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P. Zanella
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DATA HANDLING SYSTEMS FOR LARGE MAGNETIC SPECTROMETERS

(Lectures given at the "International School on Use of Computers in Nuclear Research", Taschkent, URSS, September, 1974.)

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1. INTRODUCTION

These lectures are about computer systems devised to acquire and process data produced in experiments with large magnetic spectrometers. These notes are only intended as background material for the lectures.

Spectrometer techniques are used at present in almost all counter experiments. In recent years the idea of building "general-purpose" multiparticle spectrometers has been widely accepted in the major high-energy laboratories. One has in mind such experimental facilities as Omega and Split-Field-Magnet (SFM) at CERN, LASS at SLAC, PLUTO at DESY, the ITEP spectrometer at Serpukhov, the People's and Muon spectrometers at FNAL, etc. For a recent review of spectrometers, see A. Michelini[1].

The design criteria of these large set-ups aim at covering a wide range of experiments with minimal changes to the basic apparatus. The detector is meant to cover as much as possible of the solid angle around the target and of the useful space inside and outside the magnet. Typically, these devices are characterised by large size and complexity; they must, however, retain a good measure of flexibility in order to serve many different experiments. To give an example, figure 1 is a picture of the SFM installed at the

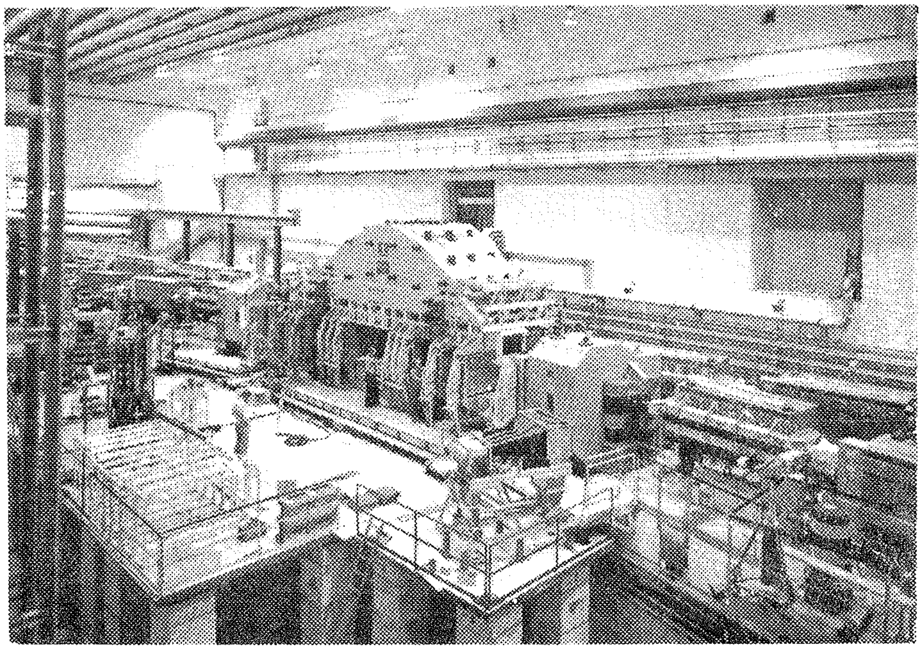

Figure 1

CERN ISR. Figure 2 is a top view of the same spectrometer showing the two storage rings intersecting in the centre of the magnet.

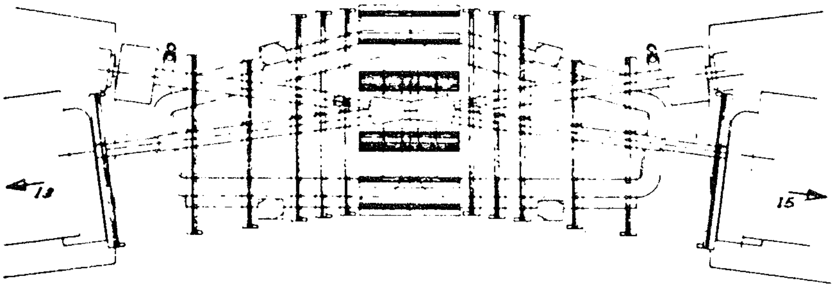

Figure 2

Figure 3 is a side view of the SFM showing the gap filled with detectors.

