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INTERACTION OF ACCELERATOR CONTROLS AND DIAGNOSTICS

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Summary

Computer control systems have been in use on operating accelerators for several years. This paper discusses and gives examples of ways in which the capability of the control-system equipment can be used by accelerator engineers and physicists to study beam properties and operating characteristics of accelerator components.

Introduction

Many of the recently constructed accelerators are equipped with computer-based control systems. These systems have provided a very flexible and reliable means of controlling and adjusting accelerator components that are spread over distances ranging to several kilometers from the control room. The philosophy, design, implementation and operating characteristics of these systems have been adequately covered in the literature, and will not be discussed in detail here.[1,2,3,4,5] It is the purpose of this paper to discuss and, through examples, to show how the capability of the control system equipment can be used by the accelerator engineer and physicist for diagnostic measurements, that is, for studying beam properties and operating characteristics of the accelerator components.

A computer-based control system may be defined by the sketch shown in Fig. 1. The system includes a computer (or computers), an adequate set of peripherals, analog and digital interface to the equipment, and a console with appropriate keyboards and displays. Also shown here is an accelerator clock interrupt to the computer, which is an essential part of any real-time, interactive system if it is to be useful for accelerator studies. In this system, it is assumed that the computer is large enough to load and execute the number-crunching routines required to reduce data to an easily understood form. In fact, it is this combining of control, acquisition, analysis and plotting programs within the control computer, that has made possible some of the measurements and displays which are being done with these systems. For the sake of definiteness, much of the following description and examples will be taken from Fermilab systems, although similar work is being done at other laboratories.

Control-System Hardware

The machine operation and studies are both carried out from consoles in the Main Control Room. A typical console includes an alpha-numeric color scope and keyboard, a plotting scope with associated hard-copy unit, incremental shaft-encoder knobs, trackball for cursor control, special-function pushbuttons and a pushbutton called "keyboard interrupt." Other equipment located in or near the console is peculiar to the area of the accelerator normally controlled by that console. The control computers are Xerox 530's equipped with 64K of core and dual-spindle disk packs. Data are collected either directly or through the front-end mini-computers.

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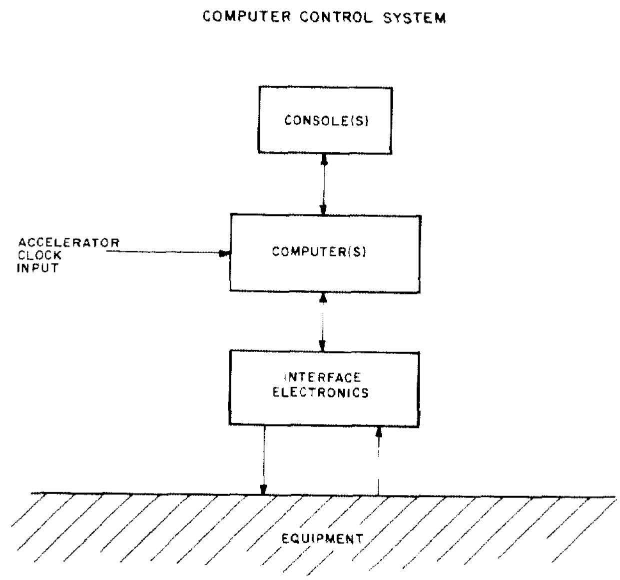


Figure 1. Simplified Computer Control System

The computer receives a high-priority interrupt from the accelerator clock every machine cycle, in this case 15 Hz. This interrupt allows the computer to synchronize its activities with the operation of the machine it is trying to control.

Using the System

Operating System

The computer core is divided into background, used for program development, and foreground. The foreground includes the vendor's disk operating system, the 15-Hz program and the application programs. Because the application programs are called into core only when they are needed, their number is limited only by the storage space on the disk pack. However, any job which is to be done each cycle must be made part of the 15-Hz program in resident foreground where the space is limited by the core storage.

The 15-Hz program takes in all the data and places them in a data pool. Simultaneously the data are being compared with preset nominal values, and out-of-tolerance parameters are listed on a separate display. The 15-Hz program must also perform special functions that are independent of application programs. Automatic reset of the preaccelerator high voltage, slow-loop regulation of linac gradients and inter-tank phases, and reset of linac quadrupoles are typical 15-Hz tasks. After completing the above tasks, the application program is triggered to execute. It is in position to read and control any parameter in the accelerator, read and store information on the magnetic disk, generate plots on the display scopes and utilize the computer's peripherals.

Software Development

Application programs are written in Fortran, compiled, and loaded onto magnetic disk. This work is done off-line, in the background area of the control computers, without interfering with operation in any way. The system uses no interpretive language. No program editing is done from the console. The consoles are in sufficient demand that only operational programs are called up and executed.

Each console has only one application program being executed at a time. The contents of the alphanumeric color scope are determined entirely by this program. Positioning the cursor on one of the forty columns of the twenty-four lines, followed by a keyboard interrupt, provides a means for the operator to cause the program to initiate some action, such as to set a parameter, start a plot, or begin some calculation.

Application programs are written by system programmers, physicists, engineers and operators. They have access to about one-hundred machine-language subroutines written to do specific small jobs such as setting a parameter value, or plotting a point.

