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LAWRENCE RADIATION LABORATORY
UNIVERSITY of CALIFORNIA BERKELEY

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Summary

A computer-based digitally-structured, data acquisition and control system has been developed for on-line programmed control of external beam transport magnets at the Bevatron. The control algorithm achieves flexibility to accommodate all possible modes of Bevatron operation by separating the operating cycle of the accelerator into several zones. This method allows independent processing of Bevatron field within each zone, and the introduction of zone-related time-variable functions in each of the magnet currents.

Evolution of the hardware is discussed and use of small computers is considered for each well-defined project, over a time-shared single large computer. The technique utilized to provide time-sharing of peripheral hardware between small computers is described.

Pertinent details of methods used to reject noise in transmission of both analog and digital data are examined.

Communication between digital systems and the human operator is discussed in terms of minimizing the number of operator responses required to establish a series of functions to be performed by the system.

Introduction

With the progressive expansion of the external-proton-beam facilities at the Bevatron, the operator-controlled beam transport magnet system (Fig. 1) has become sufficiently complex to warrant serious consideration of a replacement for the multiple-control--"several knobs/magnet" technique. Additional flexibility also seemed advisable in the control of these pulsed magnets over a wide range of possible operating modes of the accelerator. Accordingly, a digital system has been created and placed into full-time, on-line service in control of the pulsed magnets.

General Considerations

At the outset, a decision was made to push the boundary between the analog and the digital as far from the center of the system as possible. This defines the system as strictly digital, with coupling from the analog world as soon as possible for data input, but retaining the data in digital form to the last possible point. To implement this requires the transmission of data in digital form.

The power supplies to be controlled are 3-phase full-wave rectifiers of two types. Most are SCR, and four are magamp with shunt transistor actuators. In any case, the digital system responsibility rests with providing a reference voltage to the regulator. The reference must be essentially noise-free, and must appear as a continuous signal insofar as no discontinuities may be present in magnet current due solely to the digitally quantized reference amplitude or to the selected update rate. The time allowed between reference changes is at least the period of the gate triggers to the SCR's. Three milliseconds was selected as the minimum period required between control adjustments. This decision specifies much of the balance of the system. The number of magnets and the extent of the calculations are required to define the computer to be slected and the data rate specified for the transmission system. In our case, the maximum number of pulsed magnets was set at 35, since only those of the pulsed variety require careful tracking with Bevatron field and therefore require on-line operation. There is provision for 64 magnet conrol channels, dc and pulsed combined.

The Bevatron operating cycle has been divided into a number of independent zones. In general, a zone is defined as the region between points of discontinuity in the $\dot{B}$. An example of this type of zone assignment is shown in Fig. 2. Zones may be arbitrarily defined as well. Regions between accelerator current markers, and regions bounded by limits in real-time are examples.

Control Algorithm

The calculations required for each magnet at each 3-ms update point must satisfy the requirement of independent processing of each magnet current and must track to the required proportion of Bevatron field within each zone of operation. That is,

$$I_{mag}=\rho_z\int\dot{B} \qquad (1)$$

where ρ_z is the zone-dependent, operator-determined proportionality factor which provides proper rate of rise within a zone, or attains the proper current level at the end of a zone; either point of view can be taken by the operator. The calculations must also allow introduction of zone-related time-variable functions in each magnet current.

Considering all of these factors, all data

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* Work done under the auspices of the U. S. Atomic Energy Commission.

processing is performed relative to the beginning of the current zone, so that:

$$CW \quad CW^i_\phi + (B-B^i_\phi)x^i + (t-t^i_\phi)y^i \tag{2}$$

where CW is the control word to the magnet, B is the Bevatron field value, X is the operator-specified ratio (ρ specified above), t is the time quantized to 3 ms update periods, and y is the operator-specified time-dependent slope. Subscript φ denotes the value of the parameter at the beginning of the Ith zone. If it were intended to run "open-loop" without considering slow-drift correction or ripple-detection, the operator could operate directly upon x and (or) y to achieve control. To "close" the loop to the extent that magnet-power-supply drift or reference-related gain change effects can be removed from the operating system and thereby reduce operator "trimming", our x and y include information about the control-word/magnet-current transfer function. A dimensional analysis from (2) reveals:

$$X\left[\frac{\text{control word}}{\text{gauss}}\right] = A\cdot BR\left[\frac{\text{control word}}{\text{ampere}}\cdot\frac{\text{ampere}}{\text{gauss}}\right], \tag{3}$$

where A is the transfer function (digital input to analog output of power supply), and BR is the operator-specified magnet current to the Bevatron field ratio, (B ratio). Similarly: we have

$$y\left[\frac{\text{control word}}{\Delta\ \text{time}}\right] = A\cdot S\left[\frac{\text{control word}}{\text{ampere}}\cdot\frac{\text{ampere}}{\Delta\ \text{time}}\right], \tag{4}$$

where S is the operator-specified magnet-current change per unit time.

