GROWTH OF THE IUCF CONTROL SYSTEM*

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Abstract

The IUCF control system has grown steadily during the first two years of operation. All RF devices and power supplies are almost entirely under computer control so that cyclotron operation is approaching a one man/one chair state. A variety of different areas have seen active development:from sophisticated magnetic field controls to transient suppression in logic power supplies. Analog and digital data isolation for the new 800 kV preinjector is provided by an optical fiber data transmission link utilizing a V/F-F/V conversion scheme. The wide range of beam currents used at IUCF necessitates the use of stable, reliable logarithmic amplifiers and a special antilog routine for the control computer which is both accurate and fast. Energy and particle changes are simplified by using programs to predict appropriate cyclotron operating parameters and to correctly scale older device settings for new beams. Finally, microprocessor systems are being developed to decrease the constantly growing responsibility of the heavily burdened control computer.

Introduction

The Indiana University Cyclotron Facility (IUCF) uses a three-stage acceleration process to produce proton beams of energies up to 200 MeV, with beams of deuterons, alpha particles and lithium ions also in regular use. The acceleration system consists of one of two electrostatic preinjectors, an injector cyclotron and the main stage cyclotron.[1,2] The control system used is almost fully computerized, and its basic features have been described previously in detail elsewhere.[3,4] However, in two years of actual operation, the control system hardware and software have evolved as more devices are used in a more sophisticated manner.

Two major thrusts may be identified in this development. One is toward attaining complete control of all devices. This tends to reduce the amount of physical movement required of the operators during setups and energy/particle changes, thereby speeding up the process. The second thrust is toward automating procedures and reducing the operator's reliance on information not immediately available through the control system.

Basic Hardware

Let us briefly review the IUCF control system. The system hub is a Xerox Data Systems Σ-2 computer with 32K words of 16-bit core memory and a 2.88 Mbyte, fixed head disc. This machine communicates with the operator through three color TV terminals and with the cyclotron through a 16 bit "direct input/output" (DIO) bus. This bus is wired to six multiplexing (MPX) stations which are placed strategically throughout the building. Each MPX station is a locus about which are grouped the various chassis and wire-wrap bins which perform control and readback functions. This decentralization minimizes control-room congestion and saves greatly on cabling costs. Whenever possible, the electronic building blocks at each station are identical for ease of trouble-shooting and construction. To add a quantitative perspective to this description, the control system recognizes some 660 devices of which 500 have associated readouts, 300 are controllable and 170 allow on/off switching.

Most of the data acquisition system is built around 12-bit "circulating" analog-to-digital converters (ADC's) which have been described before.[5] Many of the signals fed to these ADC's require prior conditioning. Beam currents in the nanoampere range (from beam stops, slits, probes) are fed into a logarithmic current-to-voltage amplifier which responds accurately to currents from 1 nA to 500 μA (Fig. 1.). A double pole R-C input filter shunted by a fast avalanche diode protects the sensitive circutry from spark-induced transients. For very small currents (e.g. heavy-ion slit currents) a special log-amp is available that can perform properly at 100 pA. The output of all these amplifiers falls between ± 1.0 V for ADC compatibility. A special software antilog routine converts the logarithmic digitized voltage back to current units. To meet the particular demands of the standard display software which requires small size and fast execution, this routine achieves 0.5% accuracy in its results using only 58 words of memory and executing no loops.

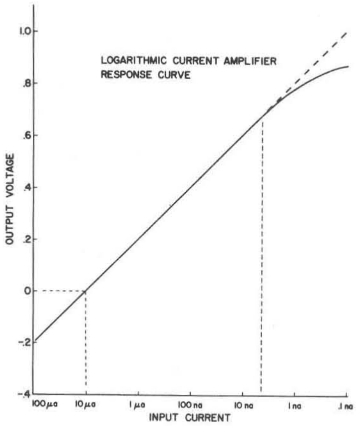

Fig. 1. Logarithmic current amplifier response curve. Useful low current limit and reference current (0 V) are marked.

Position readouts are from precision 10-turn follow pots supplied with 1.000 V from our reference chassis or from four-decade absolute encoders. The latter have proven more reliable, although more expensive and harder to install. We do not use incremental encoders.

The double width NIM-standard modules used for ADC's or digital-to-analog converters (DAC's) on ungrounded power supplies have been described before.[5] With slightly over one hundred of these modules

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installed, their reliability record is excellent.

Almost all control motor applications in the lab use one of the several types of M-Series Slosyn stepping motors, and they all can be driven by our standard translator chassis.5) This chassis may be run in either local or computer mode. Limit switches may be used to gate out steps to the motor if it has reached its end of travel. We found it wasteful to devote one translator circuit per motor, and so in some cases we switch the translator output among 16 different motors with a motor relay multiplexing chassis. This is practical if there are no limit switches and if there is no need to drive two motors simultaneously.