The Parameter Display

In any accelerator control system, there is a need for a program to perform general-purpose readout and control of individual or groups of accelerator parameters. In the Fermilab system, this program is called the "Parameter Display." An annotated example of the display is shown in Fig. 2.

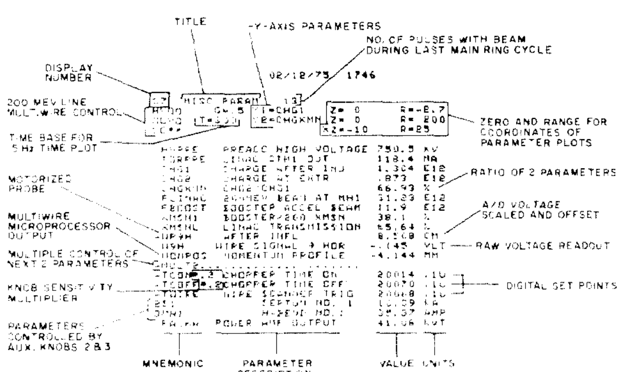


Figure 2. Annotated Example of the Parameter Display.

The four top lines of the display are used for title, selection of y-axis variables for parameter plots, offset and gain readout and control for the plots, and con- and readout of transfer-line multiwire profile detectors.

On the remaining twenty lines, the operator may enter the mnemonic code for accelerator parameters, thereby generating his own selection of variables to read and control. The readout is in engineering units and the available control functions are knob adjustments, entering and transmitting a setting, and ON - OFF - RESET.

Although it is possible to change the contents of each line, in practice it is more convenient to have available several pages of this parameter display with devices grouped by areas (200-MeV line or injection area) or by similarity of devices (timing triggers or motorized probes). In the booster system, there are 20 parameter pages. Each is stored and returned, when called into execution, with the arrangement of parameters last entered on the particular page.

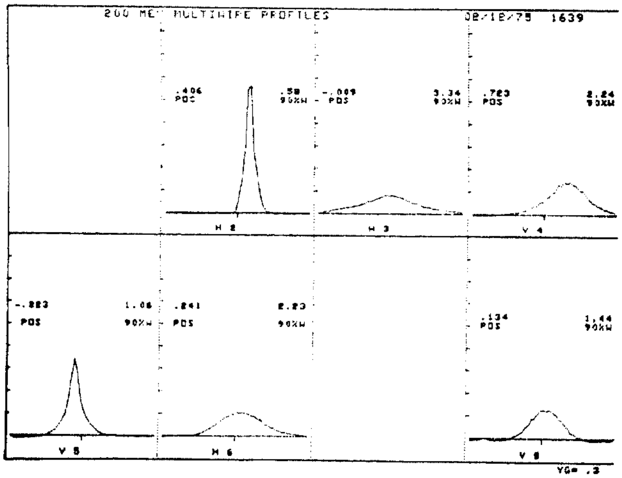
The plotting capability includes beam current at several locations, multiwire profiles from detectors in the transfer lines and an X-Y plot of any two parameters. Scale expansion of the axes is possible by selecting the diagonal corners of the region of interest using the plotting-scope cursor, positioned by the console trackball (Fig. 3).

The X-Y plot is a useful display for tuning short-pulse machines such as linacs. In synchrotron accelerators, many parameters vary as a function of time in the cycle and therefore time plots of these parameters are needed. For the main accelerator, this requirement is fulfilled by the "fast time plot," that is, repetitive digitizing and plotting of selected parameters by the control system equipment (Fig. 4). The fast time plot data are gathered at about 3 ms intervals. Although this rate is adequate for many main accelerator needs, the booster requires a much faster digitizing rate. Fast digitizer techniques will be discussed later.

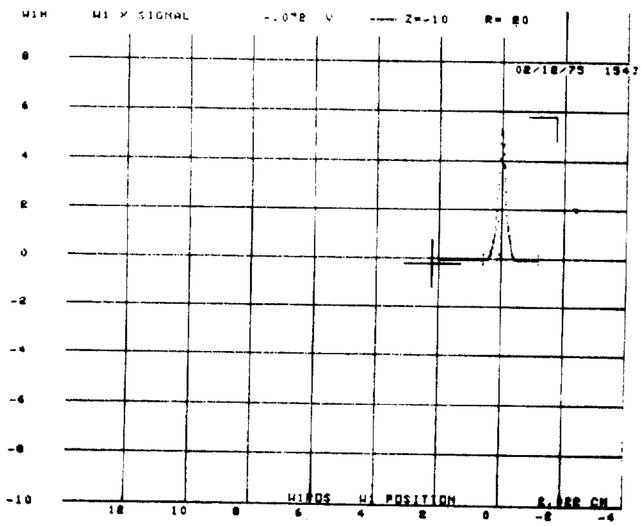
Special-Purpose Programs

The parameter display allows the operator to interact with one or a few parameters at a time much more conveniently than would be the case for non-computerized control systems. Other operations, involving large numbers of parameters, not only are made convenient, but are made possible by the computer. Single-knob control of the radial injection tune of a synchrotron, while holding the vertical tune constant, is an adjustment that could only be imagined before computers were incorporated into the control system. The operator feels free to try more adjustments because he can literally transmit a whole "accelerator-full" of previous settings to the remote equipment and recover from tuning that degraded the machine performance. Several files are available and can be sent to the hardware within a few seconds. These files may contain recent conditions, alternative operating modes of the accelerator or special conditions set up for accelerator research.

