communication with the people in the collision hall was often a problem in that many different repairs and studies were going on simultaneously, leaving phone and walky-talky resources in short supply.

It turned out to be important that diagnostic tools be able to be operated in a stand-alone fashion at the same time that the main data acquisition system was operating with the same detector pieces. If a scheme had been rigidly adhered to wguch required that detector elements could not be used simultaneously by different programs, the testing would have been greatly impaired and temptation to circumvent the test would have been high. Given the situation of unscheduled accesses, it was crucial that the system be known to work before the access was over, as the next access might be several weeks away. The philosophy was that if little was to be gained, then do nothing. A high priority would be assigned for fixing a problem which affected an entire crate, in that the detectors vision would be impaired in a large region rather than a single isolated channel.

3.4. System Problems/ Noise Considerations

It was not possible to maintain a uniform design approach over such diverse and widely separated groups of collaborators. Some design groups made errors that were understood and avoided by others. A particular failure was the inability to design and implement a consistent ground procedure - though it was tried. In searching for noise problems, multiple unanticipated ground connections were often uncovered.

The design philosophy was to allow noisy operations only when the digital systems collected data and to maintain quiet operation during the time signals were acquired and stored in sample-and-hold circuits. Where this procedure was followed, the system is very quiet. With detector components being implemented by a large number of collaborators, systems continue to be found which violate the above philosophy and cause noise during the sensitive data acquisition phase of operation. In each of these cases, the digital activity is subsequently required to be synchronous with data-taking or made to take place at times other than actual data acquisition.

Where the procedure was followed not to build more than an additional order of magnitude of a design at once, the design process went smoothly, albeit slowly, since four or five design cycles were required. Where designs went from a few dozen prototypes to a large production run, a number of very expensive to make changes have been required.

It does not seem to be possible to make too many transfer function measurements on amplifiers. Oscillations were uncovered at almost every stage of manufacture, test, and installation.

After early tests indicated that switching power supplies could not be used near the front-end circuits and still maintain accuracy, linear supplies were specified. For line isolation and efficiency considerations, the supplies were designed to operate from three-phase 400 cycle power. While the same decision would be made again, it should be noted that the commutation diode noise, which can be picked up by the two-sample scheme, occurs 20 times as often as with an equivalent 60 cycle linear. The solution is not to run sensitive signal cables near the power supply transformers.

A problem with this sixteen bit system is that every little effect can be seen and therefore must be explored. Many of the effects that have required intensive research would simply not have been seen on a 12 bit system.

In an earlier paper[2] it was estimated that changing a single part in every channel for a major part of this detector would take 2000 man-hours. Now serious consideration is being given to the possibility of making several "one part" changes and it appears that the above number of man-hours was an underestimate. Plans are being made to implement a change for the next run on approximately 10% of the detector with the possibility of installation of the full change for the following run 18 months later. It is clearly important to test designs thoroughly the first time. Access has turned out to be even more restricted than had been anticipated.

3.5. System Successes

The multiple sample scheme has proven to work very well, have fewer problems, and to be generally easier to implement than any other system of similar accuracy. This scheme is also insensitive to low frequency noise. The application of this technique to phototubes is novel and has worked extremely well. The phototube is very close to being an ideal current source and it would seem possible to operate at several orders of magnitude less gain than the CDF system used. Now that the technique has been proven in this detector, it would seem likely that a phototube with fewer stages could be made to operate providing greater stability.

The central calorimeter modules have proven to be exceptionally quiet. Here, advantage was taken of the natural Faraday cage created by the calorimeter plates and care was taken to route all wiring to a RABBIT crate mounted on the module.

The most recent run was made with full sets of redundant power supplies. Calculation from typical mean-time to failure data would indicate a supply failure every 50 hours or so for the system and a double failure about every ten days. There were no known failures in three months of operation for five million supply operating hours. Only half the supplies are presently monitored so there may have been failures that were not detected. One reason for the lack of failures is that both supplies share the load. Thus a power supply never sees more than about half of full load (no attempt is made to balance loads). This results in very cool operation, heat being a primary cause of power supply failure.

The designs which followed the order of magnitude rule were quite successful, though everybody tired of testing and re-testing. Many of the production boards were "baked" at 60 degrees C for eight hours. The boards which were "burned in" appeared to give less trouble later, though there are no good statistics available at this time. When the percentage of channels working exceeded the purity of Ivory Soap, this fact was posted on the bulletin board. Often there were no bad channels in major sections of the detector.

All RABBIT modules have a PROM which contains the module type and serial number. This has been a very useful feature, particularly during testing or installation. It is very comforting to have the correct board number appear on a monitor, having found its way through a very complex operating system.