As stated above, one of our major concerns is to bring all devices into the standard control system so that their point of control moves from the building corridors to the control room. On/off control and load switches have been added slowly because if the power supplies were not originally built for remote switching it is expensive to modify them; and conversion has a low priority, since switching is normally required only during energy changes. Of more continuous usefulness is control of the RF voltage amplitudes of the beam chopper and buncher and the dee voltage and relative dee phase. This last parameter is actually obtained by converting two voltages from phase detector circuits to one angle using a special arctangent software routine. This routine is only 104 words long and accurate to 0.1° from 0° to 85°, being most sensitive near 0° (or 180°, the two desired values for even or odd harmonic acceleration).

Special Hardware

Magnet Control

Control of the cyclotron magnets has become more sophisticated with two networks of active current-regulating shunts now under computer control. One network controls trimcoil currents, allowing the 21 trimcoils of the main cyclotron to be driven from only three power supplies. Each trimcoil shunt may be controlled individually or groups of shunts may be controlled by one (software generated) pseudo-variable. A change in a pseudo-variable generates changes in each shunt weighted according to a pre-defined formula such that the net effect is to produce a local phase bump without causing a net phase change.

Each sector of the main stage magnet also has an active transistor bypass shunt across its coils rated at 750 W and capable of bypassing as much as 15 A with 0.01% regulation. Although these shunts may be separately controlled, it is much more useful again to use pseudo-variables which give the operator a fine control on the field level, two orthogonal first harmonic field components and a second harmonic component. These are simply four linearly independent combinations of the four individual shunts which reflect the physical quantities the operator actually wishes to vary to improve extraction efficiency.

800 KV Pre-Injector

One of our most recent controls projects has been the new 800 kV terminal containing both PIG and polarized ion sources. To deliver logic control signals across the 800 kV gradient, we use a synchronous 1 MHz fiber-optics serial data link employing 15 m of fiber-optic cable (Meret MDL 421). Within the terminal, this link controls 22 on/off channels and 64 stepping motor channels. (Fig. 2.)

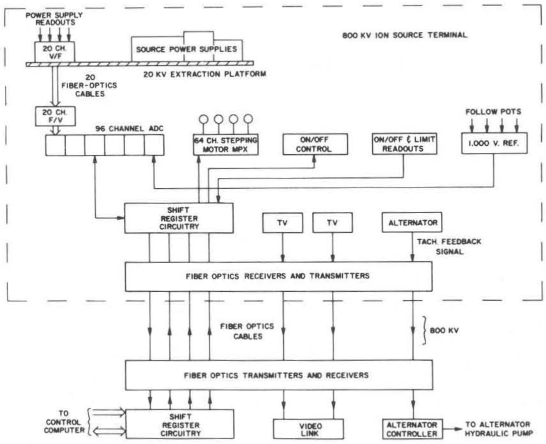


Fig. 2. Schematic representation of data communications with the 800 kV preinjector. The "light link" carries logic, video and feedback signals.

Eight of each type of channel also have local controls. In addition, the link can read on/off/fault status for all on/off channels. Ninety-six 12-bit ADC channels are piped down to the controls computer; these channels carry power-supply, vacuum, or follow-pot information. An additional complication presents itself when trying to read the status of power supplies which are (along with the source) at a 20 kV extraction potential, relative to the terminal. To solve this problem, a second fiber-optics link is used, but of a different type. On the source end, IC voltage-to-frequency converters (V/F) drive each fiber-optics line (Meret MDL 124) at a frequency proportional to the analog signals from the power supplies (1 V = 10 kHz) at the ground end, the pulses are transformed back into analog voltages by frequency-to-voltage converters (F/V). This smaller link has fourteen 'down' channels and six 'up' channels.

The terminal is powered by a hydraulically driven 75 kVA alternator which is connected (across the 800 kV gradient) to a pump by plastic oil lines. The pump control circuitry uses a feedback voltage from a tachometer on the alternator to insure 60 Hz ac under varying loads. This feedback signal crosses to real ground again via a V/F-fiber optics-F/V channel.

In addition to these two systems, there is a fiber-optics system (MDL 225) to carry two separate video signals from TV cameras in the terminal to monitors at the control desk. These will supply pictures of beam viewers for tuning purposes.

Power Line Monitor

The Power Line Monitor at IUCF is used to monitor any voltage fluctuation that may occur on the incoming service lines. Undervoltages of sufficient duration and/or loss of phase will turn off the cyclotron power substation while smaller fluctuations can cause beam stability problems. Clearly the operator must be made aware of these events. Input voltage to the monitor comes from our main substation 460 V distribution bus. The input is stepped down to 120 V, and the individual phases are fed to three rms-to-dc converters scaled such that 160 V ac gives 1 V dc. This dc level is then connected to an analog multiplexer driving a 12-bit ADC.

