DEUTSCHES ELEKTRONEN-SYNCHROTRON DESY

DESY 85-074
July 1985

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ISSN 0418-9833

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THE DATA ACQUISITION SYSTEM FOR THE JADE DETECTOR

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ABSTRACT. An outline of the data acquisition system for the JADE experiment at PETRA, DESY is presented. After describing the hardware configuration, we describe our guiding ideas for the design of the data acquisition system, which is followed by accounts of the implementation of real time software, the data flow, the monitoring and detector control as well as the online event analysis and filtering. Finally we summarise our experience with the system.

Introduction.

With the growing complexity of high energy physics experiments the demands on the data acquisition and control systems have increased. In this paper we discuss some of the prime objectives for the design of such a real-time system and how it was realised for the JADE experiment.

The JADE detector[1], installed at the PETRA e^+e^- storage ring at DESY, Hamburg, is shown in a sectional view in Figure 1. It consists of a cylindrical drift chamber inside a 0.48 Tesla solenoid. Between the drift chamber and the solenoid are time-of-flight (TOF) counters; outside the solenoid there is an array of lead glass blocks for the electromagnetic shower measurement, and further drift chambers interleaved with absorbers for muon detection (the muon filter). With up to 240 words (of 16 bits) per track, the central drift chamber supplies the largest amount of data. The average event length varies between 2000 and 3500 words; multihadronic events, which occur at a maximum rate of a few per hour, are longer — typically between 4000 and 8000 words. The trigger rate varies between 2 and 6 Hz depending upon the beam conditions.

In this paper we briefly describe the hardware configuration, explain our main ideas on the design of the JADE Data Acquisition System (JDAS), and discuss our experience with the whole arrangement so far. The experiment commenced data taking in Spring 1979.

Computer Configuration.

Since for a complex detector one wants to have a large amount of feedback information, considerable computing power online is required. The choice made for the JADE experiment was a NORD-10S/50 dual processor[2] from Norsk-Data, Norway.

The NORD-10S is a general purpose 16-bit computer with a memory management system that allows a 16-bit virtual word address to be mapped into an 18-bit physical address. This means that the maximum memory available to a user program is 128 kbytes and the maximum physical memory is 512 kbytes. In addition the memory management system swaps 2 kbyte pages to and from a 66 Mbyte disc, thereby extending the memory size almost indefinitely.

A cache memory of 2 kbytes reduces the memory access time by retaining the most recently used words in bipolar memory. Care has to be taken that the cache does not include areas addressed by direct memory access (DMA). The possibility of efficient interrupt handling and fast context switching is provided by a 16-level priority scheme, each level having its own set of registers including a program counter. The uppermost 6 levels are accessible to external interrupts.

The NORD-10S is equipped with two 66 Mbyte disc units, two floppy-disc units, one card reader, a 1600 b.p.i. magnetic tape unit, ten terminal drivers and two external bus drivers (one for CAMAC I/O and the other for a PADAC[3] crate which provides the IBM link), a colour TV screen and a Gould printer/plotter. The hardware configuration is shown in Figure 2.

The NORD-50[4] is a 32-bit single-program computer which is about a factor of 3 faster than the NORD-10. It controls no peripherals at all and needs a NORD-10 which drives it via a set of registers. The particular advantage of the NORD-10S/50 system is that the two processors can access a common part of a multiport memory[5] and are not simply linked by I/O channels as in many other configurations. This means that control flags and information exchange between the processors can be handled in a way similar to that amongst real-time programs within the NORD-10S. The multiport memory consists of two distinct parts so that the two computers do not compete for memory cycles except when they access the common segment; and it also ensures that two successive 16-bit words of the NORD-10S can be fetched as a 32-bit word by the NORD-50 in a single cycle. The memory allows for up to 4 ports, out of which two are used for the processors and one serves for the DMA transfers to and from the discs. The heavy traffic on the memory ports in our application makes it essential that the memory hardware is equipped with error logging and single-bit error correction devices. The memory allocation most appropriate for our application is 384 kbytes for the NORD-10S, 128 kbytes for the shared segment and 256 kbytes for the NORD-50.

In order to accommodate the digitising and control electronics for the JADE experiment 40 CAMAC crates are needed. These are interfaced to the NORD-10S via two Norsk-Data CC10 crates[6] and via the commercially available System Crate of Fisher/GEC-Elliott[7] and the RTX-N10 I/O bus interface[8]. The System Crate physically consists of two CAMAC crates with the dataways operated in parallel* in order to accommodate an executive controller, 6 branch couplers for 38 CAMAC crates, and the following autonomous source units (listed in order of decreasing priority):

- Programmed transfer unit for the NORD-10S,
- DMA transfer unit for the NORD-10S,
- Interfaces for the Plessey microprocessor MIPROC-16[9],
- Graded LAM scanner and interrupt vector generator.

