The cyclotron and the computer: a look at the present and the future*

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ABSTRACT

This paper shows that current approaches to computer control are philosophically the same and that there is a second approach which the author hopes to see implemented in the future, since it offers advantages in both cost and flexibility. Some details of computer hardware and software are described because they are of importance to persons making long range decisions. At this time, without sophisticated systems of logging and analysis which future cyclotron control systems will have, it is not possible to forecast in detail the changes computer control will bring to beam quality; however, computer control will dictate more careful attention to the engineering details of beam defining and measuring devices.

1. FUNDAMENTAL CONTROL CRITERIA

Two basic and obvious principles have dictated all control systems whether computerised or not. (1) All important settings of cyclotron parameters must be available to the human operator at all times. (2) The operator must be able to alter those settings without introducing undesirable step changes.

These two criteria have been responsible for the complexities of current systems in which the computer is an appendage rather than an integral part of control systems. We cannot do away with these criteria, but we can alter the method of control to eliminate complexity and duplication of hardware.

2. GENERALISATION OF THREE BASIC CONCEPTS

It is important to note that initial setting up of an accelerator (before knob twiddling) is a digital process as far as the operator is concerned.

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For example, rf frequency is set to some *number* of Hertz; trim coil currents are set to some *number* of amperes, etc.

The human operator must know what the existing settings are, so he gathers this information through 'analog to digital converters', ADC's, if we generalise the term ADC to its broadest sense. In this sense a panel meter indicating a number of amperes is an ADC just as much as a digital voltmeter is.

The same generalisation applies to the 'digital to analog converter', DAC. Hence, we may refer to a console knob as a DAC. The human operator inputs a number of turns of the knob. The result of his action will be the setting of some analog quantity, for example, the mechanical aperture of a collimating slit.

To clear up any possible confusion about terminology—the words digital quantity refer to any numerical expression of some physical situation. Analog quantity refers to the physical situation itself. Although the origin of the word 'analog' would not imply this interpretation, it has historical reasons for its existence and, if we are going to talk computer language, it is best to stick with it.

The third concept is that of the multiplexor, MUX. In its broadest sense, it is a device which can route information from many sources to a single receiver or from a single source to many receivers. In this sense, the human operator is serving as a part time multiplexor when he reads first one panel meter and then another.

All setting up operations may be described in terms of these three concepts if we include the human as part of some of the control loops. Someone who holds down a toggle switch until he sees a given number on a digital display is himself part of a DAC.

3. THE CLASSICAL CYCLOTRON CONTROL SYSTEM

The generalisations made above allow us to describe the conventional control system by the diagram in Fig. 1.

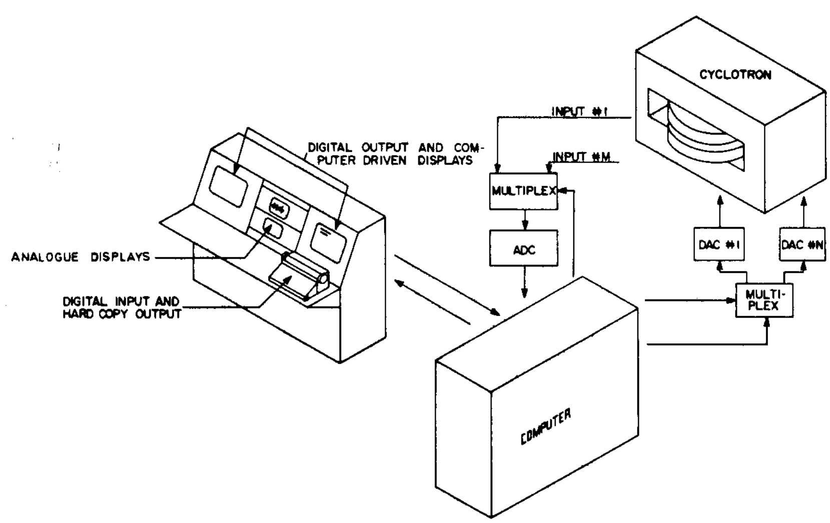

Fig. 1. Classical computer control

It is important to notice the duplication of equipment. Any single direct ADC is read very seldom on the average. Yet it and its associated hardware must be paid for in installation costs.