All modules contain some form of calibration circuit. In most cases this worked by charging a capacitor to the BAT variable reference voltage which is distributed over the RABBIT bus. Calibration circuits on the board work by dumping this charge into the integrating amplifier. This scheme worked well and it was relatively easy to achieve 0.1% precision. Because the amplifiers are designed to integrate, they are relatively insensitive to calibration pulse shape and the signals can be distributed and multiplexed on the board without problems.

Where the amplifier input impedance was matched (by active feedback) to the cable impedance, the amplifiers seemed more stable and gave fewer problems. This procedure is recommended where possible.

4. Summary and Conclusions

This paper describes a readout system suitable for making precision measurements on detectors with a very large number of readout channels. The system is well beyond the prototyping and debugging stages, and large numbers of crates, power supplies, RABBIT modules, and MX processors are in operation. There exist many CAD libraries for module layout, greatly facilitating the implementation of additional designs.

Small systems, consisting of one or two RABBIT crates, can be easily integrated into an existing experiment or test system. The EWE can be controlled directly from a small computer programmed in BASIC,PASCAL, etc. , or in assembly language if greater readout speed is required. For systems without FASTBUS[20] capability, but requiring the readout speed of the MX, there exists an interface for connecting an MX scanner to UNIBUS. Although the modular 400 Hz linear power supplies have definite advantages, crate power can be provided by standard 60 Hz linear supplies.

Decisions made in the early design stages have proven to be correct. The choice for power supply voltages incorporates low power designs while permitting adequate range for all the necessary functions. The RABBIT card size is well matched to the number of channels which seem reasonable to have on a single card, and the bus interface sections occupy only a small fraction of the card area. The card is not too large for automated assembly using surface-mount components.

Finally, the reliability and performance of the RABBIT system have been excellent. There is presently a large database of board designs and a great deal of accumulated experience with the system.

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TABLE CAPTIONS

Table 1. Summary of existing RABBIT modules: (a) System modules, (b) Instrumentation modules, (c) Utility modules. Modules whose names appear in upper case contain on-board PROM identification. For instrumentation modules, the readout types "Q", "V" and "C" are charge, time and voltage. Under Trigger Outputs, "a" and "d" are analog and digital. Thus "8+1 d" refers to eight individual digital outputs and one digital OR output.

Table 2. Summary of the performance characteristics of the PMA Photomultiplier Amplifier Rabbit Module.

Table 3. Summary of the implemented MX instructions. There are 22 basic MX instructions presently implemented. These are configured into 25 instruction types by the MX assembler and include simple memory to memory calculations, loop control, subroutine organization through call and return instructions, and various EWE control instructions.

(a) SYSTEM MODULES

Module (qty)	General Description	Features
BAT (230)	Gate-Timing Generator.	Type 1 generates five gate-timing signals, a TVC run-stop and a programable calibration pulse. Type 2 generates two gate-timing signals and two programable calibration pulses. Both provide readout of crate temperature and power supply voltages.
EWE (140)	RABBIT Crate Controller-Digitizer.	Direct addressing of 64 module addresses and 64 sub-addresses. Digitization to 16 bits. Channel-by-channel pedestal subtraction, threshold comparison and data sparsification. Multiplexed analog inputs can be differential or single-ended. Performs 8-bit digital reads and writes from/to modules.
ibu (40)	Personal Computer to EWE Interface.	Contains registers necessary to translate 8-bit IBM PC port output data to 32-bit U-BUS format. Requires "PIGTAIL" card in IBM PC.
ter (125)	U-BUS Terminator.	Active termination for MX-to-EWE communications bus.
uls (110)	Dummy EWE.	EWE substitute in case either top or bottom RABBIT crate bus is not to be under EWE control. Sets address lines to defined state.