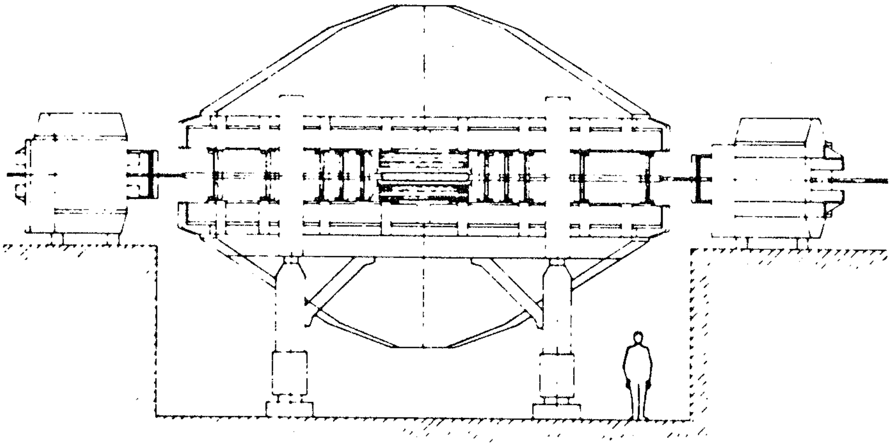

Figure 3

Figure 4 is an example of a reconstructed event.

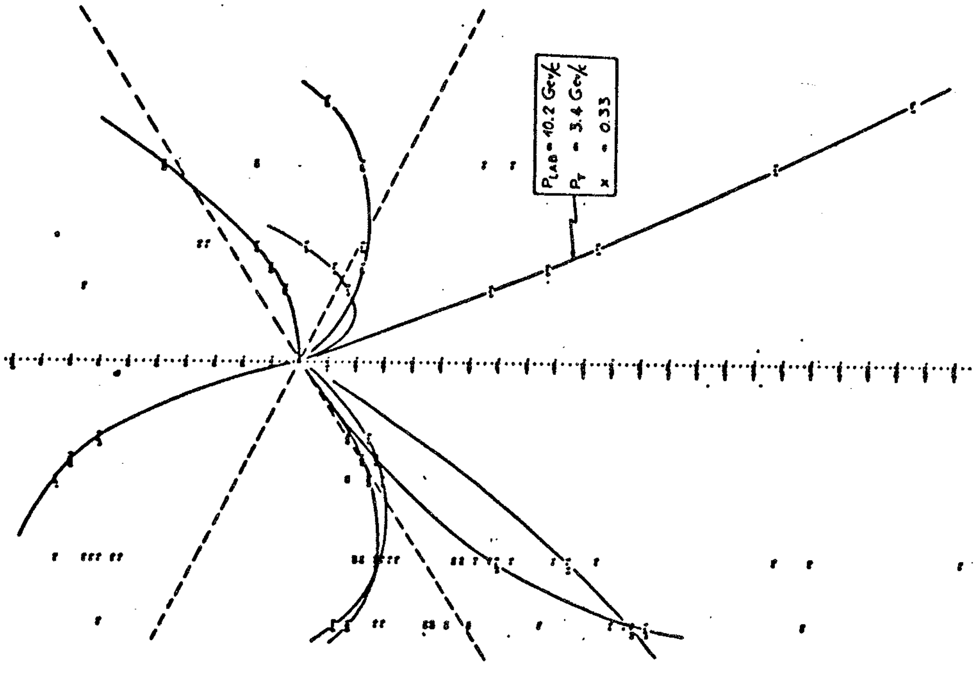

Figure 4

Because of the substantial investments of financial and human resources required for their development, such tools tend to be shared by several groups of experiments. As to the way of sharing, it has evolved from simple-minded time scheduling to more sophisticated concurrent operations. Like bubble chambers, these huge devices are semi-permanent on the experimental floor and require some sort of organised operations.

The complexity of the tasks involved in setting up an experiment and analysing its data, encourage the physicists to join in large groups or collaborations. The resulting style of research and the working conditions in large spectrometer environments are quite unique.

As far as the data is concerned, in order to increase the "productivity" the trend has been definitely away from film. The large majority of the detectors have filmless read-out systems handing over digital information directly to on-line computers. Plate spark chambers with TV-camera read-out and wire chambers with magnetostrictive read-out have been quite popular so far.

Figure 5 shows the plumbicon-camera read-out method used with the Omega Magnet. Note the radial arrangement of the spark chambers. Figure 6 is a picture of an Omega event shown on a display.

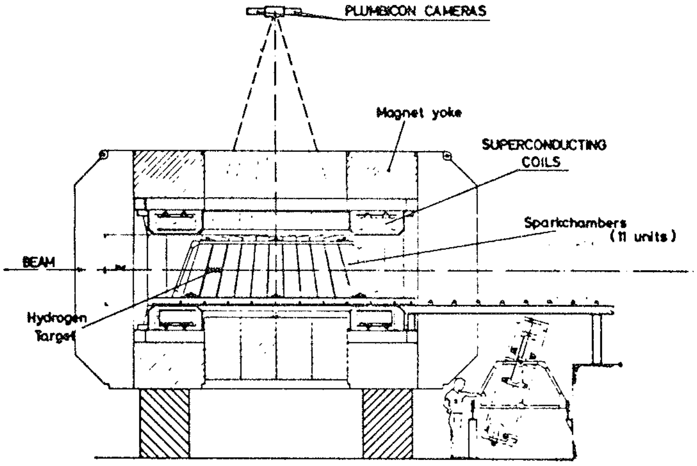

Figure 5

Recently, Multi-Wire-Proportional-Chamber (MWPC) systems have become operational in large scale spectrometers. Figure 7 shows a proportional wire chamber module of the type used in the SFM. The chamber consists of two gaps with horizontal and vertical wires. The dimensions: 200 x 100 cm^2. Wire spacing: 2mm. Inclined high-voltage strips give some extra information in case of coordinate