It is also important to note that the human is performing a task which is trivial for electronic equipment but to which he is not well suited. He is working as a multiplexor, a very bad multiplexor. He is slow; sometimes he turns the wrong knob; sometimes he forgets a set-point altogether. Who would want to buy a human multiplexor when it has these specifications?

I think we are all agreed that it would be wiser to let computer hardware take care of the trivia and leave the human to perform as decision-maker and analyst, a role in which he has at least a statistical chance of doing some good.

4. PRESENT CONCEPTS OF COMPUTER CONTROL

The preceding remarks have gone through many people's minds with the result that there has been much talk about computer control but, to my knowledge, very little implementation.

Berkeley[1] introduced computer controlled set-pointing on the 88 in and MSU has implemented set-pointing and data gathering via their computer-beam probe collaboration (this is not to say that MSU has any intentions of standing still at its present level of accomplishment). The Maryland Cyclotron envisages computer control[2] and the SIN group in Zurich has been making studies.[3] All of these systems are essentially the same in basic philosophy. They consider the computer as an appendage to the control system. They do not see it as an integral part. Fig. 2 illustrates the current philosophy.

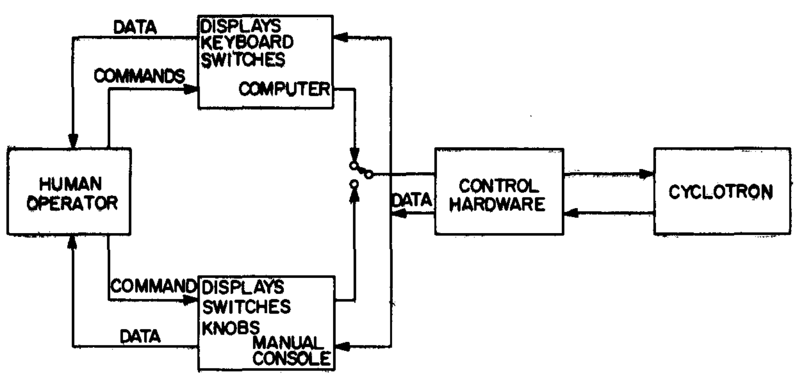

Fig. 2. Current concept of computer control

Fig. 2 is not the simple structure it appears to be, because the box labelled Manual Console is in fact a duplication of the complicated structure of Fig. 1. Fig. 3 shows the same system as Fig. 2 with sufficient detail added to allow us to look at the inefficiencies of current systems.

Now we come back to the two basic criteria mentioned earlier. The operator must have all settings available to him and must be able to intervene to change them. There have been two approaches to this problem, both within the context of the computer appendage. LRL, Berkeley and MSU have used helipots driven by motors to perform as both DAC's and set-point indicators. The proposals of Maryland and the SIN group use digital switches on the manual console exchangeable with digital output from the computer to set electronic DAC's which perform as references for various devices. In the Maryland-SIN system, another path must be provided to inform the human operator of any current set point.

This approach invokes considerable duplication of hardware. If one has plans for beam optimisation, the same information which is supplied to the