A voltage comparator is also connected to each rms-to-ac level output. The Hi and Lo reference values for the comparator can be set remotely from the computer. When any of the limits are violated, the comparator triggers an interrupt to the computer which then drives the analog multiplexer and reads the ADC for all three phases. The ADC values are stored in memory, and this process continued every ac line cycle until the voltage returns to the correct limits. When the voltage has recovered, the computer prints a summary of the event, including the number of cycles during which each phase violated the limits.

Noise Suppression

Particularly troublesome to the control system has been radio frequency interference (RFI) generated by the sparking of high voltage power supply loads such as the ion source terminals or electrostatic inflectors. Since identifying the mode of transmission of the noise (conducted and/or radiated) is difficult, brute force transient suppression methods have been resorted to in most cases. Along with accepted grounding and shielding practices, we employ the following techniques:

- damping resistors in series with high voltage loads;
- multiple grounding of coax cable shields;
- "TRANSORB" type transient suppressors on signal, control and power cables;
- double pole RC filters and diodes for slowly varying and dc signals;
- delay one-shots (see "Fault Checking" section below);
- isolated ac power distribution via box shielded isolation transformers;

- IC opto-couplers (6N138) for digital signals;
- industrial grade high threshold logic gates;
- Motorola MC3423 overvoltage protection circuits to trigger logic power supply crowbars.

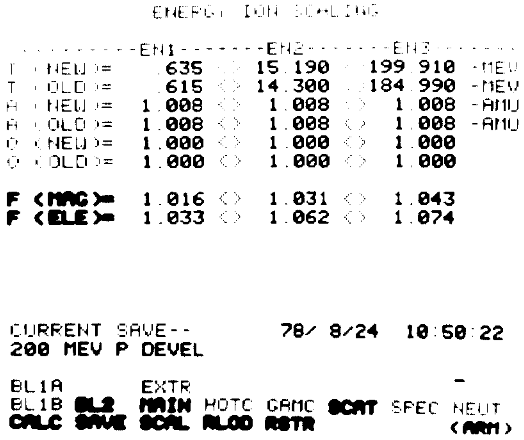
Software

Cyclotron operating parameters may be predicted by a program which bases its calculations on values input by the operator for a particle's charge state and mass, an RF frequency and the assumed extraction radii of the cyclotrons. Inflection radii, magnet settings and dee voltage are among the derived values displayed. However, the program also allows this calculation to be performed in reverse so that, in fact, any variable can be changed and the model recalculated to reflect this change. Parameters are grouped so that changes affect only certain other values. For instance, changing the dee voltage causes only the calculated number of turns to change; while changing the final beam energy changes almost everything except particle charge state and mass.

The calculated values act as guides and reference values from which the operator should not deviate too strongly during the tuning procedure. The final, "tuned" parameter values generally agree with predicted values to within less than 1%, while discrepancies tend to be reproducible and systematic. Empirical corrections to the model have been few, partly to maintain its integrity as an "ideal" and partly because it is not clear how corrections should be made. For example, discovery of a faulty shunt calibration served to improve agreement between the model and the measured magnet current.

As an example of how programs become more operator oriented, it is interesting to note that this program allows the user to input either a five-digit number (with decimal point) as an ion mass (in AMU), or the digits 1-6, in which case the program supplies the appropriate ion mass. Therefore, the operator (or the physicist in charge) need remember only the mass number of the ion in which he is interested.

A second major program assists in setup and energy/particle change operations by allowing the operator to save existing device values (DAC's or counters) on a disc file, transfer the file to tape, recall another file from tape and restore device values from the new file. This provides a mechanism whereby previous runs for a given energy/particle combination may be reproduced as a starting point for the tuning procedure. It also makes previous runs useful even for totally new beams by including an electrostatic and a magnet scale factor (Fig. 3.) calculated from old and new values of particle mass, charge and final energy. For the purposes of this program, all devices are divided into functional groups such as Beamline 2 (between injector and main cyclotrons) or Scattering Chamber. The operator may choose to scale and/or restore only single groups or any combination of groups, leaving unselected groups untouched.



