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ADVANCEMENTS IN CONTROL TECHNOLOGY AT THE BEVATRON*

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Introduction

Advancements in accelerator technology require an accompanying innovative approach to controls. This paper describes several new developments at the Bevatron. The "learned curve" concept of accelerator rf frequency modulation control is explained as it applies to increased performance of radial positioning of beam, and as it provides for open loop operation of the accelerator with low intensity ion beams. A major innovative step has been taken in the utilization of sampled data techniques in a multi-channel digital closed loop power supply regulator in the new 750 keV Ion Gun. Pulsed quadrupole magnets in the drift tubes of the 50 MeV Linac are continuously monitored by a fast digital scanner to provide radiation interlocks as well as comprehensive diagnostics with an eye toward detection of incipient failures. A new logically oriented interlocking and chain control system is described. An important axion for modern control systems is proposed and analyzed.

Digital Control of the RF Frequency Modulation

A new system for controlling the final accelerating frequency is to be implemented. The new system will allow easier change over to heavy ions and more accurate control. The present master oscillator will be replaced by a voltage controlled oscillator. The control voltage supplied to this new VCO will be developed by a digital to analog converter. A new digital word will be sent to the DAC at each incremental change of magnetic field. The present plan is to use 1 gauss increments.

A plot of frequency versus field value will be computed for any desired particle. These frequencies will be then stored in one half of a 32 K core memory. Each memory address will correspond to a particular field value. The numbers stored at that address will be the value of the desired frequency.

$$F = \frac{c}{(2\pi R_o + fs)\left[1 + \left(\frac{mc}{eBR_o}\right)^2\right]^{1/2}}$$

Where:

- F = frequency in Hz
- c = speed of light
- R_o = radius of Bevatron
- ℓ = Length of straight sections in Bevatron
- m = mass of particle
- e = electron charge
- B = field in gauss

The Bevatron Guide Field changes at the rate of 10 G/ms as injection with a corresponding 40 Hz/G change in the rf frequency. The range of frequency to be covered is 120 kHz at 0 field to 2.5 MHz at 6.3 GeV. The implication is that the frequency has to be controlled to 1 part in 60,000, which dictated a 16-bit digital system.

The address register for the memory is incremented by 1 G markers of the main guide field. The calculated curve in the memory is then transmitted to the digital summation hardware every 100 μs. In the summation hardware, the least significant 12-bits can be modified, either by radial feedback information or open-loop control by the operators, at a 1 ms rate. The output of the digital summation hardware is then transmitted by Pulsed Duration Modulation -- PDM (an encoded self-clocking 1 MHz serial data transmission system that is used extensively throughout the Bevatron) to a 16-bit digital to analog converter. The output has been integrated to remove the finite steps of the digital system.

The output of the 16-bit DAC can be modified by ±5% by two systems. A fast analog correction signal with a bandwidth of 30 kHz obtained from the phase feedbacks system used to maintain phase stability of the beam, or by a 12-bit digital-analog converter. The input to the 12-bit DAC is a PDM signal that is used to correct for slow drifts in the system. The rf frequency is measured when the guide field is zero and a calculation is then made to determine the correction needed to return the rf frequency to a predetermined value.

The output of the analog summation now becomes the input to the Hewlett-Packard voltage controlled oscillator. The voltage controlled oscillator output is the desired rf signal to the final amplifier system. (See Fig. 1). The Hewlett-Packard Voltage Controlled Oscillator was selected for its low inherent FM of less than 40 Hz, low drift, high slew rate, and wide frequency range.

The digital controlled rf system now provides the ability to use the "learned curve" concept. The output of the digital summation can now be written into the second half of the 32K memory. On the following Bevatron pulses, the rf signal can be programmed by this new curve, reducing requirements of the radial feedback system. This results in a system with very high gain, the fact being that the gain can be increased by repeated use of the "learned curve" concept until the system oscillates. Radial feedback is not used with heavy ions because of the lower intensity involved and an open loop control is essential.