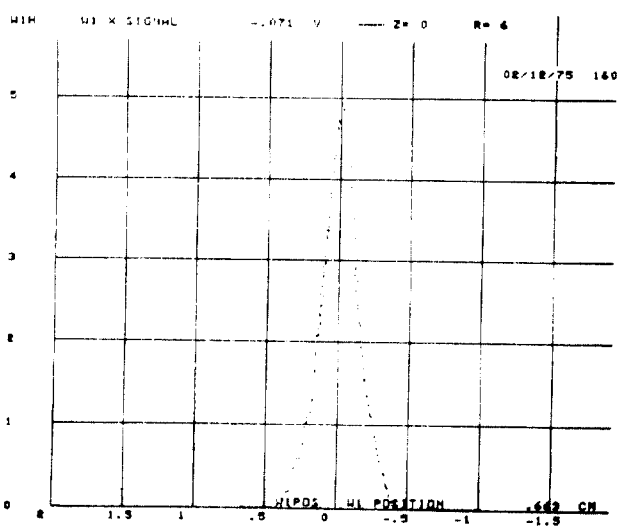
Computers are so proficient at collecting data that the operator has available to him several thousand parameter values each second, enough data to be completely useless if not properly treated. A measure of the success of a computer system and its application programs is - How well can it present pertinent information to the operator? For example, the monitor routine is a resident-foreground program that checks binary status and analog readings against nominal conditions. Improper status or out-of-tolerance analog readings are reported on a dedicated display. In this way, the operator is not encumbered by thousands of good status or within-tolerance readings. Ideally, if the beam disappears, there should be a message on a monitor display, indicating the name of the device that caused the beam to disappear. This ideal has been very nearly realized in the Fermilab linac since the monitor routine was installed in 1971.



(a)



(b)



(c)

Figure 3. Plots generated by the parameter display: (a) 200-MeV multiwire profiles; (b) an X-Y plot showing the region to be expanded; (c) expanded X-Y plot.

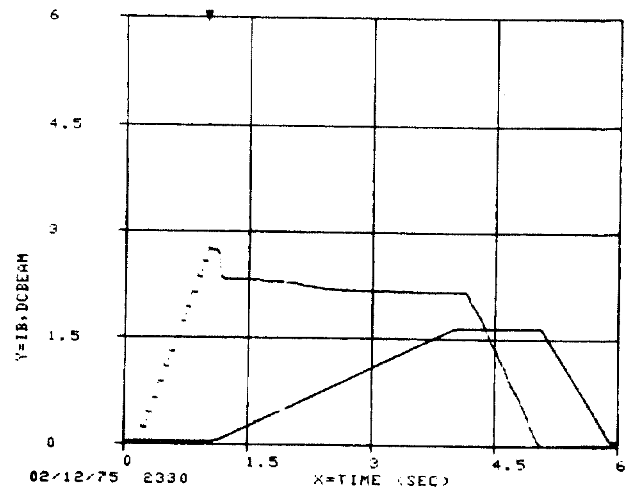


Figure 4. Fast time plot of the main magnet ramp and accelerator beam.

Operators can most easily interpret large amounts of data if they are presented in graphic form. The complexity and amount of calculation performed by the computer before the plot is generated varies depending upon the application. Some plots need only sorting and perhaps normalizing data points. An example of this type of plot is the display of losses along the extracted beam lines (Fig. 5). These data, which can be shown either unnormalized or normalized to beam at that location, are used as a tuning aid in the switchyard. Another plot used for switchyard tuning is the segmented-wire ionization-chamber (SWIC) profile display shown in Fig. 6.

Some plots require more calculation to get the results into an easily recognizable form. The main accelerator is a separated-function machine, so the betatron tunes may be calculated from the quadrupole and bending magnet currents. Repetitive sampling of these currents within a single cycle provides the data for tune calculations, and the results are presented as the locus of the operating point on the familiar tune space diagram of Fig. 7.

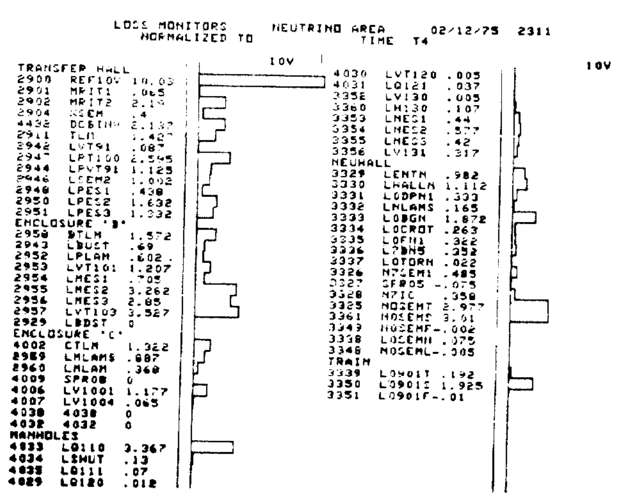


Figure 5. Neutrino Area loss monitor plot.