Table 1A

(b) INSTRUMENTATION MODULES

Module (qty)	General Description	--Readouts-- No.	Type	FS	Trigger Outputs	Features
CRA (510)	24 input QVC for gas calorimetry. Mix of + and - inputs.	24	Q	500pc	4 a	High DC gain amplifiers for use with detector capacitance up to 100 nf. On-board test pulser.
CRB (390)	24 input QVC for gas calorimetry. Mix of + and - inputs.	24	Q	500pc	4 a	On-board test pulser.
GMA (25)	16 input, high-sensitivity QVC.	16	Q	8pc	16 a	Fast amplifiers with 1800 nsec internal delay before sample-and-hold section. On-board test pulser.
HRW (100)	32 input high-range QVC for wire chambers.	32	Q	250pc	none	On-board test pulser.
LAC (600)	16 input QVC-TVC for liquid argon type calorimeters.	16 8	Q T	50pc 1us	16 a	High gain-bandwidth amplifiers. On-board test pulser. Four common-stop, dual-hit TVCs with auto reset, started by 4-fold sums of inputs. 800 nsec internal delay lines.
MAT (300)	16 input QVC-TVC for charge division drift chambers.	16 8	Q T	250pc 3us	4 a 8 d	Eight sections, each with two QVCs and one common-stop TVC. Serves eight charge-division drift wires. TVC test.
PMA (300)	12 input photomultiplier QVC with large dynamic range and current readout.	12 12 12	Q Q I	750pc 47pc 1ua	12 a	Normal charge readout, x16 charge readout and current readout for each input. On-board test pulser.
PMT (120)	8 channel photomultiplier TVC for 16 low-level inputs.	8	T	3us	8+1 d	Common-stop TVCs. TVC started by sum of two inputs. Threshold approximately 1mv at input. TVC test feature.
RAS (30)	32 input voltage-amplifier and sampler. Strapable polarity.	32	V	12mv	32+4 a	x200 video amplifiers followed by before-after sample-and-hold. Two on-board test pulsers.
SCA (250)	32 input QVC for pad readout. Positive inputs.	32	Q	19pc	none	On-board test pulser.
WCA (150)	32 input QVC for wire chamber readout.	32	Q	75pc	none	On-board test pulser.
HVS (50)	4 channel 6KV high voltage power supply with monitors and trips.	4 4	V I	(9KV) 1ma	----	Delivers 1ma at 0 to 6KV. Polarity must be preset. Log scale DC current readout from 10na to 1ma. Programable trip points. Additional 48 volt supply required.

Table 1B

(c) UTILITY MODULES

Module (qty)	General Description	Features
barst (25)	Backplane gating signal repeater.	Transmits backplane gating timing signals via front panel connectors. Output is differential ECL.
cub (25)	32 channel charge pulser/multiplexer.	Pulser delivers positive or negative charge pulse through one of 32 outputs to an amplifier card under test.Uses backplane timing pulse and voltage reference.
nimbat (25)	Gate generator with external NIM control.	Front panel inputs provide external control of individual backplane timing signals and voltage references. Signal polarities are selectable.
rabdac (15)	16-bit DAC card.	Front panel output provides programable voltage for external pulsers, etc. Voltage can be multiplexed onto backplane for digitization by EWE.
qmux16 (10)	16 channel charge pulser/multiplexer.	Pulser delivers negative (only) charge pulse through one of 16 outputs to an amplifier card under test. Requires external trigger and voltage reference.
(20)	Backplane data visual display card.	Front panel LED display of backplane activity.
(100)	RABBIT crate extender card.	Passive backplane extender.
(100)	ECL/TTL RABBIT kluge card.	Full-size RABBIT breadboard card, with ECL and TTL sections.
(50)	32 channel readout kluge card.	Test-bed for prototyping amplifiers, etc. Layout provides prototype breadboard sections and all bus logic and multiplexers necessary for readout.
(10)	NIM and TTL I/O card.	Front panel input and output of NIM and TTL levels and pulses.

Table 1C

Performance Characteristics of the PMA module

Characteristic	Value
Full scale charge - x1 channel	750 pc
LSB charge resolution - x1 channel	11.4 fc
LSB charge resolution - x16 channel	0.7 fc
Integral linearity error - x1 channel (0.004 to 0.9 full scale range)	<0.02 % FS
Typical noise charge - x1 channel	140 fc
Typical pedestal variation	+/- 15 ppm/^{o}C
Pedestal variation over 80 day period	< 0.3 % FS
Crosstalk rejection - adjacent channels	> 65 db
Power consumption per card	12.5 Watts

Table 2

Evaluate Arithmetic Expression
- load memory, inc register
- load index register
- increment
- evaluate [do not save result]

Branch Instructions
- unconditional
- indirect
- conditional
  - arithmetic
  - fastbus
  - ewe

Subroutine Control
- call
- return

Context Switching Instructions
- swap index register
- swap program counter
- swap T context
- swap B context

EWE Control Instructions
- load ewe from list
- load ewe from ALU
- load ewe 'til condition
- read ewe
- read ewe 'til condition