These source units can apply for control over the system crate and its branches and the executive controller grants the CAMAC access in order of priority.

The read-out and control logic is arranged such that the high priority NORD-10S task which compiles the events has exclusive control over the system crate, while all asynchronous tasks for magnet and voltage control may only reference the CC10 crates. One of the CC10 crates contains some serial CAMAC drivers in order to check control bits in a remote crate and to enable the testing of CAMAC equipment in parallel to the data acquisition.

Several microprocessors operate within individual crates in order to pick out lead glass pulse heights above a preset threshold[10] and to select pulse height and timing information for those time-of-flight counters which generated a stop signal[11]. An additional microprocessor (Plessey MIPROC-16) is more closely related to the data acquisition. It normally acts as a slave of the NORD-10S, communicating via interrupts and control words, but can also access any crate in any branch of the System Crate independently. Details on the operation of the MIPROC-16 are given elsewhere[12].

Philosophy of Operation.

The operator of JDAS is concerned only with a single steering program and does not have to know the arrangement and actions of the other real-time tasks. He communicates with the steering program via a dedicated command terminal and is aided by a colour TV screen for status and error message information. A high quality Tektronix 4014 graphics screen (with a resolution of 4096 by 3200 points) is used for histogram and event displays. Commands may be entered either as a text string or by pressing one of up to 24 function keys whose meanings are displayed as a menu in the protected lower part of the screen, just above the keyboard. Pressing a function key may cause some immediate action, may initiate some dialogue if parameters are required, or may start up a new context with a different command assignment of the function keys and a new menu. In this way the operator has only to know the command to start the steering program and the two typed commands STOP (to stop a run) and EXIT (to terminate the steering program) as well as the two standard NORD control characters CTRL/A and CTRL/Q for erasing a character or whole line. All other actions are guided by the various levels of command menus.

During data taking formal errors which occur when reading data from CAMAC or writing events to tape or the IBM link are reported back to the steering program and displayed on the command terminal. The large CAMAC system can give rise to a large number of possible errors. In some cases a brief single-line message is displayed including key numbers which must be looked up in the operator's manual for further details. More general errors such as magnet field fluctuating, high voltage outside preset limits or missing information from a formally correct event, are flashed onto the colour TV screen. In some cases — such as wrong high voltage or missing microprocessor response — more detailed information is logged on the console writer together with the current run number and time.

A standard set of histograms is provided in order to help monitor the various detector parts. At regular intervals a spy program searches selected histograms for holes. In this way a failing component is often discovered before the operator can find it himself. Due to the large number of detector components, the operator's attention cannot always be focused on the performance of a particular detail. Therefore, the spy program has proved to be most valuable. Failing units may be disconnected from this error search if they cannot be repaired immediately. If the operator wishes to check a pulse height or some timing information, which is not amongst the standard monitoring histograms, he may use a separate monitoring task to book a histogram for this particular channel and accumulate the information for a preselected number of events.

For detector check-out and for pulser calibration runs the group responsible for a particular detector component has to write its own event analysis program and run it in a time-sharing mode from a vacant terminal. The reading and compiling of events will still be carried out by the standard data acquisition system. Special test-run start procedures on the command console allow the operator to select specific detector components to be read out and to choose the trigger conditions. The test events will be compiled in the standard fashion and will be sent on request to the time-sharing user for his analysis. This relieves the user from having to write his own CAMAC input task. This method of event transfer is also available during normal data taking. At present one active user can be supported by the system.

Depending on the type of data acquisition run, a varying number of tasks and buffers are required. During calibration or check-out the user may need only a single large buffer and do all the analysis himself without using the standard NORD-50 analysis program. For the standard data-taking for subsequent physics investigations it is always necessary that the NORD-50 is attached in order to continuously monitor the performance of the various detector components. The full system of course requires a larger number of tasks and buffers in order to communicate with the NORD-50 and to record the events on tape or to transfer them to the IBM computer. However the operator does not have to be concerned with details. He can switch between different configurations of the online system by issuing commands which simply read different sets of control parameters from the disc. The current configuration is always displayed amongst the status information on the colour TV screen.

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* This version of the System Crate required some modifications to the branch couplers and the executive controller, which were carried out by the company at our request.

Software Implementation.

The NORD-50 processor is used for a single program which performs event validation, analysis and monitoring, which includes histogram filling. The NORD-10S performs all other tasks such as interrupt handling, CAMAC readout, communication with the operator and event and histogram display.

In order to achieve a modularity which makes it easy to attach or detach tasks or buffers, we have adopted the DAS data acquisition system which was developed at CERN[13]. Its central part is a data acquisition monitor which operates on a hardware priority level (level 9) next to the external interrupt service routines (levels 10 to 15) and above the actual operating system (levels 3 and 4). The DAS monitor schedules tasks and controls the access to buffers via a well defined set of parameters: the task and buffer control blocks. The individual tasks may in turn reside on hardware priority levels (and are then called Direct Tasks, DTs) or they can be Real-Time (RT) programs (on level 1) under the control of the operating system. The most time-critical process is the assembly of events from various parts of the CAMAC electronics. The CAMAC readout task is therefore written as a Direct Task (level 8) and, together with the monitor, can lock out the operating system. In this way very short response times to external interrupts are achieved (a few 100 μsec), and the event acquisition is accomplished by the Nord-10S without any preprocessor residing in CAMAC.