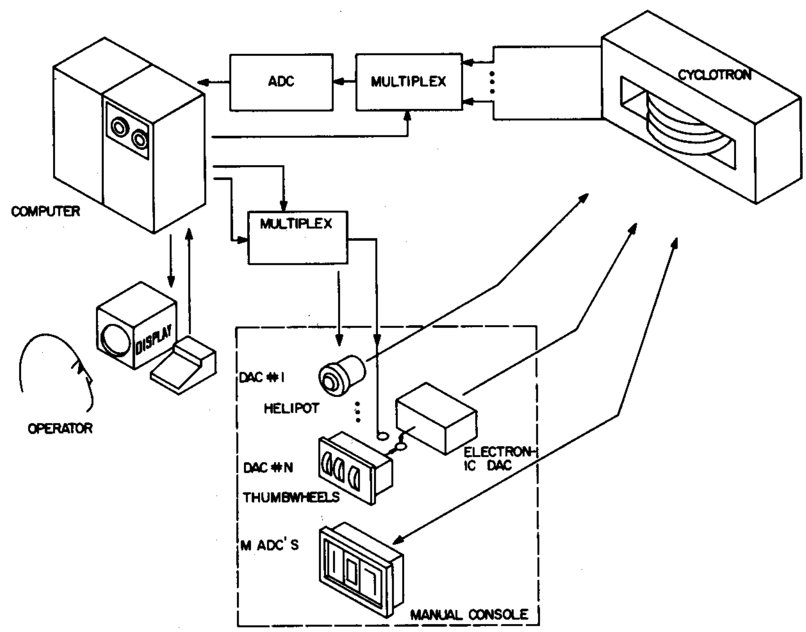

Fig. 3. Complexities of current computer control

human must be supplied to the computer, but via a second path. The human–computer interface implies some communications device, at its simplest level a teletype or electric typewriter. But, if the computer is able to keep tabs on everything, why not let it report information through its own link to the human? Why supply a second information reporting path? Further, the information reporting system on the manual console uses a large number of ADC's whereas the computer can get by with one or two. This extra equipment is outlined with the dashed line you see in Fig. 3.

5. A NEW APPROACH TO COMPUTER CONTROL OF CYCLOTRONS

The approach I am going to present is not new in itself; it is only new to cyclotrons. The idea is to eliminate the manual console altogether and take all communications through the computer. This is illustrated in block diagram form

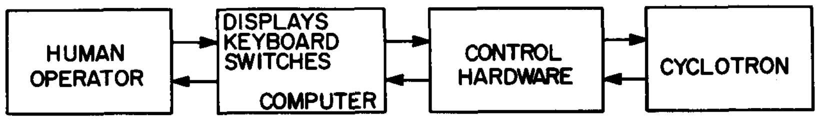

Fig. 4. Simplified control concept

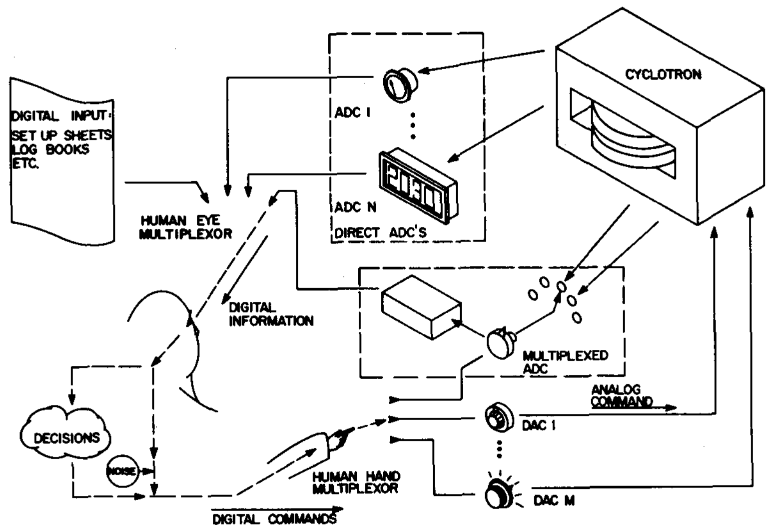

Fig. 5. Some details of simplified control concept

in Fig. 4 and in some greater detail in Fig. 5. Note that this approach implies no more DAC's than the totally computerised control system and has reduced ADC's to one.

The Los Alamos LINAC group has done considerable investigation of this control method.[4,5,6] Butler reports[4] that a study by EG & G indicates that the fully computerised system with no manual console costs the same to construct as a manual console system without computer. This study was a quantitative measurement of points we have just discussed qualitatively.