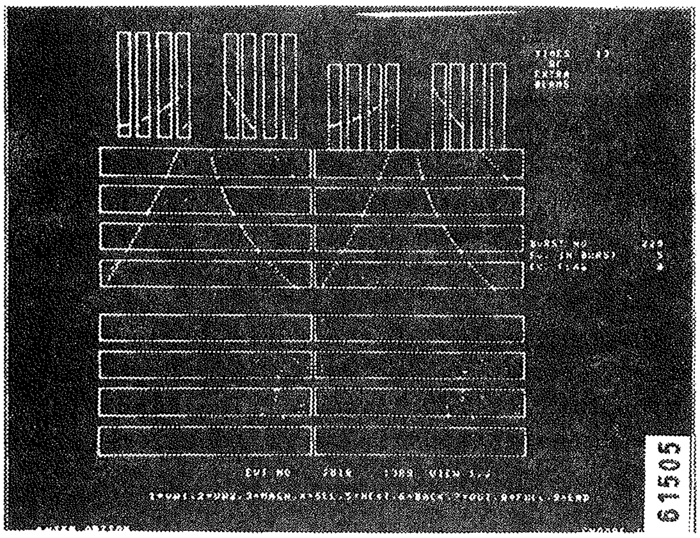

Figure 6

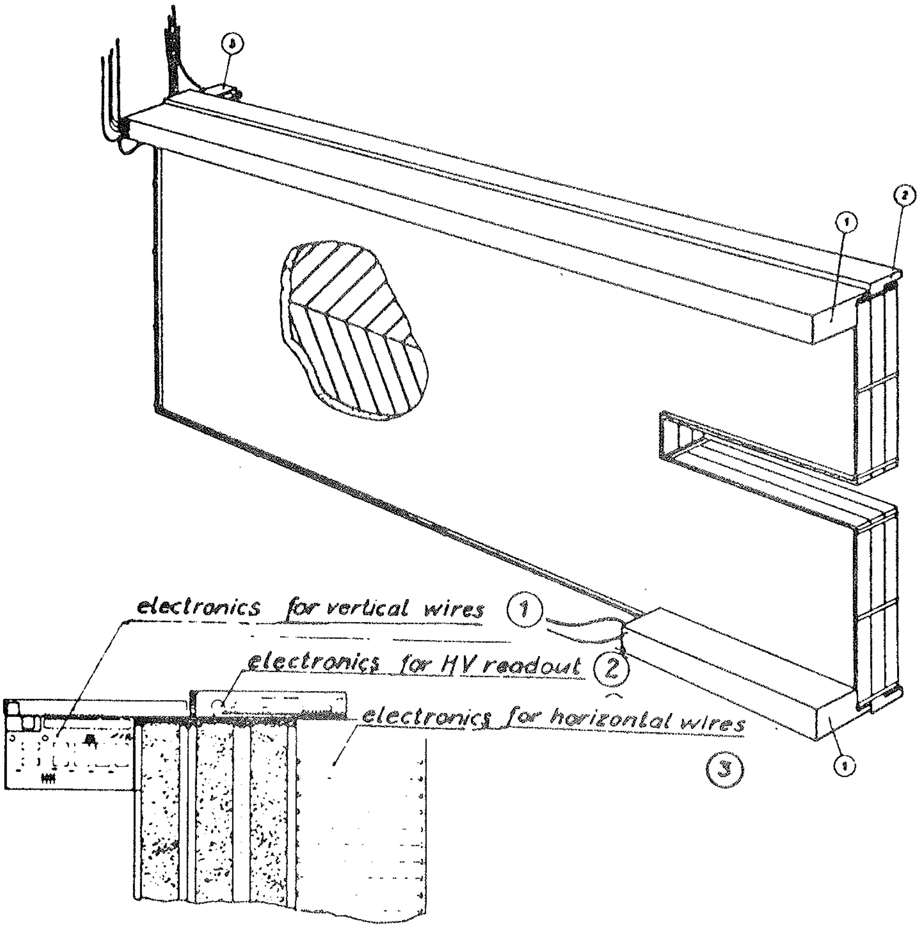

Figure 7

ambiguities.

