A REVIEW OF DEVELOPMENTS ON THE IUCF CYCLOTRON CONTROL SYSTEM[*]

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Abstract. The continued expansion of IUCF has been accompanied by an expanding control system. New vacuum control systems include automated features, e.g., foreline recovery cycling for the 35" main stage diffusion pump and microprocessor-governed fully-automated pumpdown for the 162 cm scattering chamber. The operator consoles have been give expanded 'touch-panel' page-selector switches and CAMAC driven alphanumeric strips showing analog meter characteristics. The neutron TOF facility has a computer-controlled Gray Code target ladder. New floating-output DAC modules using DC/DC converters have been developed, at a fraction of the cost of commercial units. Multiplexed floating-input ADCs (with common mode voltages above 2000V) are under development. To facilitate load and polarity switching, mechanical switches have been replaced by SCRs controlled via computer. The main magnet current and voltage are monitored by a hardware/software interlock circuit designed to shut down the power in the event of a ground fault. A number of beam steering loops are now closed through the computer and a program is used to oversee all the particle/energy change procedures which are computer controllable. The implementation of a CAMAC based LINK joining all four IUCF computers gives the experimenter access to and limited control of variables in the control computer.

The continued expansion of IUCF and the desire for more automated control features has led to the search for, selection of, and purchase of a replacement control computer.

1. Introduction. -The Indiana University Cyclotron Facility has been in operation since 1975 and its operational characteristics have been previously reported.[1] Likewise, the basic control system, largely designed about 10 years ago, has been described elsewhere[2] and will be reviewed here only very briefly. The schematic layout of the system is shown in Figure 1. The hub of the system is a Xerox Data Systems Sigma-2 computer which uses an extension of one of its internal buses (DIO) to communicate with six multiplexing units. These units access ADCs, DACs, stepping motor controllers and signal conditioners, most of which are contained on in-house designed printed circuit boards in Xerox-style wire-wrap bins.

We intend here to review recent developments in the control system and related areas to illustrate evolutionary trends in a computer-based system.

2. Cyclotron Operator Station. The interface to the human operator consists of three identical stations, each having a color TV monitor, a trackball-driven cursor, a set of program selection buttons, a set of thumbwheel switches, two knobs, two levers, two analog meters, two alphanumeric display strips and three special function buttons (Figure 1). The cyclotron operator's console TV display is little changed from its original form. Two significant technical improvements have been made, however, in other parts of the operator station. The program selection pushbuttons have been replaced by touch panel (membrane) arrays (Centralab "Monopanel") and covered by a plastic mask which guides the finger to the active switch area. Flanking rows of LEDs indicate the current button selection and a Sonalert supplies audio feedback when any switch closure is detected. To cover anticipated laboratory expansion, the button array size was increased from 2 by 8 to 2 by 10. It should be pointed out that, while this is a great mechanical improvement (old switches stuck, broke and collected Coca-Cola), pecularities in the contact bounce of these new switches gave us more trouble than expected. We finally resorted to the straight-forward if inelegant solution of using one-shots to ensure accurate input to the computer.

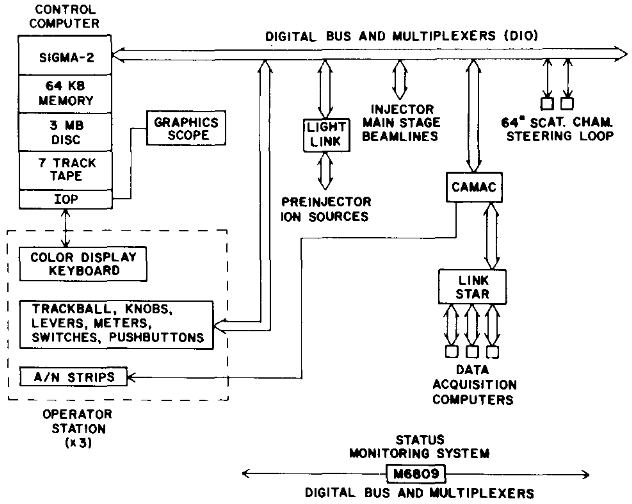

Fig. 1. A schematic view of the existing control system.