An important feature which had to be added to the data acquisition package from CERN was the communication with the NORD-50. It transpired that the NORD-50 monitor supplied by Norsk-Data, which is a task controlled by the NORD-10/S operating system, was only suited for loading and initial start of the program. We integrated the NORD-50 start-up procedure into the command and dialogue context on the command terminal in such a way that the operator again does not need to be concerned with any details. He can select a specific load module for the NORD-50 by name or use the default load module which is installed for the standard data acquisition runs.

A much larger effort was required to accommodate the event transfer and the signalling of the availability of events between the NORD-10S and NORD-50. This has been accomplished by using a shared memory segment which contains a set of control flags, and the data buffer which can be loaded with several events. A Direct Task (level 7) is used to transfer an event from the CAMAC input buffer, which is in the NORD-10S local memory, into the shared memory buffer. It then activates the NORD-50 via a special section of program on level 11 unless it is already busy with a previous event. In a similar way the NORD-50 can start via interrupt level 11 another direct task (level 6) which copies one or several events into the NORD-10S local output buffer, from where events can be made available to a large number of consumer tasks (see the next chapter on data flow). In the first copy step the event's size is already extended to allow space for the Nord-50 analysis results. These are then appended to the event and copied in the next step so that event classification and the pattern recognition results, etc., can be viewed on the local graphics screen or at the IBM. The arrangement of the JDAS tasks and buffers within the various processors is shown in Figure 3.

Communicating the accumulated histograms from the NORD-50 to the NORD-10S for display is less of a problem. Once again the shared memory segment is used to hold all the current histograms. In this case no synchronisation between the computers is required since the NORD-50 only writes and the NORD-10S only reads from the histogram space.

In coding the software, the use of assembly language has been confined to routines which serve to communicate between the two NORD computers, between the various hardware levels on the NORD-10S, and between the DAS monitor and its associated tasks. Additionally all input/output related routines have to be written in assembler; in particular the complete CAMAC task is written in machine language in order to avoid numerous subroutine calls and to speed up the most time-critical process. All other code, including the analysis, control and display programs is written in FORTRAN.

When developing the online software it is important to maintain compatibility with the available offline software at the central IBM. Using FORTRAN at both ends is a first step. Secondly, the events have to be formatted online in the same way as they will be used offline. For this purpose a Bank Organisation System BOS[14] has been adopted. This provides the framework for collecting the information from separate detector components into separate banks of data which are equipped with headers containing their identities and lengths. An event record is formed by an assembly of such banks which can easily be rearranged or expanded. As a third compatibility measure, the application graphics software for detector and histogram displays is based on a common set of subroutines resembling the Terminal Control System package TCS[15] for the Tektronix storage screens. The high-level histogramming is based upon the CERN ZHIST[16] package. By observing these rules it is relatively simple to implement programs which have been developed offline.

For the microprocessors which help the data acquisition on the CAMAC side, in particular for the MIPROC-16 which plays an important part in the first stage event filtering, the programs have to be written in machine language, cross-assembled on the Nord-10S, and downloaded to their memories. These processors run without an operating system; the tasks they have to perform are driven by interrupts and operate at fixed priorities. However, resident monitors allow one to look at and modify memory locations as well as registers, which helps in the process of debugging applications programs.

Data Flow and Task Configurations.

Having discussed the basic ideas for implementing the software in the previous chapter, it is an easy matter to illustrate the data flow. As shown in Figure 4, the event trigger arrives at the NORD-10S which starts to collect data from 38 CAMAC crates, with the ability to wait at those crates where longer conversion times are involved. In particular, the microprocessors in some of the crates may not have finished compressing the relevant ADC and TDC data, in which case the CAMAC task is put into a wait state and is reactivated by a LAM interrupt. The MIPROC-16 processor, which can act independently from the NORD-10S as a master on the System Crate, could have served as a fast processor for reducing the readout time. It has a shorter cycle time of about a factor of between 8 and 10 when compared to the NORD-10S, and does not suffer from any software overhead. In practice it turned out that the NORD-10S by itself was fast enough for our purposes and so the MIPROC-16 has been used to implement a first stage event filter. If the trigger condition requires the presence of one or more charged tracks in the inner detector, then that detector data and some selected trigger information — at the direction of the NORD-10S — are strobed into the MIPROC-16 memory at the same time as they are written into the Ring Buffer 1 in the NORD memory. When the event readout is complete, CAMAC is cleared to accept the next event, and the NORD awaits the decision of the MIPROC-16. If the event is flagged as a reject candidate, it is purged from Ring Buffer 1 (see the chapter on event filtering for details). If the event is flagged for accept, it is released for transfer into the shared Work Buffer where the NORD-50 validates and analyses the event. In contrast to the ring buffers, the Work Buffer has no wrap-around in order to facilitate the unpacking and checking of the events by the NORD-50. If the NORD-50 decides to reject an event, it is not copied into Ring Buffer 2. The events which finally arrive in Ring Buffer 2 have the NORD-50 analysis results appended, and are available for inspection on a graphics screen and for additional monitoring tasks. The event display can select events according to either the trigger bits or their classification by the analysis programs of the MIPROC-16 and the NORD-50. This has proved useful not only to check out the analysis programs but also to visually monitor the performance of the detector.