The characteristics of the MWPC, for example, very short resolution time (can be as good as 25 nsec), very high repetition rates (practically no dead time), optimal multiparticle efficiency (each wire is an independent detector), no need for a separate triggering system, etc. make it very attractive for use with high intensity beams. The designers of the spectrometers for future SPS beams at CERN can now build their detectors with the help of two extremely powerful building blocks: the MWPC and the drift chamber, a device closely related to the MWPC but posessing two distinct advantages over it, namely a lower cost and a higher spacial accuracy. See G. Charpak[2] for a recent survey of detectors and a description of the drift chamber.

In the foreseeable future the trend should continue in the direction of higher data rates if the computer capacity necessary for the analysis is supplied. Obviously the operation of a large and complex device, producing data at Megabit/sec rates for a multi-user community, has to rely on a quite powerful and sophisticated computer support. In the following sections the computing requirements of large spectrometers will be analysed in some detail; possible solutions inspired by the available technologies will then be examined.

2. MAIN FUNCTIONS OF THE DATA HANDLING SYSTEM

The main purposed of any computer system supporting a spectrometer could be broadly subdivided as follows:

a) On-line data acquisition and collection.

b) Equipment monitoring and data quality control.

c) Facilities for setting-up and developing the experimental hardware and software and the computer system.

d) Data reduction and analysis.

This merely represents the list of computer-related headings one has to worry about when designing a large magnetic spectrometer. It has now become quite clear that these functions must be planned from the start as an integral part of the project. Clearly some of these functions are to be executed on-line, some may well be handled off-line; the borderline between the two is not unambiguously defined. R. Russell[3] has written a good account of the pioneering work done at CERN for the Omega and SFM projects. From his paper one also gets a fairly good idea of the lessons learnt and how they may affect the design of future systems.

Let us now examine the needs implied by the headings listed above. In reality the situation is not as clear cut as one may like it to be. There is no simple answer to the question "What is needed?". The use of computers in nuclear physics implies a non negligible amount of research and development. Computer specialists develop new systems intended to help to do better experiments. On the other hand, experimenters are usually conservative and tend to plan their experiments on the basis of what is available and proven. In this situation the established "needs" of today are often unwanted but eventually successful developments of yesterday, where successful contains an element of marketing perhaps as important as any technical considerations. In this context, words like "needs" and "requirements" have to be interpreted with care. When used in the following sections they normally mean: useful existing facilities plus those improvements thought to be feasible and highly desirable.

2.1 Acquisition and Collection of Experimental Data

A few years ago this was considered to be the only real justification for an on-line system. Although the list of requirements has been steadily expanding with the growing confidence in the computer as a partner on the experimental floor, data acquisition still stands out as the most fundamental task. It is imperative that the on-line system is able to read-out data from a variety of sources and store it safely onto magnetic tape. Typical examples of data sources are: hodoscopes, scintillation counters, digital voltmeters, ADC's, pattern units, scalers, beam monitoring devices, magnet currents and field measuring instruments, and the main detector's chamber.

The interfacing of this multiplicity of devices to the on-line computer system has been greatly simplified since the adoption of CAMAC, now widely accepted as an interface standard for nuclear and high energy physics instrumentation. The organisation of CAMAC modules and their impact on the data acquisition software has been clearly described by B. Zacharov[4].

Not all the information gathered by the computer needs to be stored on tape; in some cases it is sufficient to present a picture of the situation to the operator or to update the experiment's log, e.g. on a teletypewriter. Some of the data must be stored on tape with each set of event coordinates; some need only be recorded once per tape or once per run. In addition, the computer is quite often required to perform on the data such useful operations as normalization, conversion, packing and formatting.

Data rates may easily exceed the Megabit/sec mark. If the beam has a burst structure one can buffer the information produced during a burst, e.g. in the computer memory, and store it on tape during the relatively long time between bursts. One may thus arrive at average rates compatible with those of tape units of average performance. With beams obtained from DC machines, e.g. the ISR at CERN, the tape speed must match the average data acquisition rate. To give an example, the SFM with its MPWC detector consisting of 65,000 wires, has been running at rates in excess of 100,000 16 bit words of data per second, thus saturating a very fast tape drive (1600 bpi, 240 Kbytes/sec) and filling a tape reel in less than five minutes. This is admittedly a rather extreme case today, but is probably going to be less exceptional in the near future.

The standard medium for storing "raw" data is still magnetic tape. Attempts to substitute it with mass storage devices with very high capacity (10^{12}-10^{13} bits) have generally failed so far. At CERN, we are experimenting with video-tape techniques[5]; the intention is to record the 10^{11} bits typical of a large experiment in a single reel of tape. Magnetic tapes will continue for quite some time to be used as a standard medium for transferring large quantities of data from one computer to another. Operations with large numbers of reels have been a source of headaches for many experimenters. It is of primary importance that any computer system dedicated to a large spectrometer be well equipped, both technically and operationally, to handle large quantities of tape reels. For further reading on the subject of this section see H.E. Davies[6].