Miscellaneous
- code
- repeat
- scan
- wait for condition
  - ewe
  - fastbus

Table 3

READOUT SYSTEM BLOCK DIAGRAM

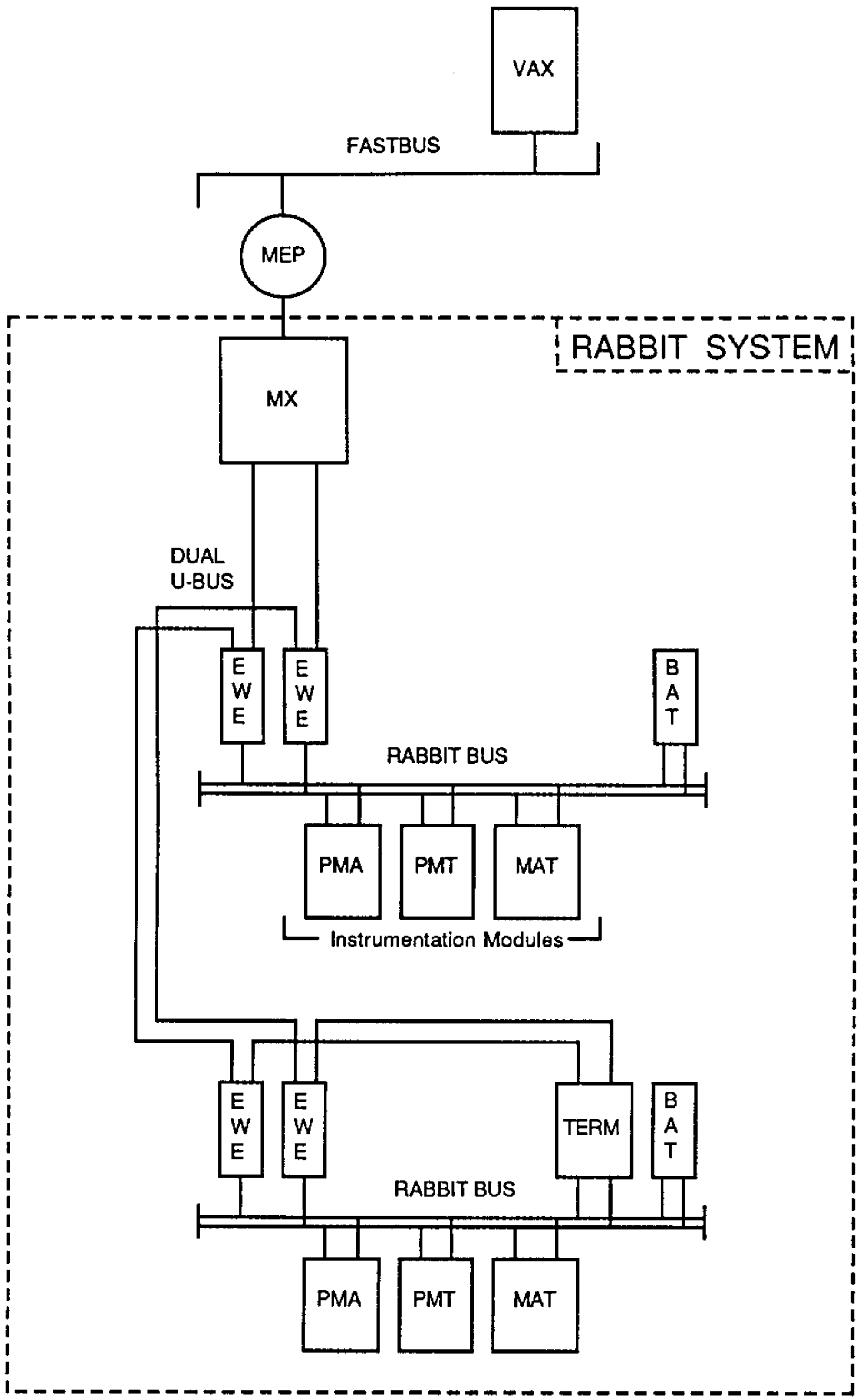


Fig 1

```
line  PC   execution          ASM/MX 1.10   source: example.mx   page: 13
           time (ns)

                            FUNCTION example

                            STORAGE
      006A                     a.active    : 1 word = 0
      006B                     a.top_data  : 1 word
      006C                     a.top_flag  : 1 word
      006D                     a.stop_mask : 1 word = (hex) 80

                            BEGIN

                               /* Check to see if the top ewe is done. */

      001F  100    tscan:      eval um_low(ax1) and a.stop_mask
      0020 15/20               if last_result = 0 goto bscan
      0021  100                   load a.active = 1
      0022 15/20                  load utr,                        /* Latch status, data. */
                                  if not done(top) goto bscan
      0023 15/20                     if not data(top) goto tnext
      0024  100                         load umtr = um(ax1), ax1++     /* Change UBUS to READ */
      0025  100                         load a.top_data = utr          /* Read data from ewe. */
      0026  100                         load a.top_flag = 1
      0027  100                      goto tload
      0028  100    tnext:               inc ax1
      0029  100    tload:            eval um_low(ax1) and a.stop_mask
      002A 15/20                     if last_result != 0 goto bscan    /* Reload top ewe.     */
      002B  200                         load top ewe = um(ax1) til xqt, ax1++

                               /* Check to see if the bottom ewe is done. */

      002C  100    bscan:      eval um_low(ax2) and a.stop_mask
      002D 15/20               if last_result = 0 goto loop
```