6. SOME DETAILS

(A) If the computer is to have full control and is to be able to handle abnormal situations:

(1) Interlock status of each controllable device must be available to the computer.

(2) The computer must be able to turn devices on and off.

(B) There are always special devices which deliver many data words at a time, for example a beam probe or a beam scanning wire. The interface to such devices should be constructed so that they can 'take care of themselves'. In other words, the soft-ware should be able to request a block of data from the device without having to supervise the collection of that data. If this policy is not followed, the computer will be wasting valuable computing time on a trivial operation. The MSU implementation will be discussed below as an example.

7. TYPES OF COMPUTER

(A) A complete cyclotron laboratory requires the following computer services:

(1) Processing of codes of the type most installations take to a computing centre, e.g. DWBA codes for the experimenters and orbit codes for the machine development people.

(2) Real-time data collection. At MSU we have demonstrated that the computer is a more useful and flexible tool for data collection than specialised devices like hardwired multichannel analysers.

(3) Real-time data analysis. The experimenter should be able to determine if he is getting reasonable data during the course of his experiment.

(4) Off-line data analysis. The experimenter should be able to make detailed analyses of previously recorded data.

(5) Control of the cyclotron and the experiments.

I mention all of these computer uses because they enter into decision making when one is planning a laboratory. It is reasonable to ask, 'Should I do all of these jobs with one computer or should I use more than one?'

At the present time, the multi-machine approach has many advantages because of the recent strides which have been made in process control. Several vendors[7,8,9] offer monitors and compilers which allow process control software to be written in a high level language. These are supplied for process control machines. The vendors of big machines capable of multi-programming and time-sharing are not yet to my knowledge offering such a software package. Michigan State was able to use the single computer approach only because a number of clever graduate students were available to conceive and to implement our own systems software[10,11] but most people I believe would hesitate to attempt third generation systems software without the support of a very sophisticated staff of programmers.

8. WHAT WILL THE COMPUTER DO FOR US?

(A) Once the hardware and software for cyclotron data collection and set-pointing are available, closed-loop control will no longer be a wild dream. At MSU, for example, a simple call from FORTRAN will initiate the measurement of two beam traces using the differential beam probe. The data so acquired will be analysed and produce corrections for five cyclotron parameters, main field, dee voltage, beam phase, x centring, y centring.[12] At present, insufficient set-pointing hardware is available to completely bypass the human operator in making the corrections to the settings; however, it is only a matter of time before that will be available.

(B) With the computer at hand, gathering and processing of information can be speeded up to the point that analyses previously too time-consuming to be worthwhile will become routine. Again, I refer to our experience with the beam probe as an example of this.

(C) Data logging and monitoring will provide a useful tool for trouble shooting and machine improvement. At present, only the well trained operator can quickly pinpoint what malfunction is causing beam troubles. The ever watchful computer will be able to spot drifts in equipment immediately and report this. If the drifts are not due to a major malfunction, the computer will be able to correct for them.

(D) I firmly believe the computer will mean faster machine improvement from initial startup, more extensive investigations of machine behaviour resulting in better machines, faster trouble shooting and faster setting up resulting in more useful beam time.

9. BRIEF DESCRIPTION OF THE MSU SYSTEM

At the present time, the analog input path and the analog output paths have been implemented.

The differential beam probe is using the analog input in a manner very similar to the Karlsruhe hardware.[13] The probe is mounted on a lead screw driven by a stepping motor. The data sampling is synchronised to the stepping motor.

The analog output path has been coupled to the trim coils through motorised helipots. Most of the hardware has been installed to extend the analog output to control of the rf set-pointing and the internal beam-slit set-pointing.