Fast Digitizer Techniques

Although most of the data are collected in the usual fashion, that is, digitized by the control system's multiplexed analog-to-digital converters, there are data sources that require special handling. These are

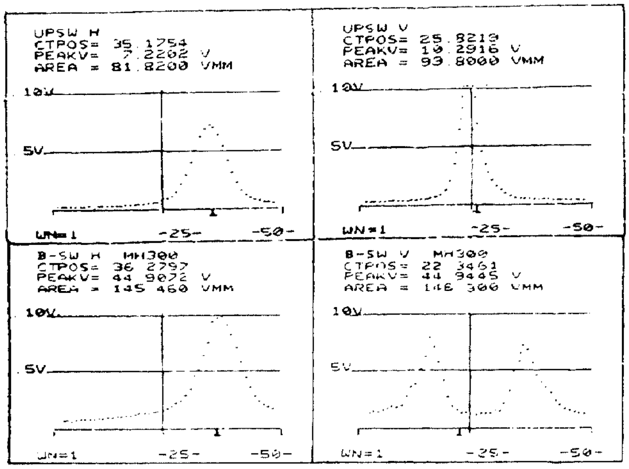


Figure 6. SWIC profiles before and after a vertical splitting station.

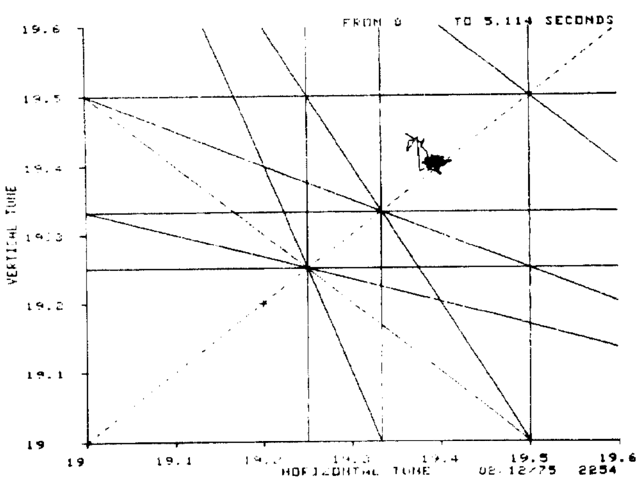


Figure 7. Main-accelerator tune space diagram.

the fast digitizers, which produce hundreds or thousands of data points at a rate that is impossible for the control system to service in real time. The data must be digitized and stored locally and transferred to the computer by the application program. Two commercially available fast digitizers are used for Fermilab booster diagnostic measurements; (1) the Nicolet digital oscilloscope and (2) the Tektronix 7912 transient recorder. Their capabilities are: (1) 4096 twelve-bit words, digitized at rates as fast as 1 μsec per word, (2) 500 nine-bit words at an effective digitizing rate of up to 10 ps/word. The Nicolet is useful for digitizing video parameters over part or all of the booster cycle; the Tektronix 7912 is used for studying faster phenomena. These two instruments make it possible, routinely, to use the computer to analyze signals that previously existed only as Polaroid pictures. With minimum software support, these digitizers coupled to the computer all but eliminate picture-taking. Figure 8 is an injection betatron oscillation and Fig. 9 shows the effect of the debuncher on the 200 MHz structure of the linac beam, after one turn in the booster. The apparent signal-to-noise ratio of weak signals can be considerably enhanced by digitally subtracting the no-beam baseline from the signal.

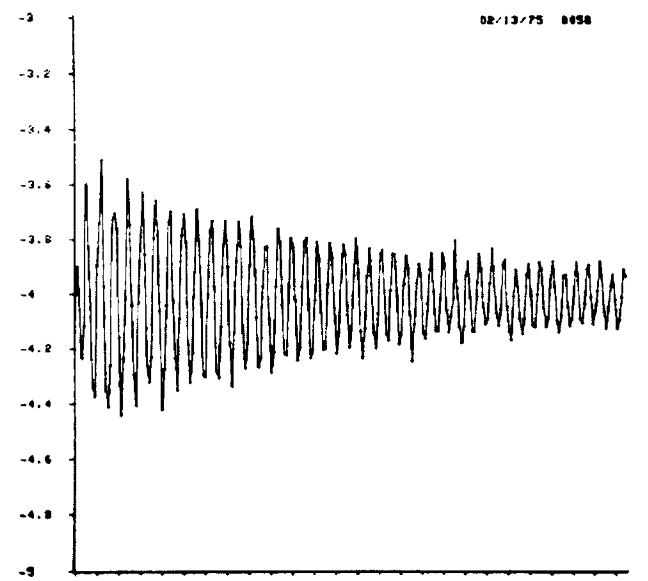


Figure 8. Booster radial betatron oscillation digitized by the Nicolet.

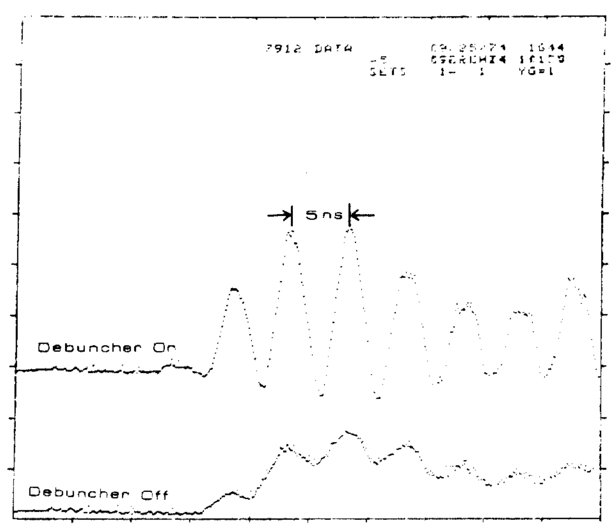


Figure 9. First turn booster beam showing the effects of the debuncher on the 200 MHz structure.