During active control changes, the magnet under control is retained in the open-loop mode. the operator request is used to modify BR or S directly, and the subroutine to calculate new x and y is called repeatedly as operator data varies. This apparently provides direct connection of the control knob to the magnet reference. Upon completion of the active control request, the magnet is again inserted into the closed-loop control mode.

Since the closed-loop is not used to provide a constant current in each magnet on a pulse-to-pulse basis, but rather must maintain a constant ratio of magnet current to Bevatron field, this closed-loop control method is thought of more as a "holding" technique. Since the initial placement into full-time control, several unusual (though not unanticipated) modes of control have been requested. These involve providing certain step functions to be applied to magnet references at various times to provide beam-channel switching or temporary fields to allow short-term extraction techniques to be applied.

This accommodation is provided by software capability to remove from or insert into the normal update cycle any magnet at anytime. While out of the update routine, the magnet may be directed to any predetermined current level.

Hardware Requirement

Figure 3 is an abbreviated block diagram of the hardware. Magnet-current data are obtained by scanning transductors on the controlled magnets with an analog multiplexer and analog-digital converter and by sampling the current value of each magnet transductor every 3 ms. There is provision for 64 analog inputs. This magnet current data is saved at the end of each zone, as are control words, in order to check the transfer function, A, in each zone, and to allow calculation of new xy values as A varies. Variation beyond allowed tolerances initiates a notice to the operator of drift or ripple problems with a magnet.

It should also be noted that the value of the Bevatron field must be used in control-word calculations. The integral of $\dot{B}$ is obtained by digitally integrating the output of a voltage-frequency converter in a 21-bit up/down scaler, the contents of which is read into core each 3 ms. Provision is made for 64 digital channels to be scanned. Other digital inputs include magnet status, operator control data and radiation-chain status.

Combining the methods of handling parameters into a reasonable hardware system results in the core of the magnet control system becoming a three-part direct memory access (DMA) device which provides completely asynchronous input/output of the three channels of data: control word out, converted analog data in, and pure digital data in. The three DMA devices are identical in most respects. The small differences will be described as they are encountered.

The PDP-8 computer utilized by the system is a 12-bit, 1.5-μs, 4k machine. Our control is 1 part in 4k, as is our monitoring. Therefore, all I/O is 12-bit data. Each of the DMA devices has a table in memory specifically dedicated to it, the starting location being defined by the contents of a dedicated pointer location in core. The pointer location is defined by hard-wiring in the DMA device, whereas the program can modify the starting location of the table to be operated on by data.

At the tick of the external 3-ms clock, each of the three devices starts a cycle, which begins by consulting the pointer in core and transferring this address into an external register. The maximum number of channels in each device is 64_{10}. This allows us to define the end of data transfer by detecting 77_8 in the address register. By blending all the operations associated with addressing during data transfer, the least six bits of the external address register point not only to the "slot" in the core table, but also to the channel of the device being serviced. This provides complete dedication of specific locations in core for parameters involved in calculations. The pointer in core can be program-modified to change the length of the table or its absolute core location, but during ordinary control, the program is not required to exercise any significant control over the DMA devices, once having started them. Since the three devices are asynchronous and each requires a different time to service one channel and move on to the next, there is a priority established such that no anomolies exist as the devices vie for access to the computer.