During normal data-taking, i.e. not for test runs, the data are to be stored for later offline analysis, and hence are normally routed via a fast serial link to the central IBM computer. At the central computer the events are temporarily stored on disc and then dumped to magnetic tape when a sufficient amount of data has been accumulated. A number of dump tapes are then combined in order to obtain efficiently filled tapes with complete runs which form the initial permanent data sets for offline analysis. Only on the rare occasions where the IBM computer or the data link is down, are events recorded on the local NORD tape unit.

The arrangement of buffers shown in Figure 4 corresponds to a particular configuration of tasks. Essentially, for each data transfer (indicated by an arrow), there is an associated task. Additionally there are tasks which are not linked directly to the data stream, such as the histogram display, the microprocessor communication and the detector control tasks. A particularly useful facility for checking out the analysis programs, is to replace the CAMAC input task by a play-back task which can feed events from tape or disc into Ring Buffer 1 or even into some dedicated memory within CAMAC. In this way various program versions can be tested with the same set of data.

Monitoring and Detector Control.

The physics analysis of events offline requires that an efficient online monitoring system either ensures the integrity of the data or causes unavoidable detector deficiencies to be registered. For this purpose the incoming data are thoroughly scrutinised for their formal consistency. Before a data acquisition run is started, a sequence of computer generated triggers is used to determine the baseline or pedestal values of all lead glass counters in the barrel, endcap and tagging components of the detector. If any values are out of range, the channel numbers are logged on the system console writer and brought to the attention of the operator. The pedestals of all lead glass channels are written to tape as part of the start-run information, and together with a preselected offset they are also fed into CAMAC processors which suppress the zero signals for the subsequent event acquisition phase. During the actual data taking the hit rate, pulse height average value and, where relevant, the average value of the timing information for each detector channel are stored in histograms. Even the current within each inner drift chamber segment is recorded and monitored for each event. For those people in charge of operating the experiment, it is normally easy to detect possible component failures by comparing the histograms of the current data with a standard set of histograms. However, it was found that sometimes failures were discovered well after they had happened. For this reason a spy program has been written which searches selected histograms at intervals for characteristic holes. If an electronic unit does not register any hits at all, the spy program typically detects this after 1000 triggers which corresponds to 5 to 10 minutes for a trigger rate of 2 to 4 Hz.

In addition to using the contents of the events to check the performance of the detector, there are a number of standard measures to ensure the quality of the data. At regular intervals control records, which mainly contain scaler information, are inserted into the data stream in order to cope with an unforeseen abrupt termination of the run. The settings of the high voltage power supplies are checked several times per hour and compared with a set of standard values stored on the disc. Variations of the magnetic field are monitored and warning messages appear if the fluctuations exceed a preset limit. The current value of the magnetic field is written into the shared memory segment from where it is copied into each event.

Event Analysis and Filtering.

The event analysis packages which are implemented on the NORD-50 range from simple consistency checks for the trigger conditions to pattern recognition for charged tracks. The packages to be used during data acquisition are determined by setting flags via the menu technique from the command terminal as previously described. Time-consuming routines such as the pattern recognition or the Z-vertex reconstruction may have to be turned off during periods of high trigger rate. Our objective has always been to analyse all events, in order to classify them online as electron or muon pairs, multihadronic, beam-gas or cosmic particles etc. In this way we succeed in rejecting a high proportion of events which are clearly identified as background, so that fewer tapes have to be handled offline and hence less offline computer time is required.

Before the various cuts of the filtering program became "live" the reject candidates were just flagged and sent on to the central IBM, where the online decision was thouroughly cross-checked. We will now briefly discuss the various steps in the event filtering process and commence by describing the initial filter program, which was originally tested on the NORD-50 and which now runs on the MIPROC-16. The JADE online event filtering scheme is described in detail in reference 17.