At present we can take a beam trace by executing the FORTRAN statement 'CALL PROBE (NERROR)'. NERROR is a flag used to indicate whether or not meaningful data has been returned. Data is retrieved by a function subroutine call to NPASS1(I) or NPASS2(I), which yield the Ith datum in the first or second pass respectively. When CALL PROBE is executed, the probe will move from outer radius to inner radius and back again. Data is taken on both passes. Data transfer is handled by two interrupt routines thereby allowing the computer to do other work concurrent with gathering data from the probe. The above-mentioned calls will retrieve data collected and stored by the interrupt routines.

To the FORTRAN programmer, setting a trim coil simply requires the statement CALL POTSET (NPOT, VALUE). NPOT identifies which potentiometer is to be set and VALUE indicates the desired setting.

A FORTRAN program called CYCSET (CYClotron SETup) generates set-up sheets for each desired energy and makes calls to set-point where hardware has been implemented. In the event a hardware failure has occurred, the library routine POTSET, described above, will generate an error message which is printed on the set-up sheet, thus calling the operator's attention to a malfunction.

It should be pointed out, to the credit of our graduate student programmers,[10,11] that the above described cyclotron-computer interrelationships are time-shared with other jobs.

Further work in progress will enable automatic control of our new scattering chamber. The experimenter will be able to request either set-pointing or end-of-run data on the four parameters of the scattering chamber.

At present, the experimenter, with four on-line ADC's at his disposal can communicate with the computer via his own teletype and CRT display. This same teletype will give him control of the scattering chamber.

10. CONCLUSIONS

The author feels that the time has come to throw away our conservatism and jump into the type of control system proposed in Section 5. Since initial costs should be comparable to those of a system with no computer, and since the proposed system offers ease in collecting large quantities of data, automatic monitoring, and all necessary hardware for closed loop optimisation, wherever studies show this to be possible, one can see the proposed system offers a lot more for the same price as the cost of a classical control system.

Those groups who do not yet have any control hardware are in the enviable position of being able to implement third generation cyclotron control. First generation control was straightforward and practical. Second generation with the appended computer has been rewarding but not spectacular. Now it is time to take full advantage of the technology which has been racing forward during the last ten years.

DISCUSSION

Speaker addressed: R. A. de Forest (M.S.U.)

Question by N. Hazewindus (Philips): A computer can be used in two ways: firstly one may supply a 'library' of settings calculated by a big computer, secondly one may ask the computer also to calculate these settings for a given output.

Which system do you favour, in view of your recommendation of the use of a small process control computer?

Answer: We use table lookup wherever possible; however, many cyclotron parameters are calculated, which gives the flexibility of a system which can adapt rapidly to any changes in the machine as it is improved. I neglected to mention, when I talked about a process control computer, that it would have to be connected to a large machine for complex calculations.

You need the large machine in any case for other types of complex calculations so we are still talking about the same amount of hardware.

Question by E. G. Auld (U.B.C.): During the commissioning of a new cyclotron does not a second generation control system have to be available to the operators before a third generation system can be developed? It requires direct control between operator and cyclotron to initially determine the interaction between various operation parameters.

Answer: No, I do not agree. During initial start up of the machine, we do not ask that the computer execute closed loop control. It must simply execute orders. For example, you tell the computer set trim coil X to Y amperes, and the order is executed. With such a system installed, the step to closed loop control comes without addition of any new hardware. All that need be added is additional knowledge of machine behaviour.

I should point out, however, that the software effort to implement the chain of command, e.g. human operator to computer–computer to trim coils, should be completed before machine start up is desired.

Question by E. G. Michaelis (CERN): What does the present MSU CYCSET programme do that could not equally well be done by a sheet of handwritten data given to the operator?
Answer: Quite a bit, aside from the fact that one would not want to re-do the job by hand each time a machine improvement is made, CYCSET can make calls to assembly language routines which set the automated helipots.