Transmission Device

The magnet power supplies under control are located at widely separated areas of the Bevatron, such that the difference in chassis ground potential during the Bevatron cycle approaches 4V due to magnetically induced currents as observed from the computer location. Commutation noise from SCR power supplies exceeds this level by about three times. The method of data transmission selected must have common-mode rejection capable of operating under these conditions, and further, must be able to reject asymmetrical noise induced into the system by asymmetry in lead-dress, wire-length or even maintenance-oscilloscope-connection ground loops. The time required to transmit control words to all magnets, separates the first transmission from the last in real time and introduces a small error, since the B-field measurement used in calculations of control words, is the same for all magnets. Therefore, the parallel transmission of all data bits is desirable. To live in a noisy real-life environment, the receiver data-buffer logic was selected from the Digital Equipment Corporation Industrial Series (K-series), which utilizes a Miller integrator capacitor in the logic gates. The next question to be met is that of common-mode noise. Differential current sources driving a twisted pair, random-lay cable with a characteristic impedance of 105Ω, provides high data reliability when adjacent line pairs in a cable are shorted together (the most likely failure mode). This technique, with differential line receivers, combines advantages of high data rates and dc operation. The data and address line data rate is 100kHz and other lines are operated dc to provide interlocking. Twelve-bits of parallel data, together with 6-bits of parallel address lines are presented to all receiver buffer registers at once, as is a strobe pulse. That buffer which decodes the address line uses the strobe to update itself and in turn, returns the strobe as a data-received pulse, which is used at the DMA device to advance the address register and obtain the next piece of data for the next magnet in sequence. Should the transmitted address be outside the range of addresses of magnets under control, or should a failure occur at a remote receiver location, the absence of the return accepted pulse creates a system error, and diagnostics are called into service to determine the offending channel. Individual 12-bit DAC's are located at the remote receiver locations to be connected by minimal-length cabling to the power-supply regulators as reference. Provision is made to allow direct remote analog monitoring of the DAC outputs in place of magnet transductors for diagnostic purposes.

Analog Device

The central element in the analog monitoring system is the 12-bit analog-digital converter, which is fed from an analog FET multiplexer with up to a 64-channel capacity. It is not expected to exceed 35 channels of magnet-current monitoring, since to obtain 12-bit accuracies at reasonable cost, the successive approximation ADC consumes 4 μs bit. An ADC complete signal requests a DMA cycle direct to core to insert the converted value into the table entry as defined by the address register in the external device. The least 6 bits of the register also defines the magnet for which current is being converted. Satisfactory insertion of the data into core calls for advancing to the next magnet and table address and a new ADC conversion of this next entry. The program responsibility for analog entries presently rests with a graphic CRT display of the instantaneous value of magnet current for the magnet selected for display. The program must also store away necessary values from the analog table at the end of each zone, to be able to calculate the transfer function for each magnet in each zone of the preceding Bevatron acceleration cycle.

Because of the presence on the analog lines, of the common-mode signals described in the transmission device, differential-input follow and hold amplifiers are used with a one-point analog ground at each remote receiver location. This allows the differential lines into the amplifiers to vary independently within the common-mode capability of the amplifiers without creating unreal analog values to be acquired which would then create a problem in calculation of transfer function on a pulse-to-pulse basis. Should the analog system include random noise in the data, the slow closed loop becomes a random-hunt system and could introduce a larger error margin than that expected from magnet power-supply drifts.

The Digital Device

This device operates similarly to the analog device, except at a higher throughput, because it simply scans data on digital lines, which are static as a rule. There are some exceptions, and to accommodate asynchronous data lines, a strobe is available which is similar to the transmission device. This DMA device does not require a return accepted pulse to advance its address register, but rather dwells on a digital channel a fixed time and moves on. If the strobe is used to synchronize variable data, it is assumed the data is on the lines within 1 μs after the strobe. One input that requires the strobe is the digital integrator for field value. The maximum frequency of count pulses to the scaler is approximately 2.0 MHz. Data must be taken from the scaler only when all 21 bits are quiescent. Therefore, if counts are occuring, the nearest one within the tolerance allowed by the digital system is synchronized to the digital-device strobe line and used to place the scaler data onto the digital input channel. On the other hand, if no (or few) counts are coming in, the digital strobe itself causes the data in the 21-bit scaler to be placed on the data channel.