CAMAC driven alphanumeric display strips have replaced the old strips used to display the appropriate name, unit and scale factor for each analog meter when that meter is in use. The old strips never functioned well in the console environment; remaining working units

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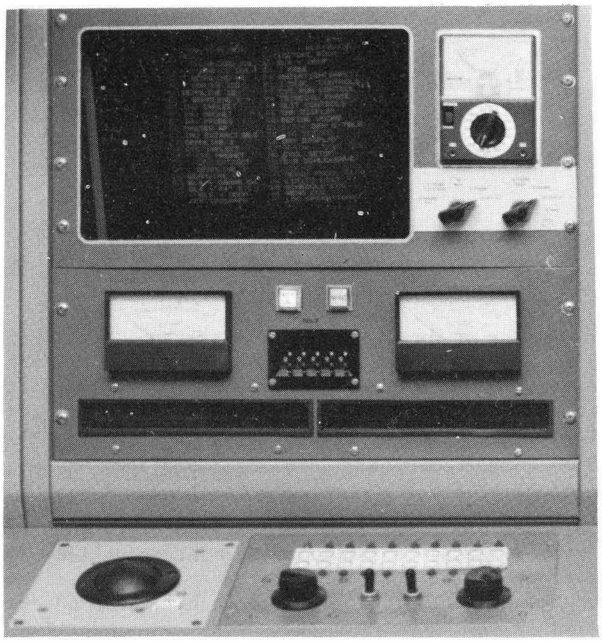

Fig. 2. One of three identical cyclotron operator stations.

are being incorporated into various microprocessor systems in quieter surroundings.[3] The new system uses fluorescent displays, (manufactured by Chemetrics, model DE/240), driven by an 8085A microprocessor based controller located in a single-width CAMAC module. The controller provides an internal buffer memory for each display device and is capable of handling a maximum of sixteen devices at distances up to several hundred feet. The controller provides for proper device selection, partial message blinking, EBCDIC-ASCII conversion and interrupt handling without any host computer intervention.

Detailed elsewhere in this conference is our radiation safety system.[3] Designed to prevent accidental exposure of personnel to radiation in the cyclotron vaults or experimental areas, this high threshold logic system shares control of certain crucial beam stops with the computer. A status and control panel is mounted on the operator's console with a more detailed display in the racks behind the console.

3. Controls Hardware - Component Level. -Many of our power supplies require 'floating' DAC control voltages which are not referenced to ground. Previously we had used expensive modular linear regulator power supplies to generate the isolated DAC operating voltages; this resulted in a bulky package housed in a NIM module containing one DAC and one ADC. The advent of small, inexpensive DC/DC converters (Semiconductor Circuits Inc. #UR332252, $38, #UD5 SS220, $25) made possible a single card 12-bit floating DAC (see Figure 3). We can accomodate 15 of these in one of our standard 5 1/4" wire-wrap bins, along with address decoding and data latching circuitry.

Of course, if floating DACs are necessary, one would expect to need floating readouts also. High quality ADCs are expensive, so multiplexing seemed desirable. Low common mode voltage ratings ruled out solid state analog multiplexing schemes: a ground fault or two would destroy the circuit. Flying capacitor relay multiplexing was expensive and slow. A magnetically coupled analog isolation amplifier module (Analog Devices #289K, $59) with excellent specifications (0.01% drift) solved the problem. The floating end is connected to the power supply readout; the grounded end to a standard multiplexed ADC chassis. This system provides 16 inputs, each isolated to 2500 volts from ground.