2.2 Supervisory Control

Given the scale and the complexity of the apparatus, the extent to which successful running conditions can be maintained over long periods depends largely on the supervision that can be exercised by the on-line computer system.

Various types of control may be envisaged; they cover a wide range of actions, from the monitoring of a particular instrument to the full analysis of event samples. For example, showing a picture of sampled events, is generally considered a very valuable help.

Systematic checks on experimental data are normal practice, their scope, however, may vary from one experiment to another. The complete reconstruction of a fraction of the events is regarded by many experimenters as one of the safest means of controlling the quality of the data. The opinions vary as to the amount of sampling necessary to control the operation of the experiments; also the depth of analysis required in each case and the delay that can be afforded to obtain such a feed-back depends on the experimental conditions and on the working style of the physicists.

When something goes wrong, troubleshooting must be done with the assistance of the computer. To find out rapidly where the problem lies, one requires a well organised set of tools, e.g. diagnostic programs, easy to use terminals, graphics facilities such as histogramming, plotting and other data presentations, easy access to data and program files and good man-machine communications through high-level command, control and programming languages.

In view of the intended general use of the spectrometer the computer system must be flexible enough to allow for user written programs of different sizes to be selectively executed, concurrently with the data acquisition tasks. More powerful computers than those normally available on-line and dedicated to the experimental facility may be needed to analyse sizable samples of the data during the runs. Nowadays it is quite natural to foresee the access to remotely located, shared computer capacity when designing an integrated data handling system for any on-line experiment.

Obviously, because of its essential role, any such data handling system must be dependable; very high standards of availability, reliability and maintainability are required to avoid frustration and chaos. As far as possible, the system should be alive; given that some piece of hardware will occasionally fail, one should plan for easy reconfiguration, graceful degradations, redundancies, etc.

2.3 Development Support Facilities

The preceding sections deal mainly with production runs. Before any such activity can be started, however, a considerable amount of time has to be devoted to the setting-up of the experimental hardware and software. One of the basic functions of the on-line system is to help commissioning complex apparatus. Because several such tests may be going on at the same time a high degree of independency and protection must be foreseen at the level of interface activities, e.g. group's private equipment, separate functional parts of the apparatus, etc. This suggests a decentralization of computer functions to minimize the interference.

Another very intense activity during the set-up phase and beyond is the preparation of users software. Around multi-user spectrometers, many experimenters may wish to do similar preparatory work concurrently. A comprehensive set of computer facilities should be available in the experiment's control room helping the developers to write, edit, compile programs for data acquisition and analysis. Utility functions in the area of magnetic tape handling and media conversion are much appreciated. It is quite common to see the variety of displays in control rooms; alphanumeric terminals with interactive program capabilities giving access to local and remotely located files are gradually replacing the slow and noisy teletype; graphic CRT displays are required to show event pictures in various projections, reconstructed trajectories, histograms or plots of any type.

It is unrealistic to plan for an undisturbed development phase. Development and production overlap throughout the life-time of the spectrometer. Detectors and data handling systems need adjustments, expansions and sometimes radical changes. The fundamental requirement is flexibility. In practice, it is translated into specifications such as modularity, expandability, well defined interfaces (between hardware and software modules), etc.

2.4 Data Processing

Analysis programs, such as Pattern Recognition, Event Reconstruction, Kinematics, Simulation, etc. are an essential complement of a general-purpose spectrometer. The design criteria should be very similar to those adopted for the set-up, i.e. usable by different experiments with a minimum of changes.

There is a very close relationship between the design of the detector and the analysis programs. They should be developed together and follow the lines of a common event identification strategy. A mismatch in this crucial area may result in a serious handicap for the utilization of the whole facility.

Descriptions of the most recent developments in this field may be found in H. Grote et al[7], D. Townsend et al[8], M. Hansroul et al[9], H. Wind[10], M. Metcalf et al [11], and P. Zanella[12].

3. Philosophy of Implementation

The facilities discussed above could be provided in a number of ways. A few years ago one would have attacked the problem by dedicating a stand-alone computer to the experimental set-up. The development of data links between computers has resulted in the appearance of small front-end machines taking over I/O tasks requiring a fast response or temporary buffering of the data and releaving the more powerful machine of the troublesome testing of special hardware interfaces. At the same time connections between on-line systems and large central machines have been introduced in many laboratories, making it easier to send some of the most demanding jobs to more powerful computers. The FOCUS system[13] at CERN is an example of a fast file transmission system of this type. Figure 8 shows the present FOCUS configuration.