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                 ENERGY ION SCALING

  ----------EN1-------EN2-------EN3------
T (NEW)=     .635 <>  15.190 <> 199.910 -MEV
T (OLD)=     .615 <>  14.300 <> 184.990 -MEV
A (NEW)=    1.008 <>   1.008 <>   1.008 -AMU
A (OLD)=    1.008 <>   1.008 <>   1.008 -AMU
Q (NEW)=    1.000 <>   1.000 <>   1.000
Q (OLD)=    1.000 <>   1.000 <>   1.000

F (MAG)=    1.016 <>   1.031 <>   1.043
F (ELE)=    1.033 <>   1.062 <>   1.074




CURRENT SAVE--          78/ 8/24  10:50:22
200 MEV P DEVEL

BL1A      EXTR                             -
BL1B BL2  MAIN HOTC GAMC SCAT SPEC NEUT
CALC SAVE SCAL ALOD RSTR                 (ARM)
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Fig. 3. Operator's display for program SCALE. Scaling factors appear in display center, calculated using data from display top. Display bottom shows a title for the current SAVE data, two rows of device groups for selection and a row of program functions. Note "ARM" safety switch at right.

This program also recognizes and treats correctly those situations where different devices are actually common loads sharing a single output channel on a power supply. Unused loads are turned off before the desired load is turned on, eliminating an operator tour of the power supply racks around the building.

The capability of the control software to combine real parameters into pseudo-variables for both readout and control purposes is extremely powerful. Besides the two examples given above, slit width and position relative to the beamline optic axis are variables read or changed by the operator even though individual jaw positions are the real independent parameters. A somewhat different variable combination is found at injection into the injector cyclotron. There two magnets are controlled by one pseudo-variable so that the angle of entrance into the first inflection element may be varied while holding the beam between two collimators fronting the inflector. The pseudo-variable actually controls the first magnet while the second magnet is changed so that no current is

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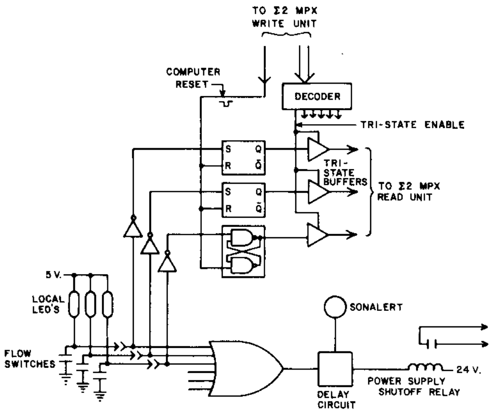

Fig. 4. Schematic representation of flow switch circuitry. Flow switch trips are reported to the computer via tri-state logic. The use of delay one-shots before the power supply relay suppresses effects due to momentary water flow disturbances.

intercepted by the collimators. One operator knob therefore uses two active power supply controls and two passive beam current readouts.

Fault Checking

IUCF, like all such machines, has flow switches in cooling water lines as interlocks for power supplies so that any one of some 240 switches can interrupt machine operation. Momentary trips, causes by bubbles or marginal flow, are especially troublesome. Our approach is to feed the switch outputs to both latches and an OR gate and delay circuit connected to the power supply trip-off relay (Fig. 4.). If any switch trips, the OR-gate triggers the delay circuit and sends an interrupt to the Σ-2, which then reads the latches, pauses, attempts to clear them, and reads them again. The computer prints a record of the interrupt occurence and whether the clear operation succeeded, showing a momentary fault, or failed, showing a hard fault. This record is useful to operators and service people for understanding power supply faults and finding bad flow switches or poor water flow situations. Note that the power supply shutoff is independent of the computer, occuring only if the flow switch trip time exceeds the delay time.

A second fault checking system is a limits-checking program described previously.4)

A third fault reporting system is now under construction using a microprocessor to scan contact closures and voltage levels. Deviations from the normal conditions of these signals will result in messages output on a separate fault printer in the control room. Initially the vacuum and cryogenic systems will be monitored in this way, but it is planned to switch the power line monitor and flow switch reporting to this system along with any new status reporting desired.

Diagnostic Equipment

Two diagnostic aids have been added recently to IUCF and will be incorporated into the control system. The system of fixed and movable phase probes is reported on more fully elsewhere in these proceedings.8) Work is underway to make a phase-related signal available to the Σ-2. When this is completed, it will be possible to obtain phase measurements and calculate trimcoil corrections by computer as a standard step in the setup procedure.

Identical rotating wire profile monitors (NEC Model BPM-6) have also been installed in beamlines 1, 2 and 3 for testing with beams at each stage in the IUCF acceleration process. Satisfactory profiles have been observed from each monitor over a wide range of conditions: from 150 μA at 500 keV in beamline 1 to 20 nA at 185 MeV in beamline 3. Further development work is planned to include profile measurements in the tuning procedure with an eye toward replacing scintillating viewers and digitizing the profiles for the computer.

Conclusions

The IUCF control system has proven itself effective and reliable under all conditions. We have had little difficulty in adding new devices or in trouble-shooting. The software system has also been demonstrated to be very flexible and responsive to the operator's needs.

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