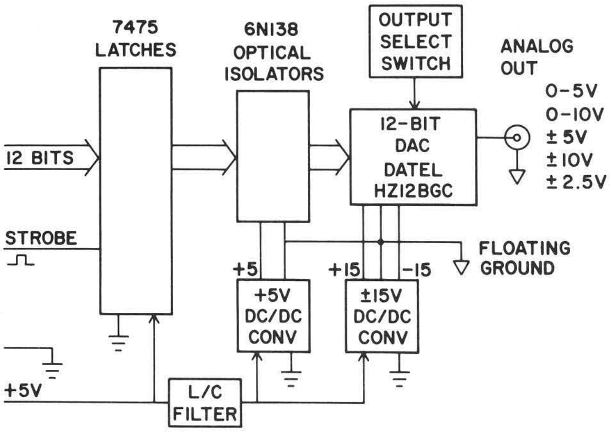

Fig. 3. Schematic diagram of the 12-bit floating DAC card.

One major component of the overhead involved in particle/energy changes is operator time spent walking through the building changing manual load selection and polarity switches. We are now installing computer controlled switching, facilitated by the use of high current SCRs. Approximately 1.5 to 2 volts is dropped across each device in the conduction mode and has to be accounted for when used with power supplies having marginal compliance voltage. Triggering of the SCRs is commanded via a logic output from the computer to a relay that is hardwire interlocked to the power supply's main contactor so that switching is performed under zero current conditions. The use of SCR's as compared to mechanical switches has proven to be very reliable and mandatory when dealing with currents in excess of 200A from both a cost and procurement point of view.

4. Controls Hardware-System Level. For its vacuum systems, IUCF has always had elaborate TTL logic controls and interlocks which have reliably protected pumps and components from vacuum accidents and misuse. Provision for computer readout of pump and valve status has been built into every system, although not generally implemented. One recent innovation is automatic switchover from slow to fast roughing to protect targets in vacuum. Another protects the oil in our main stage 35" diffusion pumps: following a vacuum accident, all valves close and the diffusion pumps turn off, then the DPs are automatically pumped down again.

The large amount of power (1200A at 300V) used to energize the main cyclotron magnet poses a threat we choose not to ignore. A ground fault, for instance, could yield truly disastrous results. Consequently we have six diagnostic readouts available in the computer to monitor voltage and current distribution in the four coils. Illicit conditions can trigger a software shutdown of the main power supply. Independently, a hardware window comparator circuit will immediately turn off the supply in the event of a serious current imbalance in the coils.

The neutron time of flight facility has been fitted with a ten-foil target ladder which was developed by

C.Goodman at ORNL. Four microswitches output Gray code for glitch-free determination of position; this code is converted into BCD and compared via hardwired logic to the desired position (selected locally or via computer). The logic then drives the Geneva mechanism in the appropriate direction via an AC synchronous motor.

As mentioned above and detailed elsewhere at this conference[4], we are utilizing microprocessor-based systems in situations where decision making and/or data processing are required and use of the central computer is impractical or undesirable. Three such systems are fully operational: a general status (fault reporting) system and arm controls and vacuum controls for the 162 cm scattering chamber. A fourth system, a prototype beam steering system has just been installed and is undergoing evaluation. We are quite pleased with the versatility and reliability of these systems. Since we have built these systems from in-house designed cards which fit in the normal wire-wrap bins, we can install μP systems anywhere in the control system.

5. Controls Hardware-Reliability. As projects age, reliability of components becomes of increasing importance: operators expect fewer problems and 2 AM call-ins for breakdowns are more irritating as time goes on. Although we do not claim a perfect record, we have been extremely pleased with the low failure rate in the control system. We are averaging about 1 board replacement per month in a system of 2000 boards.