The MIPROC-16 investigates the events whose trigger condition requires the presence of one or more charged tracks in the inner detector. The first step is to check the trigger condition. To do this the drift chamber segments in front of the time-of-flight counters, which caused the trigger, are analysed to find out whether the drift chamber hits line up to form tracks aiming at the hit time-of-flight counters, or whether the hits are just random. This gives the first class of rejected events. The second stage is a quick determination of the interaction point (Z-vertex) along the beam line[18]. The technique is to combine all hits in drift chamber layers 1 to 16 (ring 1) with corresponding hits in layers 17 to 32 (ring 2) and to form from any such two–hit combination the intercept or closest approach to the beam line. All these positions are accumulated into a histogram, and if any event has a vertex it should show up as a cluster or peak. Any event whose Z-vertex is at least 300 mm away from the centre of the detector (which is coincident with the interaction point) is classified as a background event and rejected. As mentioned in the section on the data flow, the MIPROC-16 arrives at a decision before the event is transferred to the NORD-50 for analysis. Since the MIPROC-16 rejects about 55% of the track triggers — the actual fraction depends on the beam conditions — the NORD-50 has to cope with a reduced event rate, which allows one to spend more analysis time per event if the initial trigger conditions are unaltered.

The efficiency for determining a Z-vertex is much better if a fast algorithm for finding tracks is used. Such a method is particularly useful when the tracks are accompanied by a large number of random hits. A fast pattern recognition algorithm has been implemented on the Nord-50 and is used to reject those events with a Z-vertex outside ±300 mm which the algorithm in the MIPROC-16 was unable to find. Additionally, events which have no tracks originating from close to the interaction region in the R-phi plane are rejected. This algorithm allows about 65% of the remaining track triggers to be rejected.

The NORD-50 rejects events that are clearly cosmic particles or showers which traverse the detector at a safe distance from the interaction point and leave a characteristic signature. These events include the so-called grazing cosmics which clip several blocks in the lead glass barrel and hence cause a total energy trigger. These events leave a characteristic long cluster in the lead glass barrel which can be identified. Such events can then be rejected. A second example is the low energy neutral trigger which requires two low energy deposits in the lead glass barrel. A large number of cosmic particles contaminate the trigger and so a very simple rejection algorithm is used whereby the muon filter is searched for tracks and the presence of a track causes the event to be rejected. The result is that around 85% of this particular trigger is rejected online. This is the only way that a low energy neutral trigger can be incorporated since otherwise its effect would be to swamp the data.

For each event rejection class, 5% of the reject candidates are retained in order that cross-checks can be made offline and correction factors applied if something is discovered to be wrong. The reason for rejection is appended to the event to ease the checking process.

From the original triggers, which consist of approximately equal numbers of track and energy triggers, about 30% are rejected by the MIPROC-16. Of the remaining events the NORD-50 rejects about 40 to 60%. This results in an overall reduction factor of about 50 to 70% of the raw triggers.

Performance of the System.

The hardware of the online system — except for the MIPROC-16 interface — was complete and most of the support software written before the JADE experiment started accumulating data in the Spring of 1979. The software development continued in areas like refinement of error checking, adjustment of buffer sizes and event analysis. The whole matter of event filtering had to be learnt as the experiment proceeded and events were analysed offline. Examples of later additions to the software, which however grew naturally from the scheme of event classification discussed in the previous chapter, are the instantaneous recording of the hadronic cross-section or its ratio R with respect to the muon pair cross section, and the preselection of a loosely defined class of hadronic events which then can be processed and analysed offline much faster than the whole bulk of data. Both these options became necessary and were implemented when the energy scan at PETRA in the search for the top quark started. It is estimated that by now a total amount of 15 to 18 man-years have been invested in the software development and testing.

A figure of merit for a data acquisition system is always how effectively it processes the event triggers. During normal running the trigger rate is 2 to 4 Hz and this entails a dead-time of about 5 to 10%. Beyond 6 Hz the dead-time increases non-linearly due to the analysis backlog in the NORD-50, and at 10 Hz the dead-time can be well beyond 30%. In such instances of high rates and high dead-times the sampling fraction for the histogramming procedure can be reduced, and the analysis packages disconnected. However, one never wants to cut down the filtering process because the high rates are caused by bad beam conditions, and the event filtering works most efficiently under these circumstances. In cases of intolerably high rates, the recourse normally is to reduce the number of available triggers or to increase the energy thresholds of the triggers until the machine conditions improve.

During data acquisition the NORD-10S processor uses only about 30% of the CPU cycles for standard operations and hence can provide fast response to requests for histogram and event displays.

If one has to judge the performance of a complex system, then the outcome certainly depends on one's interests and expectations. The whole online system provides a service which makes it easy for the person in charge of supervising the experiment to monitor the performance of the detector and to localise faults when they occur. During data taking an automated procedure reports failing electronics components within 5 to 10 minutes. From the purely operational point of view a single person per shift is enough to run the experiment. The functioning of the system hardware and software has been quite stable, and there have been no major break-downs which interrupted the data taking for any extended period of time, during the first 5 years of operation of JADE.

Acknowledgements.