Zone Definition-Interrupts

The zone orientation of the control system has been described, and the method used to define zones is now discussed. A hierarchy of priority interrupts has been established. The PDP-8 has provision for only one interrupt bus, so an external device has been developed, with arm, disarm capability for 16 levels of interrupt. To expedite service of interrupts, the level number is strobed to the accumulator under program control to be used as an address modifier to get to the service routine for the specific level in the shortest time. Each level, of course, can have any number of individual devices on it, each capable of causing an interrupt. An example is that of the Bevatron timing-pulse interrupts, in which case, there are 12 different pulse inputs on each of two levels. Each DMA device is assigned a level of interrupt to provide early discovery of any malfunction or error in the devices. Zones are defined as extending from any accelerator-derived pulse to any other. Those normally used are the $\dot{B}$ derived pulses such as Mag On, Flattop On, etc. Upon detection of a zone-change interrupt, the program has the responsibility to save zone-end parameters, transfer the contents of a minimal number of tables to obtain the new x and y values for the new zone and continue on until the next interrupt. The analog DMA device requires the longest time to complete its cycle of operation. Its cycle-complete interrupt is utilized to indicate the completion of table freshening, and releases the tables to program calculation for preparing control words to be transmitted during the next 3-ms cycle.

Operator Control

One of the most difficult areas of endeavor in an on-line control system is to insure that the operator has control of the situation and not vice versa. One of the major purposes in developing this system was to lessen the burden on the operator and create a more flexible tool for his benefit. It is proposed for Phase II of this systems development, that the control loop be closed on the beam position (via suitable sensors) throughout the extent of the external-proton-beam facility. At present, however, the loop is closed through scintillators, television monitors, and the operators. That is, the entire system starts out as a single knob in the hands of the operator. By a series of push buttons and graphic displays (Fig. 2), an operator may request a specific magnet by its name, i.e. X2Q7A, and may place a control request, which can be either as a request to change "BR" of Eq. (3) or, as a dI/dt request to change "S" in (4). In either case, the knob is used to insert a change in the proper direction. To closely define the region of the acceleration cycle in which the change will take place, the operator also has defined the zone by switch selection and light-panel response. That is, a lighted numeral physically located on a drawing of the magnet response curve clearly indicates the zone under control.

Any graduations on the control knob are meant only for the convenience of the operator to keep track of how far he has turned the knob. After exercising control of any magnet in any zone, before losing the original parameters, the operator must take one of two options. He may "SAVE" the new data and thus throw out the old parameters associated with that magnet in that zone, since the last SAVE, or he may "RESTORE" the parameters to those that were being used just prior to the current control request. This feature allows an operator to escape from an adjustment that has removed all evidence of beam from a scintillator. By periodically writing magnet parameters on disc, rapid set-up retrieval is accomplished to accommodate experimenter or accelerator operating mode changes.

To prevent accidental change in magnet number or zone request during an active control period, these options are disabled during control. When controlling a doublet quadrupole magnet, it has been found that duplex control is desirable and therefore, when the first of a doublet has been selected by the operator, a second knob is connected to the second magnet in the doublet.

Small Computers as Control Devices

The question of small vs large computers to exercise a control function would be better phrased as dedicated vs time-shared. When a decision is to be made as to type of computer to be utilized to accomplish an extensive calculation function, the level of sophistication of command structure and memory size are paramount. Time is important, but not of highest priority. When operating in a control capacity, however, close scrutiny of the update period and the number of controlled devices, together with the extent of the data acquisition required to provide necessary feedback often results in the selection of a computer just large enough to accommodate the active control software. This leads to serious questions regarding future expansion capability and provision for general-purpose data handling.

The point of emphasis here, is that a computer can suffer from "time-saturation". gardless of memory size and calculation capability, a practical machine can perform a finite number of input-output functions in a given time. All the additional capabilities are to no avail. Even a so-called "faster" machine is all too often speedier in internal operations and contemporary with its slower kin in the region of input/output.

These considerations point to the use of dedicated machines to perform the control function, leaving the sophistication of elaborate display and general-purpose use to another machine dedicated to <u>that</u> function. This approach speaks not at all to the "size" of the computer, but rather to a careful appraisal of the extent of data transfer, the complexity of the external interface, and the calculation requirements of the control function.

Dedicated Computer in Combination

Allowing the above arguments to rest, the question of integrating dedicated machines into a system arises. The PDP-8 in the EPB magnet-control system stands alone in exercising control. To provide backup to continue magnet operation in event of processor failure, a second PDP-8 was obtained. The aim was to provide the operating crew at the Bevatron with monitoring and diagnostic information relating to other facets of the accelerator. This is provided in a general-purpose data-acquisition subsystem without tying the second machine down so as to endanger its backup role in magnet control.