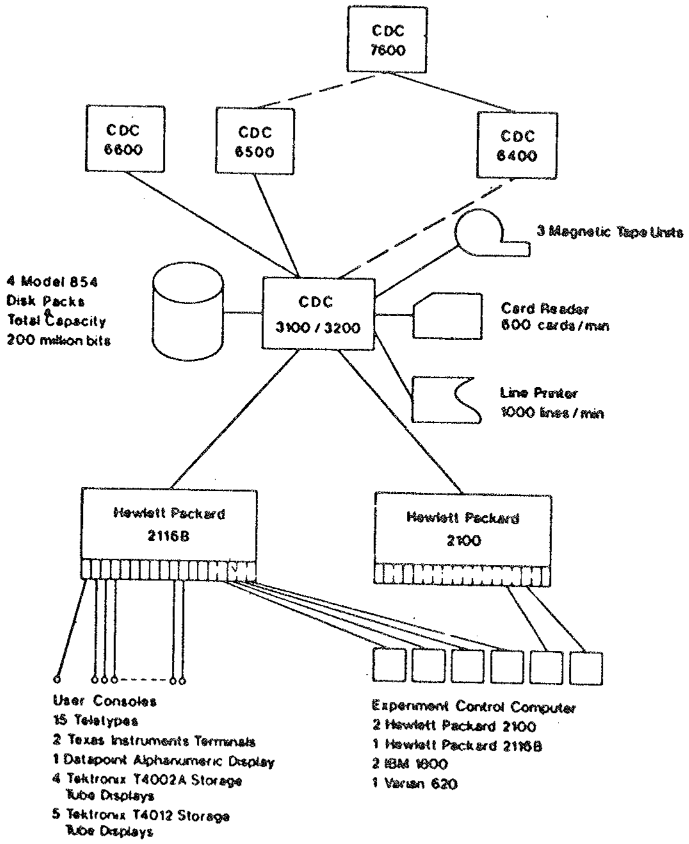

Figure 8

A concept is definitely emerging from many implementations, that of distributed computing functions. It is better to split-up the tasks amongst several machines rather than concentrating everything in a large multi-purpose computer. This approach is not unique to the spectrometer problem. People building control systems for complex apparatus, e.g. accelerators, are following the same line. See F. Beck lectures[14] presented at this school.

Several facts have led to this choice. Against concentration are the complexity and vulnerability of the operating systems required and the difficulties of connecting and debugging a variety of non-standard devices. On the side of multi-computer systems stand the rapid advances in three major areas of technology, namely:

i) the development of data communications

ii) the adoption of standard interfaces, e.g. CAMAC.

iii) the availability of powerful, reliable and inexpensive minicomputers.

3.1 Data Communications

One has learnt how to build reliable connections between computers. Complicated exchanges of signals, e.g. handshakes make sure that the information is properly transmitted and received. Hardware and software parity and checksum techniques control the integrity of the data received. Sophisticated transmission techniques and software allow for simultaneous bidirectional transmission and multiplexing of several lines into one computer. Transmission speeds matching those of standard tape units are obtainable at reasonable prices over short distances via twisted pair cables using serial bit transmission techniques. Very fast parallel links capable of several Megabit rates have also been built. The complexity of the communication software is also being mastered. Various laboratory-wide multi-computer systems have been developed in recent years, e.g. at Daresbury, DESY, SLAC, CERN, etc.

Communications between computers and people have also been vastly improved through the widespread use of terminals. Here, much slower transmission speeds are required. Voice grade lines of the type used in the telephone system have been used, at speeds up to a few thousand baud. The impact of these techniques is visible in the control room of any experiment. It is nowadays quite typical to see a multiplicity of terminals and data communication equipment surrounding some data acquisition computer.

It should be clear that the short-distance transfer of large quantities of information stored on tape from a computer to another is still more economically done by road transport. For long distances it is unthinkable to do it over telephone lines. Today data communication systems allow us to receive a much prompter feed-back on the floor than the bicycle-on-line type of service can offer. Practically without leaving the control room, one can safely communicate with on-site systems at speeds suiting human reactions while computers can exchange files of data at speeds quite compatible with other standard peripheral rates.

3.2 CAMAC

The interface between a computer and the external non-standard devices to be controlled has often been a source of difficulties. With large spectrometers the amount of equipment which need to be connected to the on-line system is inevitably quite large. Moreover, connections such as, for example, that to the read-out of the main detectors can be very complex. The home-made, ad-hoc interfaces can be very efficient in that they can be designed to match the specific characteristics of the I/O structure of the computer. Some problems arise in the area of flexibility: it may be very difficult to add or change equipment with such an interface. In a large laboratory the construction, installation and maintenance of a wide variety of special interfaces is also a source of problems.

Nowadays, CAMAC is becoming widely accepted as the standard way of interfacing. It has already proved its value as a practical system of great flexibility. Its main advantage is its independence from any particular computer. Devices can be tested using a computer, e.g. in a home institute, and then moved to another laboratory and used there in connection with a different computer system.

CAMAC modules can be added to interface new instruments with minimal changes to the data acquisition software. Physicists have now the freedom to make changes to their equipment without having to understand the I/O idiosyncrasies of the particular computer they are working with.