Several data analysis programs have been written to operate on Nicolet data. A Fast Fourier Transform routine greatly simplifies the measurement of phase-oscillation frequencies. The Fourier Transform of a position detector signal can show not only betatron oscillation frequency, but also evidence of coupling and resonance phenomena. A 1024-channel signal-averaging program is used for improving the signal-to-noise of weak signals. This technique has been used to smooth spectrum-analyzer data acquired during Schottky-scan studies. Other programs provide scaled plots of rf accelerating voltage corrected for diode non-linearity and cable attenuation, analyze and display data from an ion-profile monitor in the booster ring, and provide a means for recording digital data from video signals for off-line data reduction. Typical processed Nicolet data plots are shown in Fig. 10.

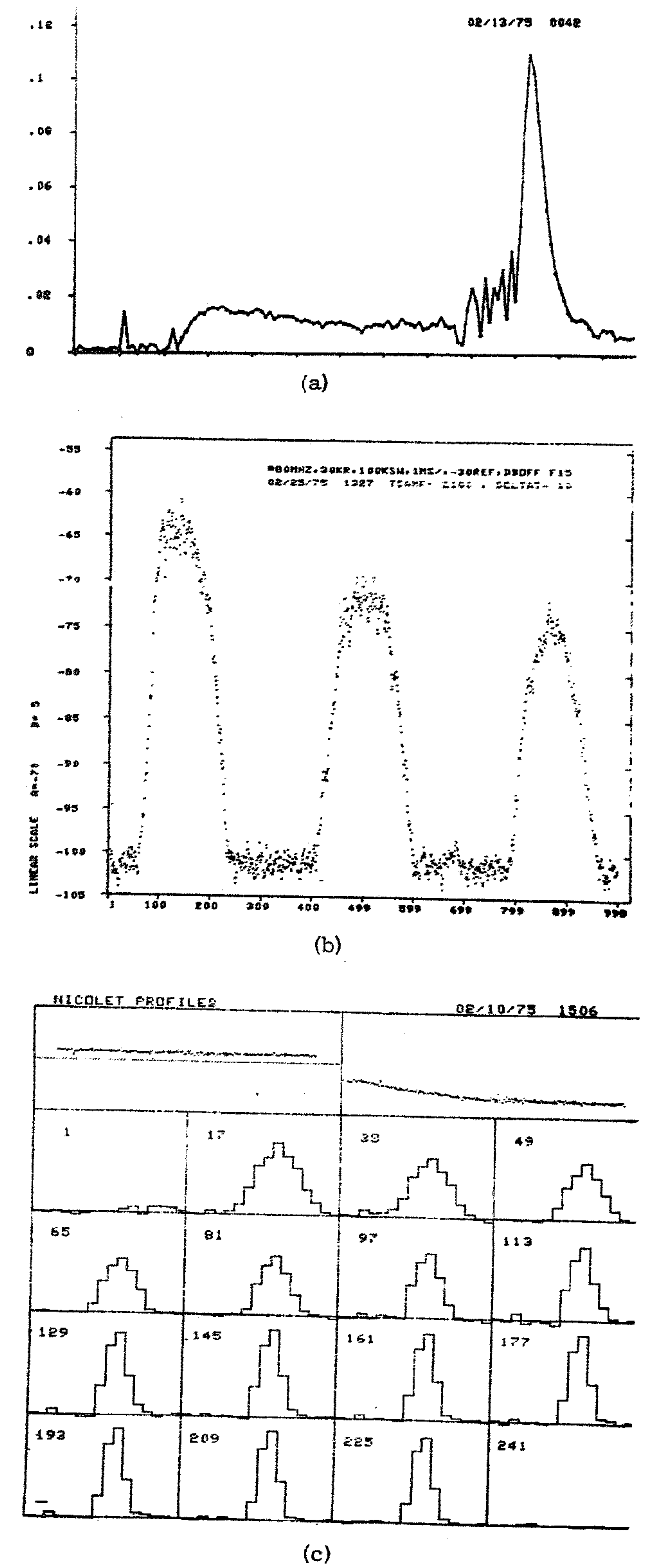


Figure 10. Examples of processed Nicolet data: (a) Fast Fourier Transform of a beam position signal; (b) signal averaged spectrum analyzer data; (c) ion profile data.