Object Code	PC	Instruction Fields																
		a	b	c	r	cjs	ja	data	alui	mli	bix	xa	xb	xc	xr	ws	m	code
6D00 0000 A871 41C0	001F	6D	00	--	--	---	---	----	54	0	E	0	5	--	--	7	0	0
0000 402C E830 000B	0020	--	--	--	--	4	02C	----	74	---	6	--	--	--	--	--	-	B
0000 016A E800 0040	0021	--	--	--	6A	---	---	0001	74	0	0	--	--	--	0	1	0	0
0000 802C 0000 01CE	0022	--	--	--	--	8	02C	----	----	---	---	--	--	--	--	7	0	E
0000 9028 0000 000D	0023	--	--	--	--	9	028	----	----	---	---	--	--	--	--	--	0	D
0000 0000 0001 40C3	0024	--	00	--	--	---	---	----	----	---	---	--	5	--	--	3	0	3
0000 006B E840 0040	0025	--	--	--	6B	---	---	----	74	0	8	--	--	--	0	1	0	0
0000 016C E800 0040	0026	--	--	--	6C	---	---	0001	74	0	0	--	--	--	0	1	0	0
0000 0029 0000 0008	0027	--	--	--	--	---	029	----	----	---	---	--	--	--	--	--	-	8
0000 0000 0000 0162	0028	--	--	--	--	---	---	----	----	---	---	--	--	--	--	5	1	2
6D00 0000 A871 41C0	0029	6D	00	--	--	---	---	----	54	0	E	0	5	--	--	7	0	0
0000 C02C E830 000B	002A	--	--	--	--	C	02C	----	74	---	6	--	--	--	--	--	-	B
0000 0000 0001 40D0	002B	--	00	--	--	---	---	----	----	---	---	--	5	--	--	3	0	10
6D00 0000 A871 81C0	002C	6D	00	--	--	---	---	----	54	0	E	0	6	--	--	7	0	0
0000 402E E830 000B	002D	--	--	--	--	4	02E	----	74	---	6	--	--	--	--	--	-	B