The JADE experiment is supported by the Bundesministerium für Forschung und Technologie, the Japanese Ministry of Education, Science and Culture, the UK Science and Engineering Research Council through the Rutherford Appleton Laboratory and the US Department of Energy. One of us (H.E.M.) wishes to thank the DESY directorate for the hospitality extended to him.

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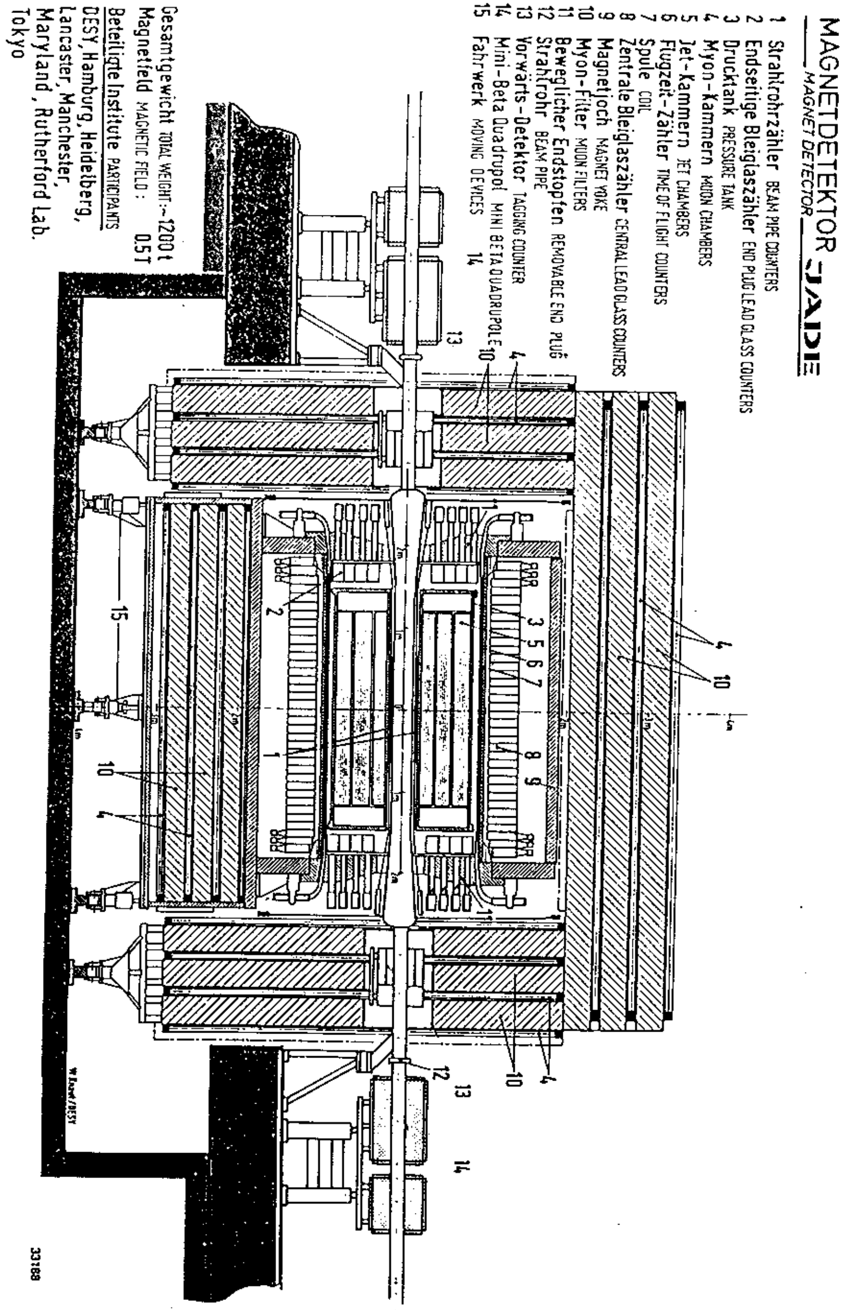