An example of the impact of the computer on diagnostic measurements can be seen by considering various techniques for handling data from the single-wire beam scanner, a device consisting of a probe drive that moves a wire through the beam. The secondary-emission current from the wire is shown on the photograph of Fig. 11. If this same type of data is sampled and read into the computer, the beam profile can be plotted as shown in Fig. 3c. If the probe is automatically stepped through the beam in 1-mm increments and a 50-μsec interval of the video signal is digitized with the 7912, data shown in Fig. 12 are acquired. The wire scanner being used here is located just downstream from the injection septum in the booster, so the wire scans both the injected and circulating beams. At a rate of one pulse per second, a seven-cm scan is completed in about one minute. Figure 13 shows the data from an entire run, about 35,000 points. The

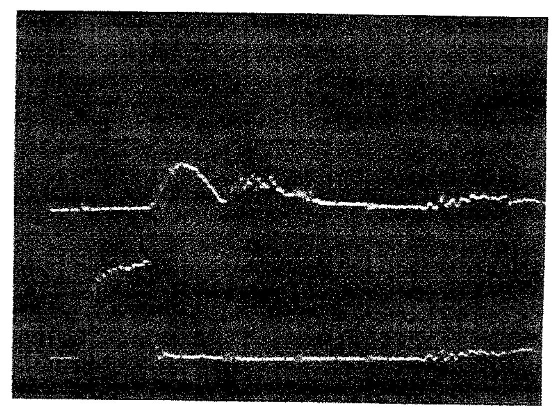


Figure 11. Secondary emission current from a wire scanner.

computer can rearrange these data into a cross-plot, as in Figure 14, where each trace is now a beam profile separated in time by 200 nsec from the neighboring profile. From this display, it is possible to visualize the multiturn-injection process and to see directly, the apparent septum thickness, the action of the injection orbit-bump and the residual betatron oscillation. For this figure, only two microseconds of beam were being injected and the radial tune of the booster was adjusted to $\nu_x = 6.50$. More normal operation, with two turns injected at a radial tune of 6.58 is shown in Fig. 15. It is interesting to point out that the data contained in Figs. 14 and 15 are the same as the Polaroid photograph; the computer has only been used to present the data in a more intelligible format.

Computer Optimization

It is sometimes desirable to have the computer automatically optimize accelerator parameters. There are several types of auto-optimization; 1) maintaining a parameter at a preselected value, 2) finding the optimum setting for parameters, by observing effects caused by adjusting (or mis-adjusting) them; 3) using measured accelerator data as input and calculating settings required to achieve some operating condition; 4) learning-mode programs.

The first method is a slow-feedback loop to regulate and stabilize parameters. This type of control is

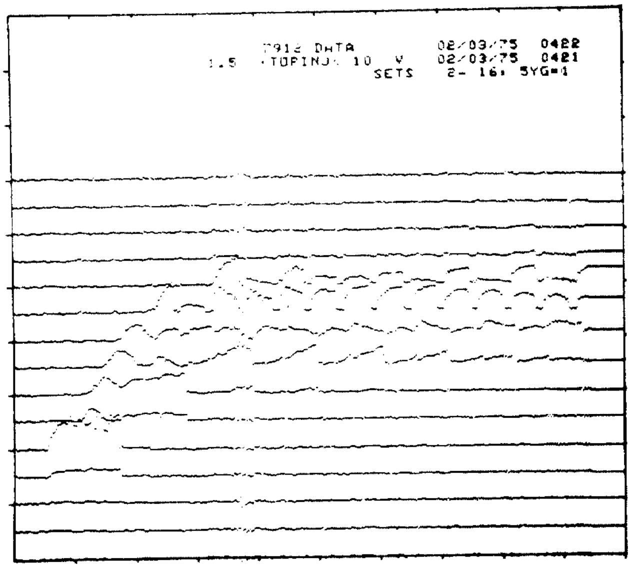


Figure 12. Digitized wire scanner data 5 μsec/division.

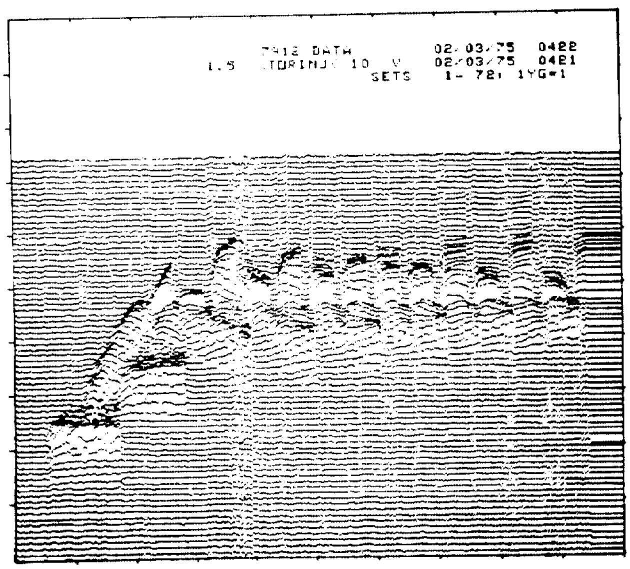


Figure 13. Complete set of data from an injection wire scan.

used to stabilize the Fermilab linac tank gradients and inter-tank phases.

Figure 16 shows the output from a LAMPF[6] optimizing routine called MESA, which finds an optimum value for two variables by detecting the effects of adjusting them. In this example, the program adjusts two steering magnets to maintain 90% beam transmission. It then calculates the optimum value for the two dipoles.

At the Brookhaven AGS, measured beam emittance parameters are entered as input to a beam-transport program. The computer then calculates the corrected magnet currents required to obtain a requested emittance orientation at the inflector. Figure 17 shows the output from this program.[7]

Programs that change the operation of a system based upon results of measurements made during previous cycles are called learning-mode programs.