Fig 2

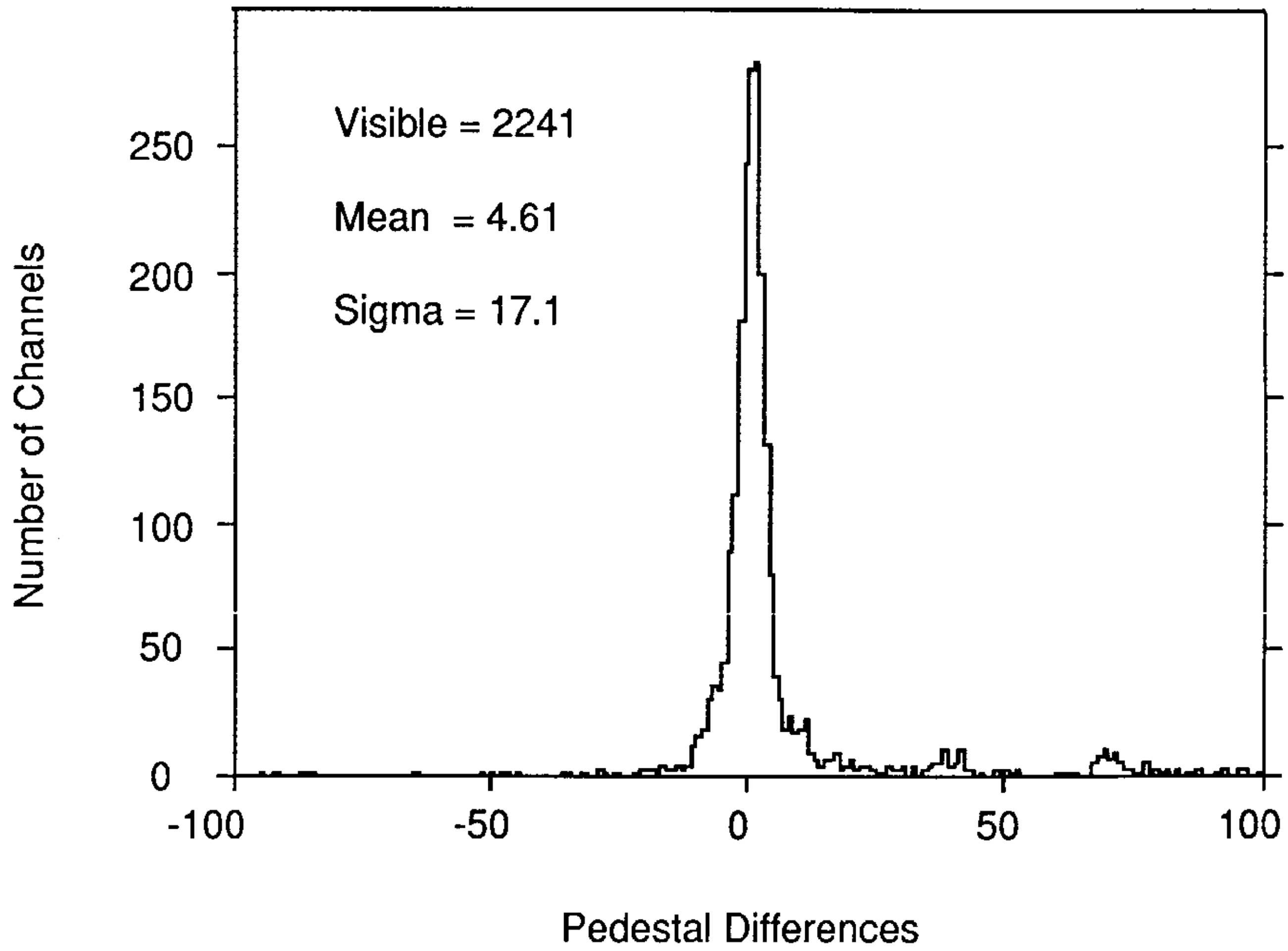
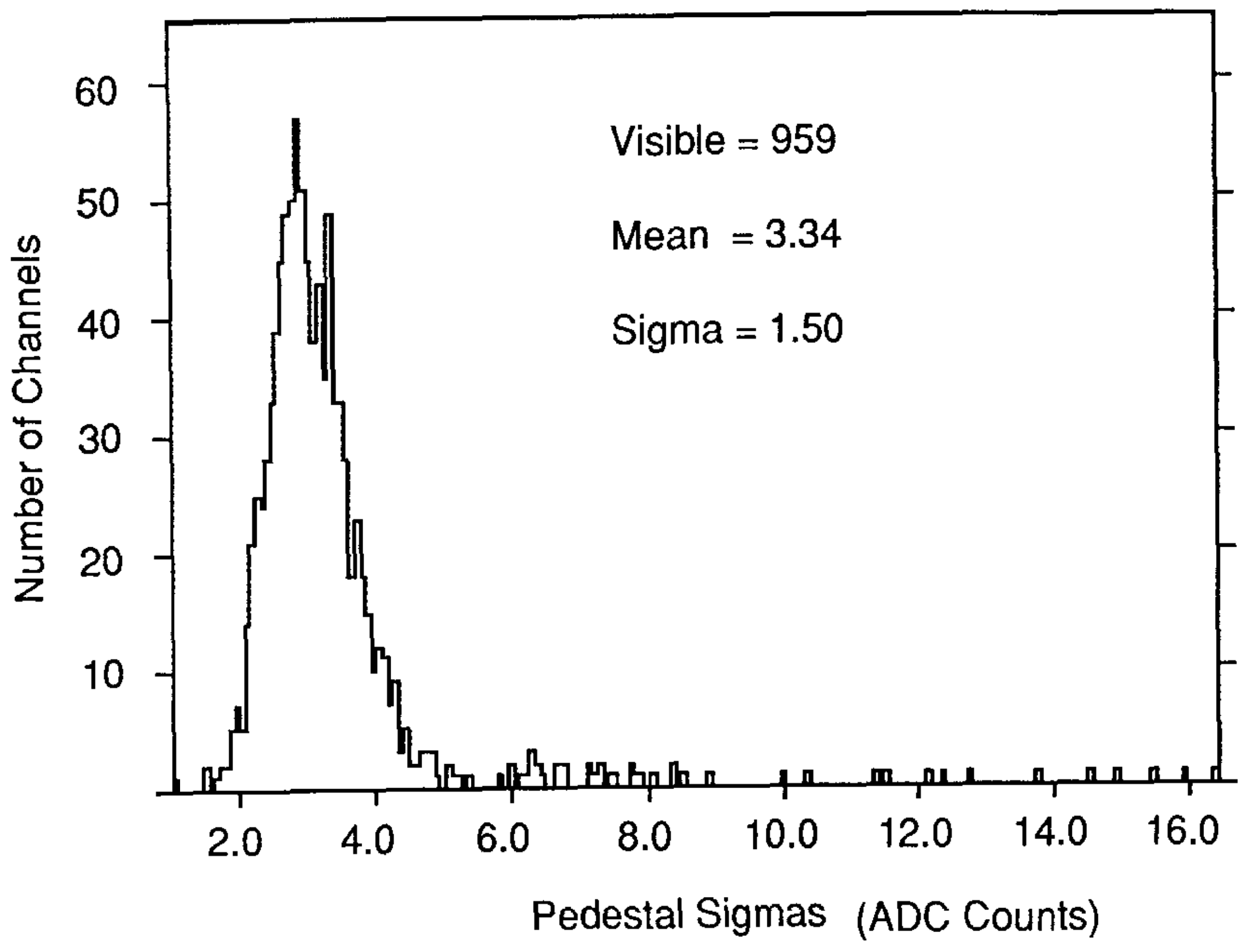