Stability of better than .001% for an 8 hour period is achieved for both the injector and main magnet linear regulator type power supplies (2100A @ 40V and 1200A at 300V, respectively) via precision temperature compensated voltage references and water cooled resistive shunts. The use of Analogic model MP1916TC 16 bit D/A converters with a combined temperature coefficient of 1 ppm/°C has a proven reliability record at IUCF over the last 3 years. The injector power supply employs a 2.5 mΩ water cooled resistor constructed of Evanohm resistive material that dissipates 10kW and is connected in series with the load to sense the output current and transform it into a voltage feedback signal. A similar type of shunt is used to control the main magnet supply.

The two preinjector terminals at IUCF employ 1MV and 620kV power supplies of the RF shunt fed cascade multiplier type manufactured by High Voltage Engineering-Delta Ray division. The 50 kHz power oscillator and controls have proven to be very reliable and the initial problems with the 50kV multipliers have largely been overcome. However, the internal resistor-capacitor divider used to provide a 100μA maximum feedback signal has been a constant source of trouble. These power supplies are required to be stable within .01 to .03% and anomalous failures of the epoxy molded resistor-capacitor assembles (most likely caused by terminal spark down) have prevented our achieving the required stability. The purchase of a more robust RC divider mounted external to the power supply should solve this problem.

Our experience with glass fiber optic data transmission links between ground and the high voltage preinjector terminals has been another reliability sore point. The major problem areas have been LED emitter degradation, transient damage to receiver modules and transmission cable degradation due to X-rays. Upgrading of the system has involved the use of higher efficiency LEDs (requiring less drive current), single fiber cable with thicker cladding, and improved layout and use of transient suppressor devices for the receivers.

6. Controls Software - Data Base Level. -Power supply load and polarity switching has been added to the device data base and the operator's TV display in such a way that, in the future, any device may be given one or the other kind of switch. To switch loads or polarity, the operator uses the cursor to select the affected device and two control verbs on a standard TV display. The display responds with an angle bracket (<) on the device line for a successful load switch, the appearance or disappearance of a minus sign (-) from the ADC readout value for a successful polarity switch or a question mark (?) for an illegal or unsuccessful change command. During particle/energy changes, all load switching is done by the program which restores DAC values from a previous run. Polarity switching is also performed for cyclotron and beamline components, but not experimental devices such as the QQSP magnet. We are replacing bipolar supplies (e.g., on injector trimcoils) with unipolar supplies and polarity switches, but only on devices which do not normally require tuning by the operator after being set by the computer. Switching is not done automatically if the operator attempts to drive a supply through zero from one polarity to the other.

7. Controls Software - Program Level. -To even out the computer load during particle/energy changes, a program was written to sequence the SEEK programs used to cycle magnets through fixed hysteresis loops or to control slow device movements such as RF frequency or beam current probes. Thus, with two button entries (two as a safety device), the operator can position the injector inflection elements, the injector magnet, the injector current probe, the momentum analysis magnet in beamline 2, the main stage magnet, the main stage current probe, the momentum analysis magnet in beamline 3 and the RF frequency.

Beam steering loops have been closed through the control computer in a number of areas. Physically, their installation has been limited to locations wherein a beam sensor already existed and their repetition rate has been kept artifically low to minimize computer loading. At present these sensors are either split (left-right), insulated Faraday cups immediately downstream from a target station or slit jaws or active collimators which constantly intercept beam in normal operation. Given our long response times, the last requirement ensures smooth, "continuous" corrections; tests under other conditions resulted in unacceptably uneven motions of the beam as current was found on one slit jaw or other other. The loop algorithms themselves have been kept extremely simple and of the form

$$\text{correction} = \text{constant} \times (I_2 - I_1)/(I_2 + I_1)$$

where I_1 and I_2 are beam currents (right and left, down and up). The resulting correction rate is slow enough that the beam may be observed "drifting" about the desired position, but fast enough to yield marked improvement in experimental measurements which are sensitive to beam position. All loops may be turned on or off by the operator. When on, the loop programs prohibit operator control of the dependent variable (steering magnet) and issue no correction when the denominator above is less than a threshold value to prevent runaway when beam is turned off. In principle, the loops can maintain any desired imbalance between sensor currents; in practice, only the balanced ($I_1 = I_2$) condition is used.