50 MeV Injector

The new 50 MeV Injector to be used for the Bevatron will use a complete digital control and monitoring system; centered around a PDP-9 computer.

Chains.

The chains for the injector is a parallel indicating, current source and logic level system. Each parameter (switch, relay contact, etc.) is driven by a 5 mA current source and the parameter value is examined by a Modulus 6 chain conditioning card. The chain conditioning card input is an Exclusive OR and a pair of NAND gates. The combination of gates, not only yields the value of each parameter but will also detect failures, such as open wires, shorted or grounded wires, missing swinger, or bridged contacts.

The output of the Exclusive OR's are connected to an 8-input NAND gate, that is used to detect an error in any parameter. The output of the chain conditioning card feeds a chain program card where the desired logic combination of the parameters can be obtained. The output of the chain program is used to drive a triac to turn on the desired device. (See Fig. 2).

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All chains are monitored by the chain-scanner. This device collects the status of all chains. The technician can examine the status of any chain by selecting the desired chain with a set of thumbwheel switches. There are eight chains per bin, 10 bins per rack, and eight racks total.

The status of all the parameters are sequentially monitored once every 15 ms by the chain-scanner. The output of the chain scanner is also sent via PDM to the computer where an operator can examine any of the chains. Software is being developed for continuous monitor and display of chains that have a change in status, ultimately, displaying the actual parameter that has changed.

50 MeV Linac

The quadrupole magnets in the drift tubes of the 50 MeV Linac are pulsed. If the magnet pulser fails to turn on before the proton source is triggered, the resulting high neutron flux provides a potential radiation hazard. There are 123 magnets pulsed by 64 pulsers. The current is a half-sine wave of 1.5 ms duration, and is flattened on the top for 400 μs. The rate of pulsing is every 500 ms. A fast digital scanner has been provided to monitor all 64 pulsers. The digital scanner provides an enable trigger to the ion source if all pulsers come on in the first 500 μs. Each pulser's current is monitored twice during the 40 μs flattop. The technician can select the pulser he desires to monitor and get a digital display of the magnet current and the value of the current slope during flattop. These two values are also sent to the computer via PDM where the operator can get a display of the data. Also provided are alarms for any failures in the system. (See Fig. 3)

The heart of the scanner is a 12-bit 2.3 μs total conversion time, analog to digital converter. The current signals are received with conditioning amplifiers multiplexed together and converted into digital information by the ADC. The digital information is compared to a predetermined value to insure that the pulser is turned-on. The slope of the current is determined by doing a full 12-bit signed subtraction of the two current values measured during flattop. The output of the analog to digital converter is loaded into a 128 word 12-bit MOS shift register to make full use of the fast ADC. The data is removed from the shift register and shipped via PDM to the computer between pulses.

750 keV Ion Gun

The ion source terminal contains 7 power supplies that have to be controlled from a remote position. The control of the power supplies is in two stages; (1) a course control obtained with a stepping motor and a Variac and (2) a fine control using a 12-bit DAC.

A PDP-9 computer is used for control and monitoring by a PDM Optical Data Link between the computer and the terminal, which is at 750 kV. In the terminal the data is received and transmitted by a 32-channel multiplexer and de-multiplexer. The multiplexer-demultiplexer handles all data communications between the computer, the semi-conductor memory and the power supplies. (See Fig. 4).

A Nyquist frequency of at least 100 Hz was desired. Because the PDP-9 was needed to monitor and control the complete 50 MeV injector, a high speed calculator was developed for the terminal. The computer transmits the reference for each power supply to the terminal and receives the data on the position of the Variacs, power supply voltage and power supply current from the terminal.