Complete I/O bus multiplexing is provided between PDP-8's (Fig. 4) such that any device can be connected to either computer. The only completely separate computer-related hardware is the interrupt and clock devices. This technique provides time-sharing capability in accessing magnetic disc for data storage or retrieval as well as magnetic tape and display. Each multiplex switch has busy flags to prevent stealing when inappropriate, but not when priority warrants the theft.

Acknowledgments

The development of the EPB magnet control system is due to the many contributions of R. A. Belshe, J. B. Greer, J. R. Guggemos, C. D. Pike and T. M. Taussig.

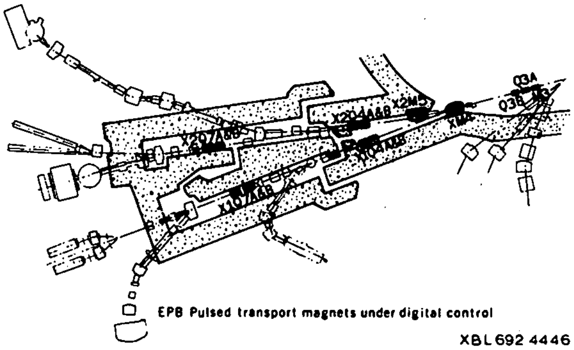


Fig. 1 The EPB Transport-Magnet System

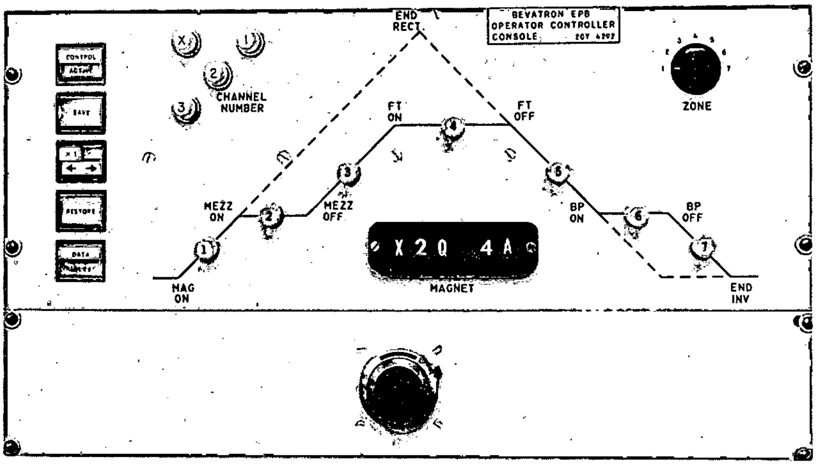
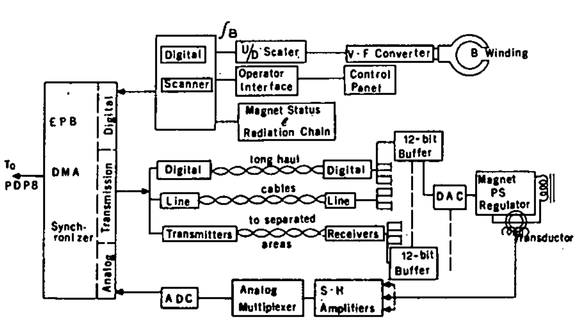


Fig. 2 Operator Control Panel



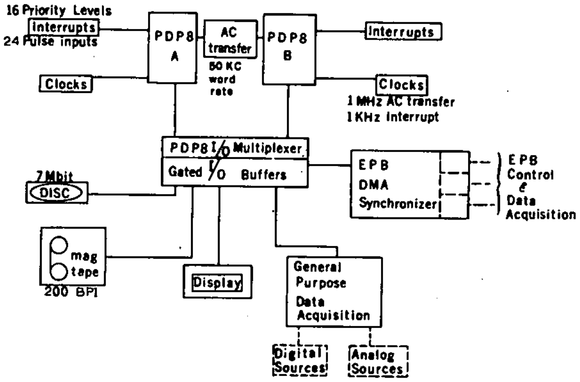
External Proton Beam

Transport Magnet

Control System

XBL 692 4450

Fig. 3 EPB Transport-Magnet Control System



Basic Duplex Computer System XBL 692 4449

Fig. 4 Basic Duplex Computer System

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