The advent of polarized ion beams at IUCF brought a strong desire for communication among the data acquisition and control computers. In response, a long comtemplated CAMAC-based network named LINKER involving all IUCF mini-computers (3 Harris S110s and the Sigma-2)

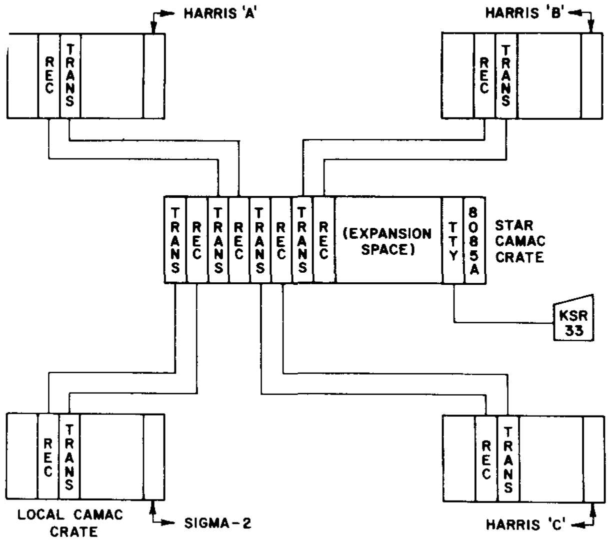

Fig. 4. Schematic view of the CAMAC based LINKER communication system.

was implemented. CAMAC was chosen because all present and future IUCF computers could be guaranteed to have a CAMAC interface and at least one crate. Since only medium speed transmission (~42 k baud in practice) was envisioned, a "Star" topology (see Figure 4) offered minimum hardware investment and satisfactory thruput. The communications protocol uses both hardware and software handshakes; system reliability has been such that, while the protocol has provision for a checksum test, it has never been implemented. Programs use LINKER via FORTRAN callable routines in the Harris computers or an interface package corresponding to Sigma-2 operating system standards. Details on LINKER may be found reported elsewhere[5].

From the point of view of the cyclotron operator, LINKER involves two major advances and one semi-major disappointment. On the plus side, experimenters can and do control and measure beam polarizations without requiring operator action. Both major data acquisition programs, RAQUEL[6] and DERIVE[7], can send commands to the Sigma-2 to produce any desired polarization state or to insert the beamline 2 polarimeter. The latter process includes inserting beamstops during insertion and extraction of the polarimeter to protect particle detectors and the gas cell, and a steering loop to center the beam horizontally and vertically on the gas cell. The operator can also use the line printer on one of the Harris computers to list a "snapshot" of device controls, including ADC, DAC and status values. This procedure is faster, more convenient and more complete than anything available on the Sigma-2, which has only a teletype for hardcopy output.

The negative aspect of LINKER is that this last kind of service (device listing) is not always available because the data acquisition programs effectively dedicate the computer on which they are running. While in principle LINKER opens up new calculational and disc storage potential to the Sigma-2, in practice questionable access to the Harris computers has inhibited software development.

8. New Computer. -The weakest link in the present control system is the Sigma-2. While it is extremely reliable, it is expensive to maintain and supports neither FORTRAN nor floating point hardware. Operators now are skillful enough to be slowed down by computer response time and operating software is complete enough that further improvements are discouraged by their high marginal cost in manpower.

After some study, we concluded that a simple replacement of the Sigma-2, with a few conditions, was the most reasonable course to follow. We found nothing wrong with our central computer philsosphy, even with the laboratory expansions which are contemplated over the next five years or so, particularly given our good experience with µP systems. Systems with several small, nearly equivalent CPUs would require us to gain expertise in interprocessor communications (good, but expensive) for no obvious operational gain (bad). However, we stipulated that any new computer must be part of a family of machines to offer us paths for modification and expansion. Of course, it must support FORTRAN, floating point arithmetic, real-time operations, multi-programming and some variety of program protection/foreground-background feature. After examining commercially available machines, including a number of 32-bit super-minis, we have purchased and have in-house a PDP-11/44.