Visible = 2241
Mean = 4.61
Sigma = 17.1
Number of Channels
0
50
100
150
200
250
-100
-50
0
50
100
Pedestal Differences

Fig 3

Fig 4



Visible = 959
Mean = 3.34
Sigma = 1.50
Number of Channels
60
50
40
30
20
10
2.0
4.0
6.0
8.0
10.0
12.0
14.0
16.0
Pedestal Sigmas (ADC Counts)

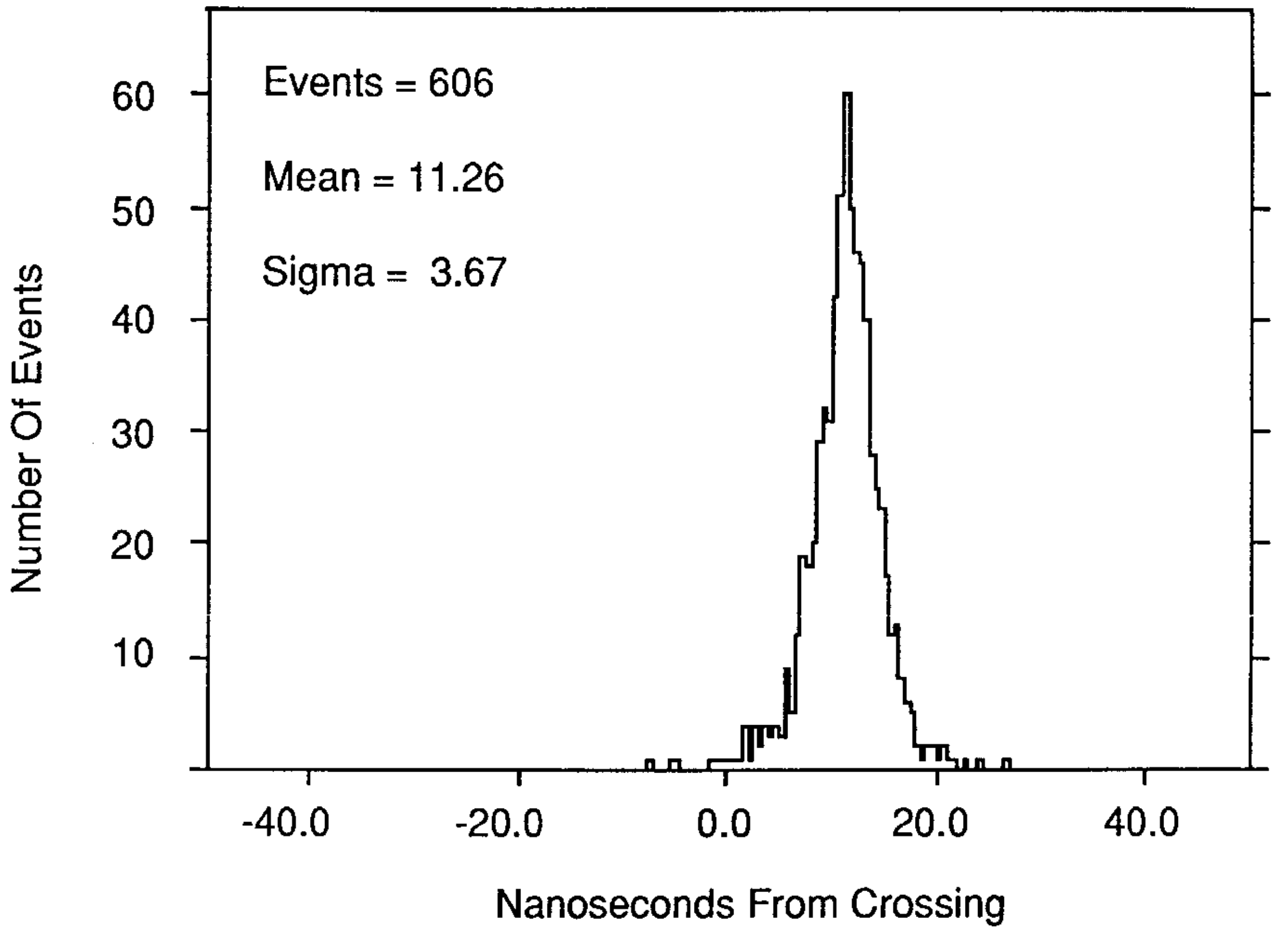

Events = 606
Mean = 11.26
Sigma = 3.67
Number Of Events
60
50
40
30
20
10
-40.0
-20.0
0.0
20.0
40.0
Nanoseconds From Crossing