Figure 1: A Sectional View of the JADE Detector

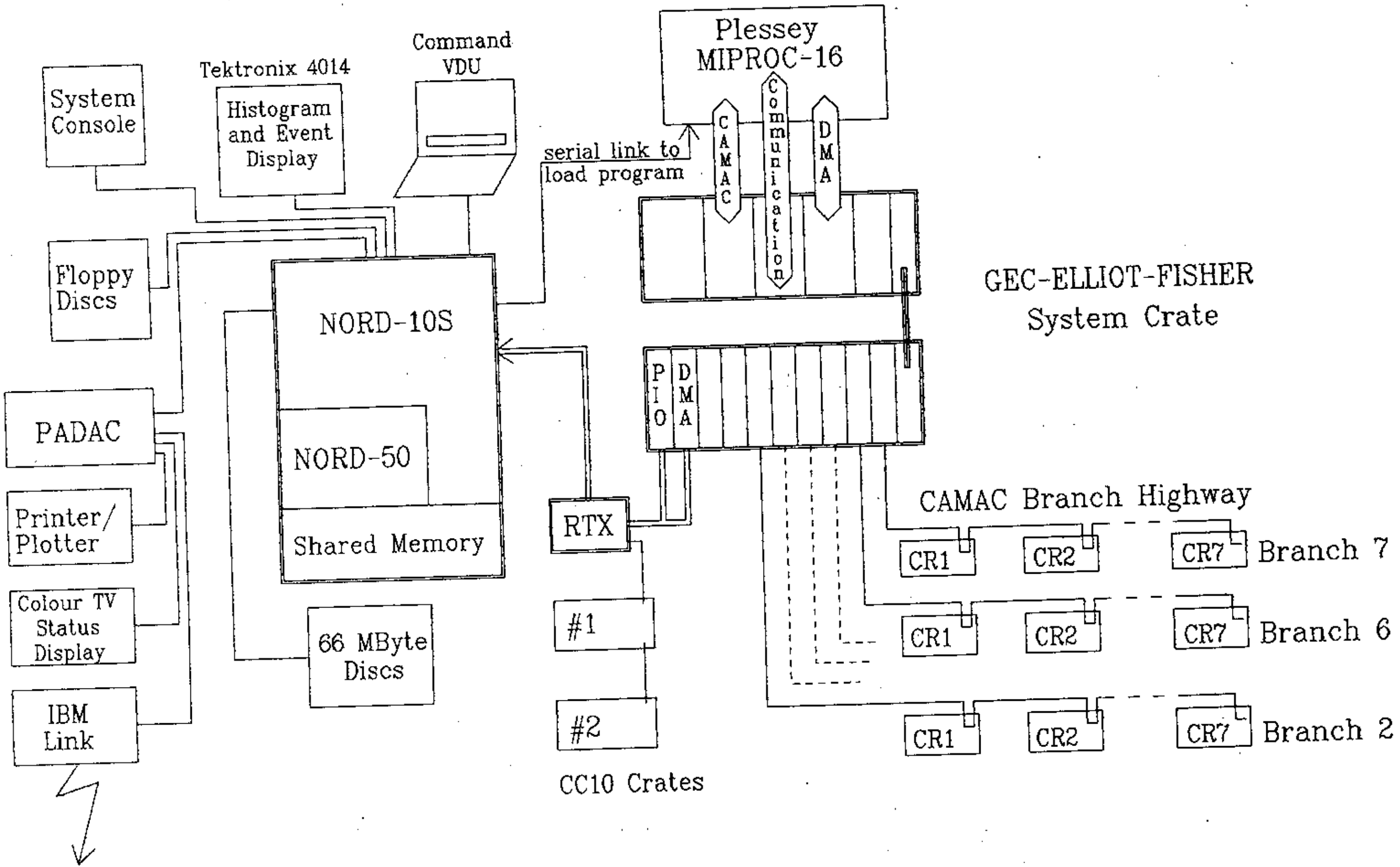

Figure 2: JDAS Hardware Configuration