Comment by K. J. Howard (A.E.R.E.): One aspect of computer control not sufficiently stressed is the opportunity it gives for a complete redesign of the whole cyclotron control system. Essentially, for communication with a computer, one needs one wire per bit of the computer word, and so all control instructions from and information fed to the computer can be carried on 12, 18, or 24 cores depending on the word length. Separating instructions or control wiring from information or data wires, except where they enter the computer, may be desirable but the total number of cores needed is still very small.
If instructions are decoded at the individual controlled devices, then a single cable arranged as a ring around the machine with 'tees' at each device to be controlled, or in which information is generated, is sufficient for all machine control. The many interlocks which are always needed on a cyclotron can be arranged in parallel groups to look like computer words, and connected to the information ring. Extension of such a control system to include new devices involves only the adding of another 'tee' into the control and information cores and provision in the computer software for the extra facilities.

Question by K. V. Ettinger (Birmingham): When you control the cyclotron by a computer, what is the required capacity, say in bits per second? Is it possible to use the same computer for 'on-line' control of the machine and similar control of experiments? How many interrupt priority levels are necessary?
Answer: If you want to control only the cyclotron the Input/Output data rate need not be impressive by today's standards. If you want to take experimental data, the data rate of the experiments will dictate how far you must try to push your I/O structure. As I mentioned, we are doing everything with our machine. We are storing experimental data in the same machine which we use for cyclotron control. At present, the data taking uses four interrupts, the cyclotron uses two.

Comment by K. J. Howard (A.E.R.E.): On the Harwell V.E.C. we could monitor and compare to limits one hundred parameters five times a second and still have half of the computer capacity available for control of the cyclotron.

Question by G. Schatz (Karlsruhe): Do you use the differential beam probe scans taken by the computer to control the machine settings?
Answer: Not directly, the probe scans are analysed to produce corrections for five cyclotron parameters which appear on printed output. We do not yet have the necessary hardware to close the loop completely.

Comment by H. G. Blosser (M.S.U.): Our trim coil calculations and field measurements are of sufficient quality that such corrections are never necessary. I should also note that in any non-linear fitting problem the computing time increases rather exponentially as the number of variables is increased.
It is therefore important to use no more variables than necessary. We believe the five which we have selected (B, V, ϕ_o, x_c, y_c) will be adequate in nearly every case.

REFERENCES

1. Struthers, D. R., 'Automatic Control of the Trim-coil Power Supplies at the Berkeley 88 in Cyclotron', *I.E.E.E. Trans. Nucl. Sci.* **NS-14, 3,** 1044.
2. Etter, J., Jenkins, K., and Nelson, D., 'Computer Control of the Maryland Cyclotron', Particle Accelerator Conference, Shoreham Hotel, Washington, D.C., March 1969, *I.E.E.E. Trans. Nucl. Sci.* **NS-16, 3,** 873.
3. Besse, L., Einige Grundgedanken zum SIN-Kontrollsystem, SIN, Zurich, Internal Report TM 13-03.
4. Butler, H. S., 'Computer Control of the Los Alamos Linear Accelerator', National Particle Accelerator Conference, Washington, D.C., 1967.
5. Butler, H. S., Gore, R. A., and VanBuren, D. T., 'Computer Control of a Linear Accelerator', IFAC-IFIP Symposium, Toronto, 1968.
6. Machen, D. R., Gore, R. A., and Weber, D. W., 'A Compact Data Acquisition and Control Terminal for Particle Accelerators', *I.E.E.E. Trans. Nucl. Sci.* **NS-16, 3,** 883 (1969).
7. Control Data 1700, Autran-PIA.
8. Honeywell DDP-516, OLERT.
9. IBM 1800, PROSPRO.
10. Kopf, J. O. and Plauger, P. J., 'Janus: A Flexible Approach to Realtime Time Sharing', Fall Joint Computer Conference (1968).
11. Au, R. and Merritt, W., Michigan State University Time Sharing, unpublished presentation at Scientific Data Systems Users Group Meeting, Boston, May 1969.
12. Blosser, H. G., Private communication.
13. Loesel, M. D., Schatz, G., and Schweickert, H., 'Control of Betatron Oscillations in a Cyclotron by Use of an On-line Computer', documentation obtained directly from Karlsruhe.