Fig 5

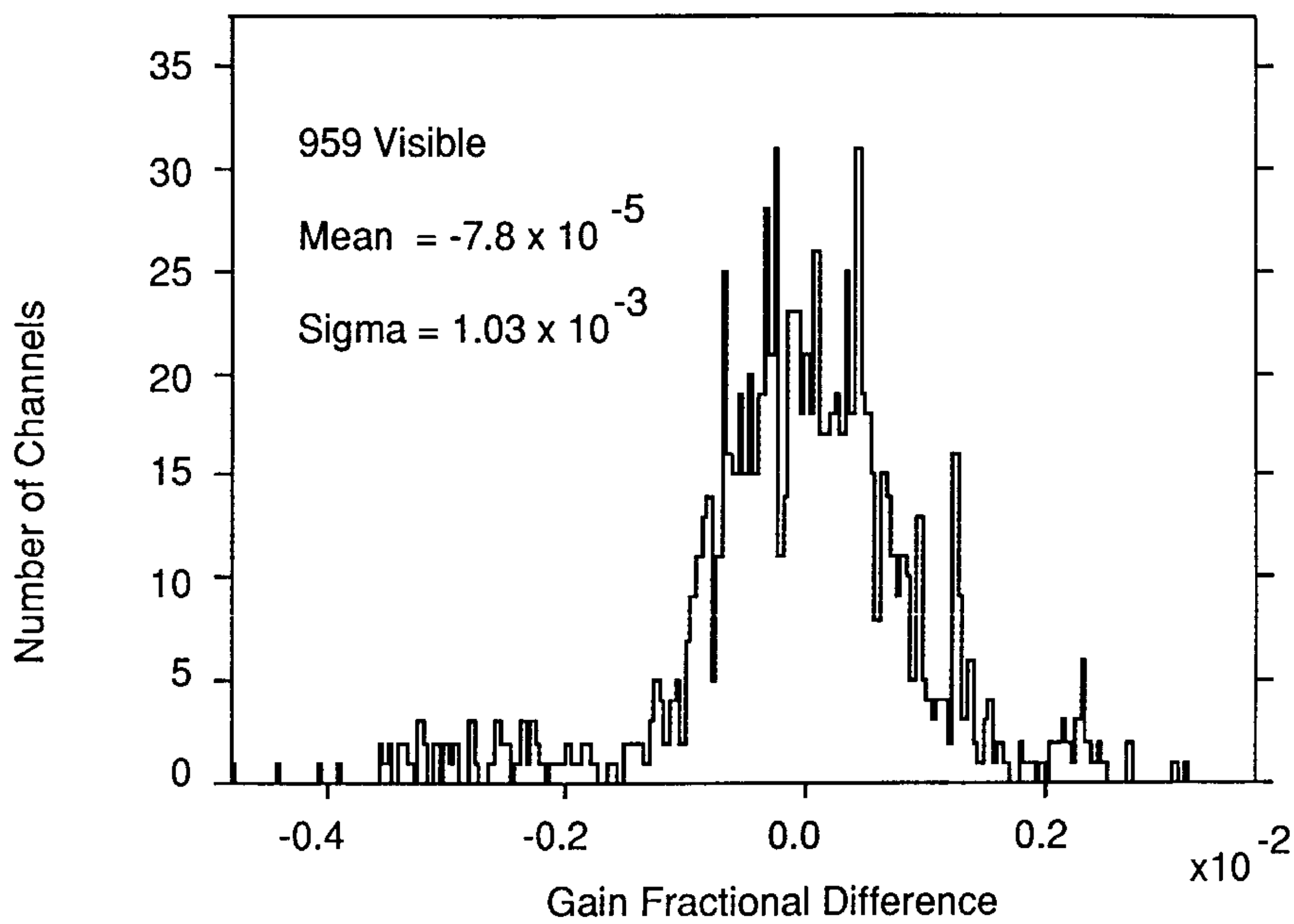

959 Visible
Mean = -7.8 x 10 -5
Sigma = 1.03 x 10 -3
Number of Channels
0
5
10
15
20
25
30
35
-0.4
-0.2
0.0
0.2
x10 -2
Gain Fractional Difference

Fig 6