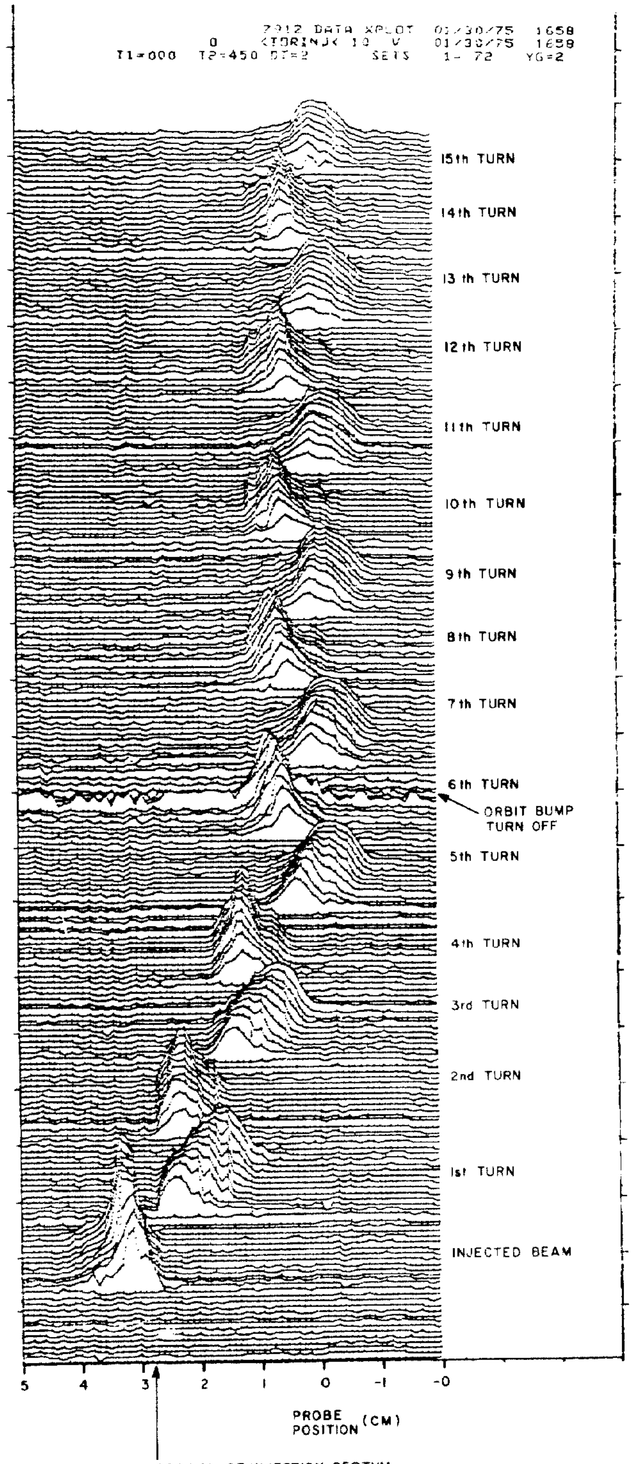


Figure 14. Cross plot of injection wire scan for $\nu = 6.50$.

They are generally used to generate curves to control larger systems such as frequency programs for rf accelerating systems. A rather complex example of this type of optimizing routine is the magnet-control program for the Fermilab main accelerator.[8]

Microprocessors

No discussion of accelerator diagnostics and controls would be complete without considering the microprocessor and its application to accelerator systems.

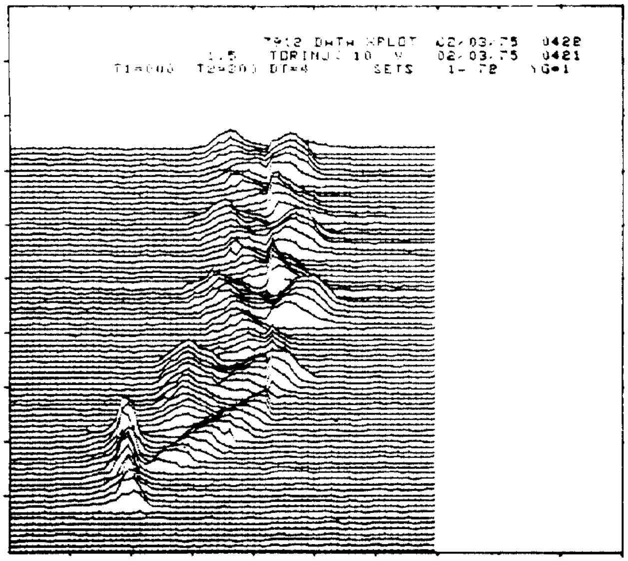


Figure 15. Cross plot of injection wire scan for ν = 6.58.

The computer-on-a-chip devices have been developed, within the past two years, to the point that 4, 8, 12, and 16-bit processors are now commerically available and economically attractive. They are used to build stand-alone "smart" instruments and to pre-process data before sending it to front-end or control computers. Microprocessors are capable of performing some of the tasks otherwise thought of as resident foreground jobs, thereby saving both computing time and core.