The control system is centered around a high speed calculator and a 1K by 16-bit semi-conductor memory. All data is stored in the semi-conductor memory and multiplexed in and out to whichever device needs or has data. The calculator only communicates with the semi-conductor memory as does any other device. The calculator will determine the control word using the program shown in Fig. 5. A new control word is calculated for all 16 channels once every 2 ms giving a Nyquist frequency of 500 Hz. The calculator is controlled by a microprocessor; 256 x 8-bit field programmable read only memory. The algorithm for the calculator is shown in Fig. 6.

Summary

An axiom for digital control enthusiasts. "The digital processor will make every attempt to destroy the hardware and humans subject to its control. Nibblers; yes, even gobblers; planted within the software will eventually consume themselves and cause the most unexpected results. Hardware must be organized in such a manner, that the software cannot damage it.

As an extension of this concept, consider the "mean time between failure". If you extend your MTBF by judicious application of "quality assurance", catasrophe will utlimately overtake you. Thus, consider not the MTBF, but rather, consider the catastrophic nature of the failure. Learn to have "well-behaved" shutdown instead of failure.

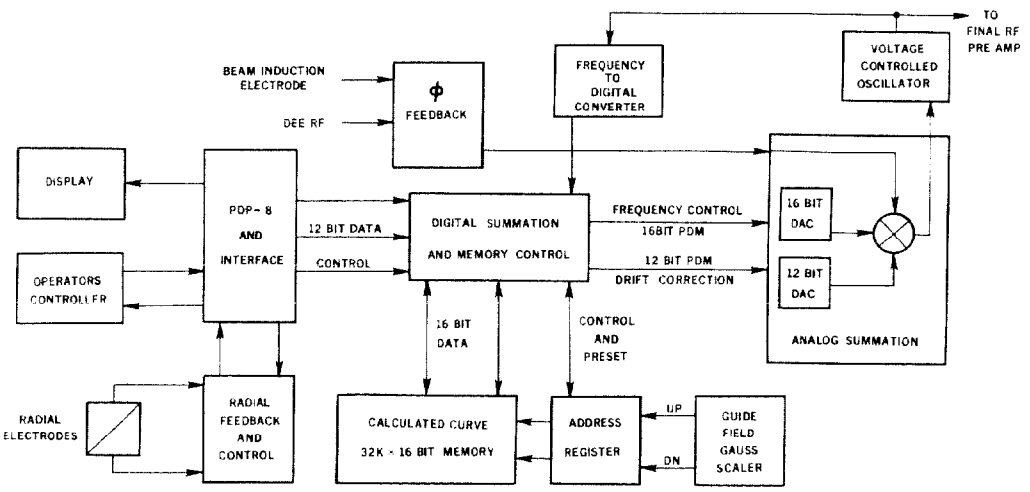


FIGURE 1 BEVATRON DIGITAL RF FREQUENCY MODULATOR CONTROL

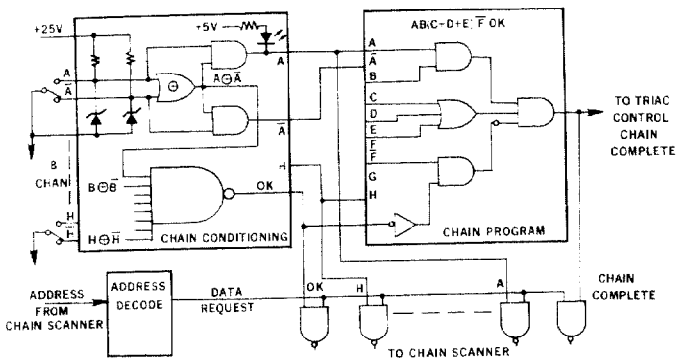


FIGURE 2 50 MeV INJECTOR CHAINS

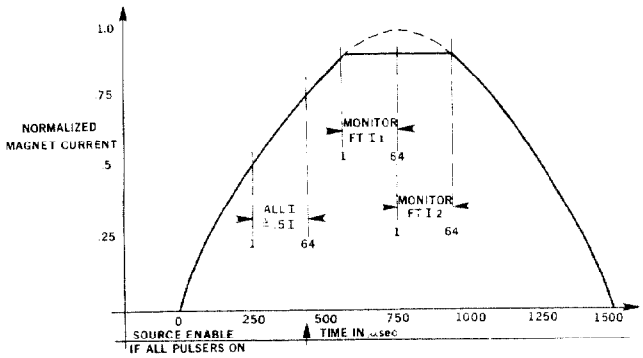


FIGURE 3 LINAC PULSED QUADRUPOLE MONITOR TIMING

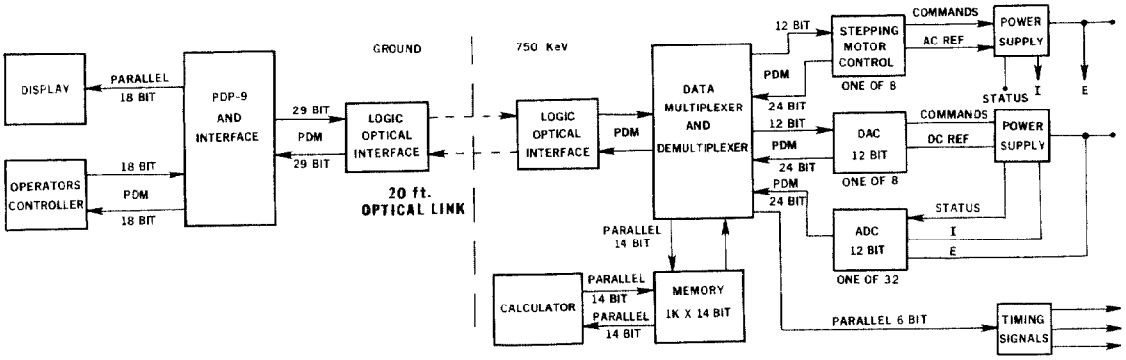


FIGURE 4 750 KeV ION GUN CONTROL BLOCK DIAGRAM

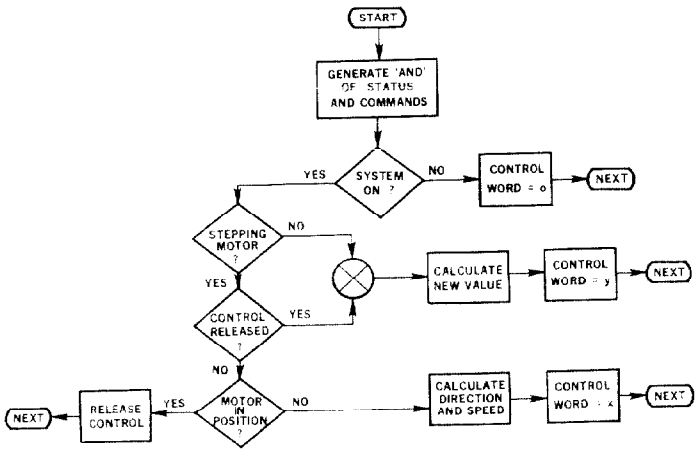


FIGURE 5 750 KeV ION GUN CALCULATOR FLOW DIAGRAM

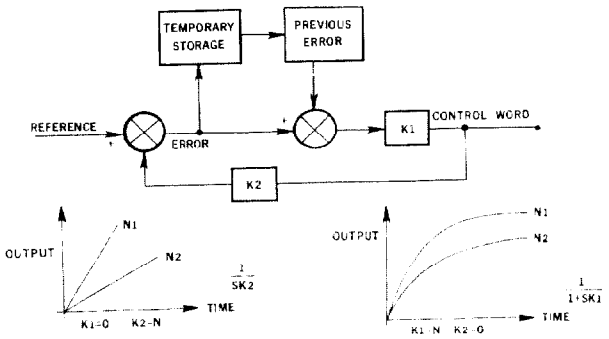


FIGURE 6 750 KeV CALCULATOR ALGORITHM