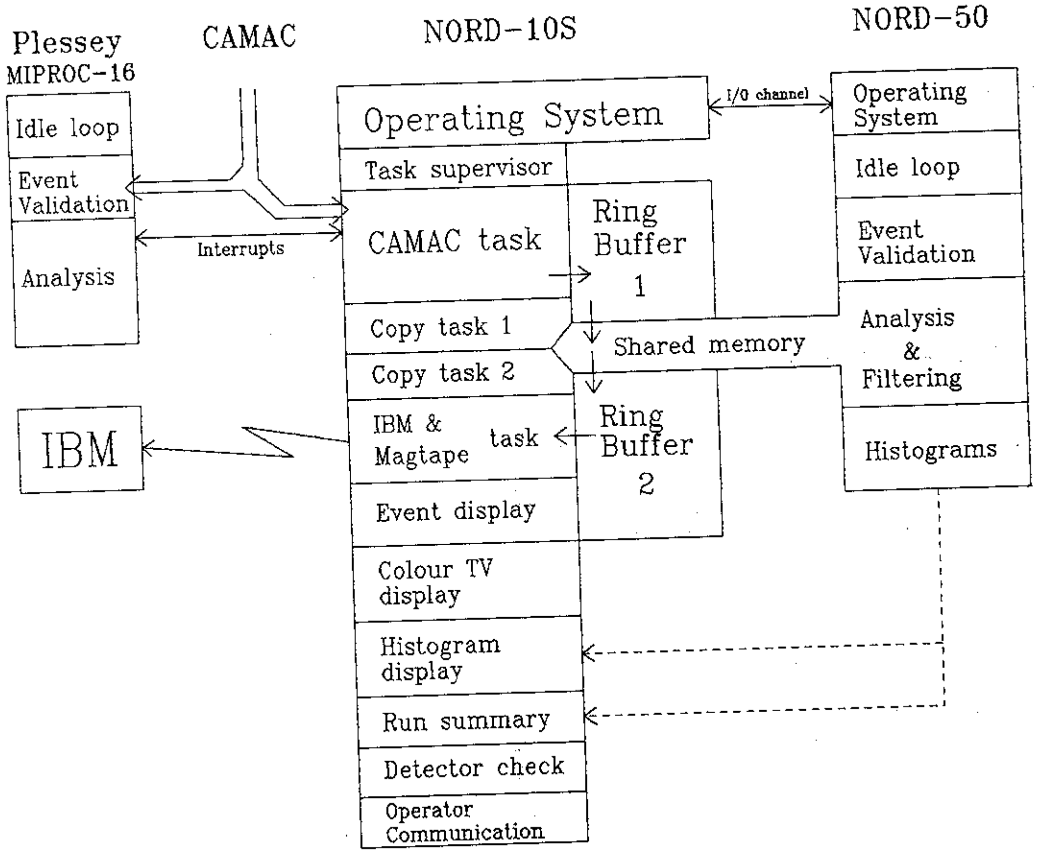

Figure 3: Organisation of JDAS Tasks and Buffers

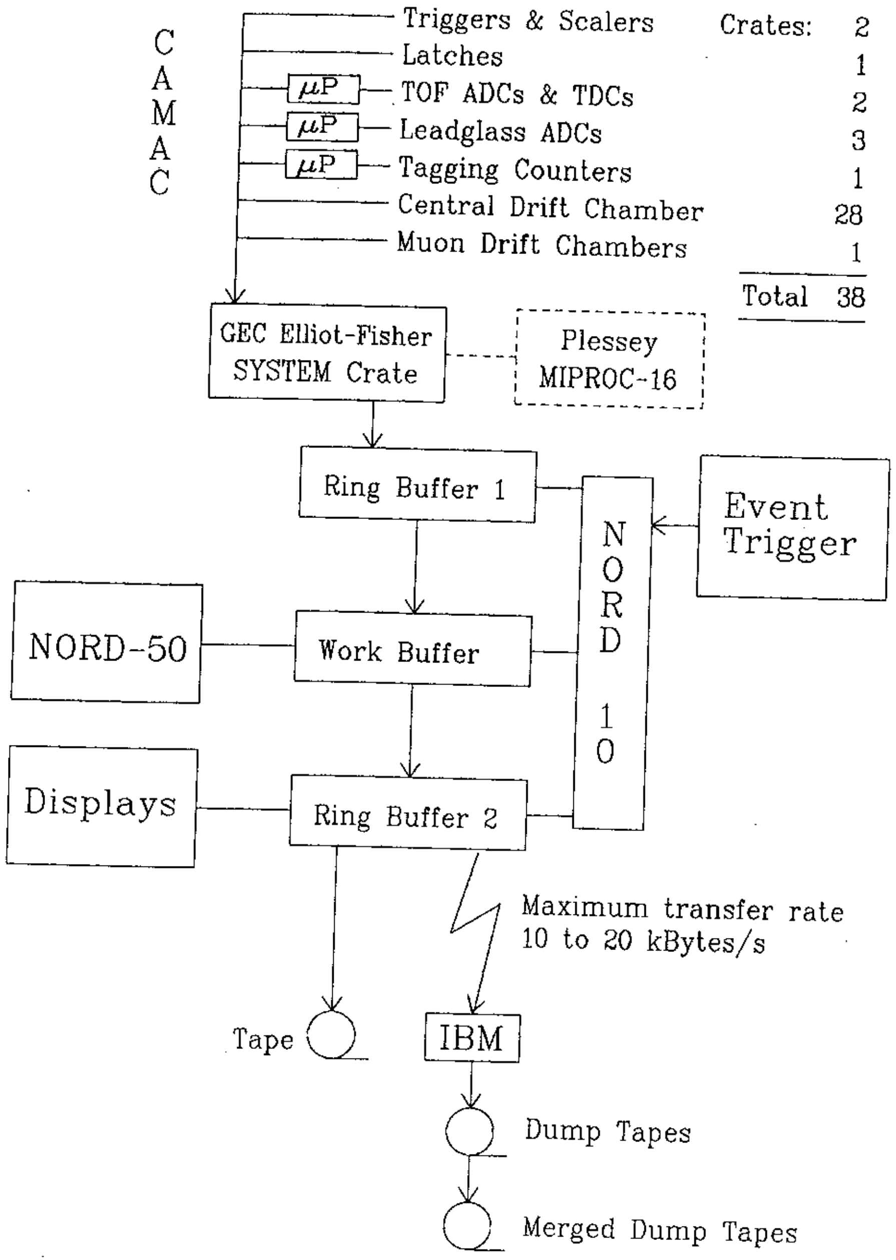

Figure 4: Data flow in JDAS