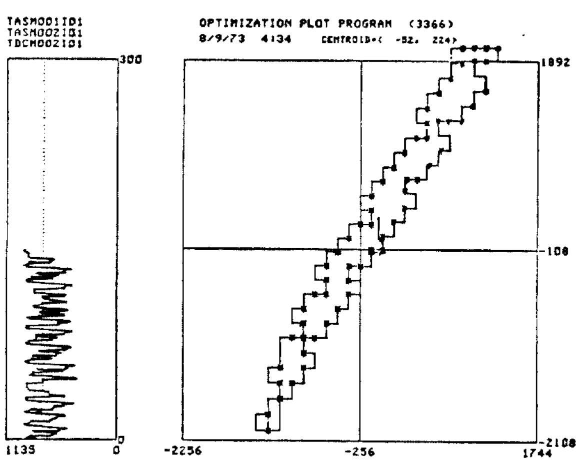


Figure 16. Computer output from LASL "optimize" routine.

Existing microcomputer systems at Fermilab include a stand-alone CAMAC crate for experimental-area beam-utilization display and logging, a processor to calculate the beam position and width from the 200-MeV line 48-channel multiwire profile detectors, and several "smart" display controllers for use in the main control room.

The background area of the control computer is used to assemble microprocessor programs. Assembly-language programs are read in from cards, and the computer prints out the listing and a binary paper tape containing the microprocessor's machine-language instructions. The contents of the tape are programmed into ultra-violet erasable programmable read-only memories using a commercially available programmer. Turn-around time using this system is only a few minutes. At the present time, assemblers for Motorola 6800 and Intel 8080 and 4004 microprocessors are available in the background area of the linac control computer.

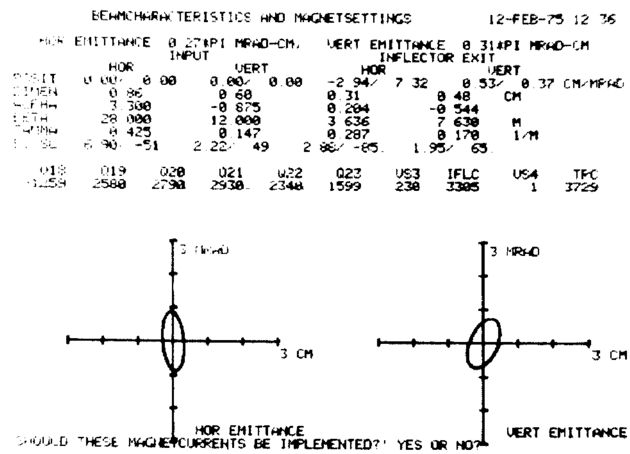


Figure 17. Computer output from Brookhaven injection line tuning program.

In general, we have found that all the arguments advanced for the inclusion of computers in control systems apply in miniature to microprocessor systems. The application of microprocessors to accelerator problems is just beginning and we will see many more uses of them in the future.

Conclusion

Control systems for various laboratories have evolved differently because the machine requirements are different and because the people implementing the systems have a variety of backgrounds. As for the machine's requirements, consider the X-Y plot in the Fermilab systems. It is a high interactive and responsive technique at the linac's 15-Hz repetition rate, somewhat tedious at the booster's accelerator-study rate of one pulse per second, and all but useless for the main accelerator's 5-15 sec cycle time. Techniques that are appropriate at the Fermilab 15 Hz may not be useful at the much higher repetition rates of LAMPF and SLAC. Preferences of the system designers are reflected in the systems they implement. In contrast to the operating mode described here, the CERN group plans to have an interpretive system; the SLAC group prefers touch panels; the LASL system, in effect, has several application programs per console, all sharing the alpha-numeric scope and other console hardware. In spite of their differences, it is the common aim of these systems to improve the operation of their respective accelerators. The extent to which they will fulfill this aim depends, in part, on how well they adapt to the diagnostic needs of the accelerator.

Acknowledgments

This work is due to the efforts of a great number of people. In addition to the entire Controls Group, I would like to acknowledge the specific work of several individuals: The linac and booster operating systems are due to Bob Goodwin, who is also responsible for the parameter display and the 7912 programs. The

Nicolet data reduction and display programs were written by Bob Peters. The main accelerator tune program was written by Rodney Smith. Though not shown in this paper, many linac and booster-application programs have been written by Ed Gray. Fred Hornstra is responsible for the switchyard diagnostics and specifications for the switchyard displays shown here.

References

1. H.S. Butler, "Computer Control of the Los Alamos Linear Accelerator, "IEEE Trans. Nucl. Sci., NS-14, No. 3, 1030-1041 (1967).
2. M.Q. Barton, et al., "Use of a General-Purpose Time-Shared Computer in Accelerator Control," Proc. of the IXth International Conf. on High Energy Accel., 495-498 (1974).
3. K. Breymayer, et al., "SLAC Control Room Consolidation Using Linked Computers," IEEE Trans. Nucl. Sci. NS 18, No. 3, 409-413 (1971).
4. J. T. Hyman, "The Computer Control System for the SPS, "Proc. of the IXth International Conf. on High Energy Accel., 503-507 (1974).
5. R. E. Daniels, R. W. Goodwin, and M.R. Storm, "The NAL Computer Control System, "IEEE Trans. Nucl. Sci. NS 20, No. 3, 505-509 (1973).
6. D.A.Swenson and J.E. Stovall, Private Communication.
7. H. N. Brown and J. Claus, "Computer Programs for AGS Injection," IEEE Trans. Nucl.Sci., NS 20, No. 3, 528-530 (1973).
8. R. Cassel, "A Multiple Flattop Control System for the Fermilab Main Accelerator Power Supplies," to be published in the proceedings of this conference.