The contemplated computer configuration and control system is indicated in Figure 5. The DIO bus system will remain in place and be interfaced to the 11/44. The hardware device drivers for the operator TV displays will be replaced by home built, M6809-based units to obtain fast, multi-color displays in 40 character by 24 line format and an option for expansion to some graphics capabilities. One objective in the entire changeover is that the operator be totally unaware of any of these changes except as they improve response times.

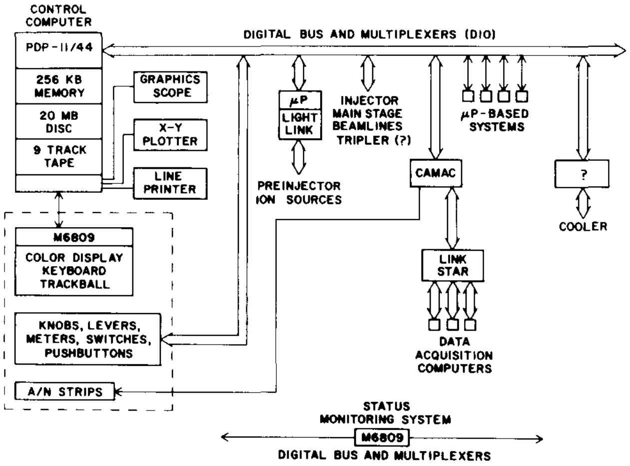

Fig. 5. Schematic diagram of the IUCF control system at the time of the next cyclotron conference.

The basic software structure will be modified to take advantage of the 11/44 architecture with (up to) 1 MB of memory and to allow expansion of the device data base, but conceptually will be largely unchanged from the present. FORTRAN programmers will have access to all control functions and a wider base for controls programming will be encouraged. However, no special or interpretive language use is foreseen.

The new spectrometer and energy tripler will be treated like the existing spectrometers and cyclotrons. To the extent that the cooler ring will look like a pulsed accelerator to the control system, we will consider adding a separate CPU for its timing and ramping. Otherwise it also will be a straightforward extension of the existing control system.

9. Concluding Remarks.-No self respecting review paper is complete without addressing the question, "Where do we go from here?, if only because "what is" is always dull compared to "what might be". More constructively, if offers an opportunity to assess the general situation, highlighting strengths and weaknesses. Our progress in some areas has been slower than we would like it to be. The lion's share of our resources has gone into replicating existing circuitry for control of new beamlines and experimental areas; an analogous statement can be formulated concerning software work. Most of the developments listed above were in response to immediate operational pressures. The other, usually more interesting, projects have been of third and fourth priority. For the future, clearly our trend is to improve our PC board level components as technology advances and to continue to install μP systems where applicable. The flexibility and reliability record of our systems is such that changeover to commercial μP systems or CAMAC is not attractive to us at all. Also clearly, our new central control computer will allow us to improve our energy/particle change procedures and operator aids. One reason we have so few sophisticated beam diagnostic elements is that the calculations involved in extracting useful numbers were beyond the patience of our programmer in the high cost/performance ratio environment of the Sigma-2. This we expect to change. One must admit that the Sigma-2 replacement, however necessary, is an expensive proposition in many ways and that designers of systems similar to ours need to pay attention to the graceful exchange of central computers.

Finally, even given familiarity with microprocessors and the capabilities of table-top, superconducting cyclotrons, one is still impressed with the technological inclusion of more and more functions in less and less space. It should not strain our credibility with the reader if we claim better than a two-orders-of-magnitude improvement in function per unit volume ratio of the PDP-11/44 over the Sigma-2. Our report at the 1987 conference may concern the control-system-on-a-chip.

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