CAMAC is also being used to interface data communication links. The advantage is again the decoupling of the transmission problems from any particular computer. Many manufacturers now produce CAMAC modules. Minicomputers are sometimes delivered with CAMAC interfaces adapted to their I/O structures. Terminals, remote I/O stations, displays are quite often connected to their computers via CAMAC. The impact of this interfacing technique on the design of on-line data handling systems has been indeed quite noticeable

3.3 Minicomputers

The largest single factor in the trend towards distributed computing systems is the existence of minicomputers. These machines have an impressive list of qualities, e.g. low-price, high reliability, simplicity of installation, modular expansion, very flexible I/O schemes, etc. The minicomputer market is large and is constantly evolving. Memories are rapidly becoming larger and cheaper, thus influencing the design of data acquisition systems. Processors outperform some of the medium sized machines built only a few years ago. They are equipped with flexible interrupt systems. The I/O systems are well suited to the intense and fast data traffic typical of data acquisition, control and communications applications. Peripherals have been constantly improving over the last few years. Weaknesses have been associated with the basic software. However, several manufacturers are now beginning to deliver reasonable disc operating systems, time sharing software, interpreters, editors, compilers, file manager, debugging aids and libraries, etc.

However, program preparation can be a tedious task with mini's, except for those with the most generous configurations. However, one has learnt how to perform these tasks with the help of larger computers.

There is another area where mini's cannot compete with their big brothers, that is "number crunching". Minicomputers are not powerful enough to carry out sample computation in large spectrometer experiments. These functions are better assigned to much more powerful machines.

Mini's have been very successful when assigned to specialized tasks. Because of their limited number of functions, the operating software can be very simple. Also, because they are so cheap, the optimal CPU utilization is much less of an obsession.

3.4 An Example of a Multi-Computer System

The number of minicomputers associated with large magnetic spectrometers at CERN has been steadily growing. An example is given by the Omega data handling system shown in Figure 9, and

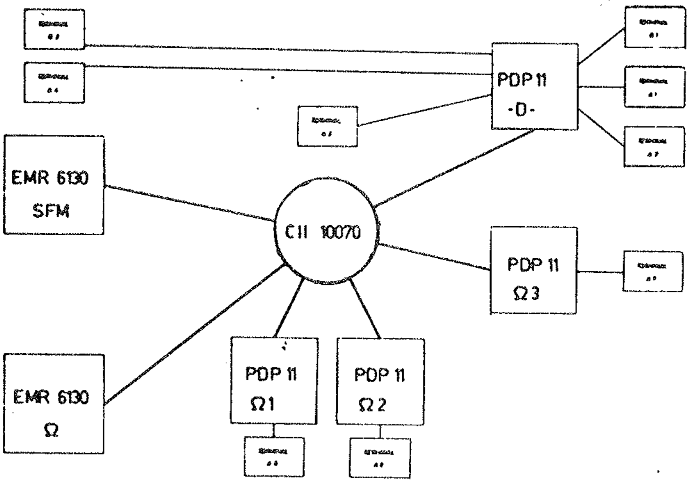

Figure 9

described by R. Russell[3] and H. Davies[6].

A major requirement of the experimental programme is that several groups be able to collect data simultaneously. The major components of the experimental apparatus, e.g. magnet, beam, spark chambers, plumbicon readout, data acquisition system are shared by the users, but one has to allow for a number of counters, scalers, CAMAC modules, etc. to be controlled by the individual groups, as they are part of their own triggering systems. In the end, a two-level multi-computer network has been implemented. The idea was to connect each set of experiment-dependent equipment to a first level of minimum-configuration mini-computers (PDP-11/20) and all common apparatus to a midi-computer (EMR 6130) and then to provide back-up capacity and facilities from a medium-sized machine (CII 10070).

It is worth noting that all the interactive graphics stations are managed through another first-level mini. A second EMR 6130 has been subsequently added to take care of the data acquisition for the Split Field Magnet Project. Incidentally, current plans envisage the addition of several mini's to the system. This is because of the future use of Omega, with SPS beams and the introduction of some parallelism in the SFM operations.

What's interesting about his system? Apart from the distributed computing solution which seems ideal for such a multi-user environment there are a number of features and approaches worth mentioning.

Firstly, which language should be used in the PDP-11's? To control non-standard I/O equipment FORTRAN is certainly not ideal; besides use of FORTRAN would require a more generous configuration. But, to bother the physicist with the details of an assembler also seems to be a bad idea. The solution was found by developing an intermediate language, PL-11 which is as "high level" as possible (looks very much like Algol) and at the same time makes available all the facilities of the hardware to the programmer. An efficient PL-11 compiler was written for the CII machine. This seems really a nice way of programming minicomputers for on-line control tasks.

A second very important question was how to provide the PDP-11 user with all those facilities necessary to load and execute his programs, manipulate his files, prepare and display histograms, etc. It was felt that the best solution would be to exploit all the sophisticated facilities offered by the advanced multiprogramming operating system in the CII 10070. Therefore the system was designed to regard the PDP-11's as remote I/O satellites of the CII. This makes it possible from the teletype of the on-line mini to manipulate and edit files on the CII disks, submit jobs to the CII and have the results at the PDP-11 terminal. Compiler, linkage-editor, loader for the PDP-11 programs are resident on the larger system. Thus one avoids the complications of communications between two operating systems, offers to the PDP-11 user the facilities of a large computer while keeping the small computer close to its minimum configuration.

Data rates of several Megabits/sec are expected from the Omega and SFM experiments. Normally, local collection of the data is envisaged via high-speed tape units (240 Kbytes/sec) connected to the EMR's. However, central collection at the CII is possible in the event of data rates exceeding the local storage capability.

During data acquisition, extensive calculations on sample events may take place on the CII, while the EMR may be checking the behaviour of the detector and the PDP that of the user's own equipment. There is a very sophisticated organisation of the dialogue between the various computers. The physicist can specify his real-time sample computations in a very simple and flexible manner through FORTRAN programs loaded on the EMR and CII machines and communicating with each other via the link. He can rely on a library of analysis programs developed as part of the system, e.g. Pattern Recognition, Geometry, Simulation, Histogramming, Graphic Packages, etc.

The fact that such a dedicated system can be easily tuned to the needs of a user community benefits both the user and the system. In this way the physicist can get the computer assistance he needs for his experiment and at the same time the system can be kept to a reasonable level of simplicity. In addition, the economical aspects should not be disregarded; jobs, tasks and peripheral equipment may be optimally distributed among the nodal machines; irregular demands, normally peaking during the runs, may be conveniently balanced by a variety of background activities, such as display work, program development and off-line analysis; the integration in the experimental environment brings in naturally a good measure of self-operation.

3.5 Alternative Schemes for Providing the Facilities

The Omega/SFM system may be regarded as an extreme solution in that it attempts to do as much as possible locally.

One medium-sized computer and several satellites are dedicated to two spectrometers. The system is not linked to the CERN central computers.

The experience gained with this particular system shows that although the CII machine is well equipped to perform such tasks as file handling, text editing, program preparation for all computers in the system, interactive graphics, tape copying and even data collection when necessary, its computing capacity is not large enough to carry out the heavy number crunching tasks required while the spectrometers are active.

The two obvious alternatives are: either increase the capacity of the dedicated computer system or transfer some of the tasks to the central computers. The extreme solution would then consist of a dedicated cluster of mini's directly backed-up by the central system. Against this scheme stands the fact that interactive work, file and text manipulations, etc. are often inefficiently done by large multiprogrammed computers. Moreover, complex operating systems do not like to be continuously interrupted by urgent requests.

The whole problem of the distribution of functions must be considered in the perspective of the laboratory-wide computer services. For example, in a laboratory as large as CERN, where several large experimental facilities and many counter experiments are grouped together in a few geographically separated areas, it makes sense to consider three broad levels of computing support, i.e.

i) on-line experiment or spectrometer facility level

ii) regional (experimental area) level

iii) central computers level.

The major functions could be roughly split as follows:

i) data acquisition, control of experiments, raw data storage on tape,

ii) programming and file handling support, loading of the mini's, job submittal to the centre, remote tape file staging, tape conversion, graphic facilities, etc.

iii) mainly batch processing.

The first level would mainly consist of minicomputers and the third of very large and powerful machines. The size and capacity of the regional work stations may vary from one area to another, depending on the facilities and the amount of computation required.

The cluster of mini's dedicated to a large spectrometer will probably tend to be internally structured. It will essentially contain two sub-levels: on the first a number of mini's either affected to a particular user group or monitoring some portion of the apparatus. On the second level, one or two larger mini's collecting the various data on tape and coordinating the linked system's work. Large, cheap memories will help to keep the speed of tape drives down. In such a scheme, the spectrometer's system would depend on the support of both the regional and central services. Economy of operations and convenience for the users may be optimized by a well balanced distribution of tasks and capacity to the three levels.

There will be connections between computers on-line to the spectrometer. The various levels will also be interconnected. This can be done in a number of ways. One extreme solution corresponds to a hierarchical tree structure: all the links from an experimental area go to a regional computer via a front-end concentrator and in turn all the links from the regional centres go to the central computer system through some other concentrator. Normally the information is communicated vertically through the hierarchical nodes.

A more flexible alternative consists of linking the computers between any two levels via a message transfer system. This type of connection can be made independent of the computers involved and essentially transparent to the users. The information flow can be vertical and horizontal through the linked system.

At CERN we are discussing at present possible ways of improving the data handling support to on-line experiments in general and to large spectrometer facilities in particular; the concepts emerging indicate an evolution towards linked minicomputer on-line systems supported by computer facilities conveniently distributed throughout the site and connected eventually to a general laboratory-wide network system.

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