12. CONTROLS

12.1 Control Requirements

In this section we will discuss the nature of the system we are trying to control, how it differs from the present Main-Ring system and what controls might fulfill the necessary functions. Certainly, as ideas become engineering realities and details implemented in hardware or software, the present concepts may be modified or destroyed by hard realities.

The superconducting accelerator-collider is a very different animal from the present Main Ring, where, if one does not know what went wrong, one can try again in a few seconds. Present measurements indicate that it may take half an hour to recover from a full-field quench, which could make for dull and unproductive knob twiddling. We must have information recorded on the pulse that went astray so that we can diagnose the problem and minimize the chance of recurrence.

The refrigeration system is very large, with many components working in parallel and series. Control must be set up to balance the satellite and central systems for stable operation, monitoring for failure of individual components, and automatic adjustment and compensation for such failure.

The magnet power supply system must at all times monitor the operational integrity of the magnets, as discussed in Section 6. It is also likely that as refrigeration capabilities change or beam-loss problems arise, changes in ramp rate, peak energy, flat-top time and cycle time will need to be made. The whole system should make it possible to make these changes easily and quickly.

Accumulating enough $\bar{p}$'s for injection into the collider is expected to take three hours. They must be injected correctly and manipulations performed on the stored beam in a properly sequenced and coordinated fashion. Coordination of the operation of the Linac, Cooling Ring, Booster, Main Ring, and Superconducting Ring over long times is also imperative. Operation will not be as repetitive as now and emphasis will be put on setting up a sequenced operation and requiring that it be initiated at a specific time and carried through.

In the following sections, we shall discuss in detail only the basic systems necessary for fixed-target operation and tuneup.

12.2 System Architecture

The control system for the superconducting ring will make use of the central computer system of the present accelerator control system. But the special requirements of a superconducting accelerator, discussed in Section 12.1 above, will mean that additions to the system will be needed.

The interface electronics for providing control, monitoring, and diagnostic facilities will use modular packaging for each of the major subsystems (vacuum system, correction element waveform generators, etc.) of the accelerator. Most monitoring and control of the individual subsystems will be done at the local level, using interface electronics that incorporate both microprocessor-based intelligence and local memory.

The orchestration and coordination of the distributed-subsystem electronics is provided by communication with the central computer system.

The local subsystem electronics will be supported from a CAMAC crate system (ANSI/IEEE Standard 583), which provides a powerful data-architecture for device interface. Communication between one or more CAMAC crates located in each service building and the central computer system will be via high-speed serial data links that will utilize existing dedicated, direct-buried coaxial cables. The protocol of the serial links will be modeled to ANSI/IEEE Standard 595 (Serial Highway Interface System) protocols to the extent possible or desirable.

The new ring will require diagnostic facilities that will involve the transmission of large blocks of data from the local electronics to the central system when unusual conditions arise (magnet quenches, etc.). The desirable aspects of the standard Serial Highway Interface System will be supplemented by block-transfer facilities, which provide an efficient method for transferring significant quantities of data from the local electronics to the central system. Correlation, analysis, and presentation of these data to the main control room will use the software facilities of the central system.

12.3 General-Purpose Multiplexed Analog-to-Digital Converter (MADC)

Each service building will have a general-purpose MADC and associated CAMAC-based controller making available digital representations of varied analog system process parameters. The MADC will have 12-bit resolution (0.025% of full scale) and will provide for up to 64 differential analog inputs. The MADC controller will contain on the order of 2K words of memory for storage of digitized data. These data will be transmitted to the central computer upon demand for correlation and analysis.

The MADC and its associated controller will provide three distinct modes of data collection:

(i) Self-Scanning Mode: The MADC will automatically digitize all channels at a predetermined or programmed rate, perhaps 10 Hz and store results as files in a pseudo-circulating memory. 1K of RAM would provide storage for 15 files. This feature will provide the necessary snapshot data in the event of a quench or abort. Provision will be made via block-transfer facilities for the central computer to read the most recent or all of the 64-word files.

(ii) Plotting Mode: This mode of the MADC will provide for plotting of up to four different channels at a user-programmed frequency. Continuous data are required for such plots and the associated memory for this function would therefore be in two sections, so that the central computer could read one section while the other was being loaded. The time resolution of such a plotting facility is expected to be 1 ms or better. Maximum time resolution will be ultimately determined by saturation of block-transfer and graphics-output facilities.

(iii) Transient-Analyzer Mode: This mode is similar to the plotting mode and could provide up to 10 to 20-μs resolution of any single analog input. This mode is an operational alternate to the plotting mode and would use the same memory. Up to four channels could be plotted at a sample frequency specified by the operator. Sampling would be triggered externally and would stop when the allocated memory was filled. Data would be returned to the host via block-transfer facilities.

The various modes of operation of the digitizer make it a general-purpose instrument that can be used for a variety of applications. For example, detailed measurements and studies of power-supply ripple can be made by digitizing power-supply readbacks at selected locations while simultaneously digitizing the output of a beam-sensitive detector in the extraction channel.

12.4 Local Control Terminal

A local intelligent, interactive, stand-alone terminal is desirable. Such a terminal will be portable and will interact with service-building devices by connection to the CAMAC system. It will be of particular use in turn-on and adjustment of the satellite refrigerators, where local adjustments of engines may always be necessary, but it will also aid in testing and development of other systems. The hardware configuration will include a floppy-disk system, a keyboard, an alphanumeric display monitor, and a video-graphics monitor as input-output devices. The processing power that is required at the local terminal is not particularly great and the local terminal will be packaged so that it can be moved easily from one service building to another.

12.5 Cryogenic System

The cryogenic system will require a number of closed-loop servo systems for process regulation. There are three independent major subsystems controlling

(i) the compressor suction and high-pressure gas systems,

(ii) the 24 satellite helium system (11 control points per satellite),

(iii) the liquid-nitrogen system.

The cryogenic system utilizes four compressors in each of six buildings with pressure regulation at each building and a master loop to balance the ring. The suction-pressure regulation must be done by a high-pressure kickback valve to the central system. This valve will control the gas inventory in the entire ring system.

Figure 12-1 is a schematic of the satellite system with the process variables labeled as letters and the control points labeled as numbers. Control of the satellite during normal operation is described below.

The amount of liquid used from the CHL is adjusted by valve (6) and is servoed from the return-gas temperature measured at point B between heat exchangers III and IV. The wet-engine speed (4) is controlled by the pressure at the refrigerator output (point C). The JT valves at the ends of the individual magnet strings (7, 8) are controlled by pressure sensors and helium vapor pressure thermometers at points D and E. The JT valves are set such that the temperatures at D and E are 0.1K above the two-phase boundary temperature to insure maximum magnet cooling. Cooling for the nitrogen shields of the magnets is maintained by constant-temperature control at the nitrogen outlets.

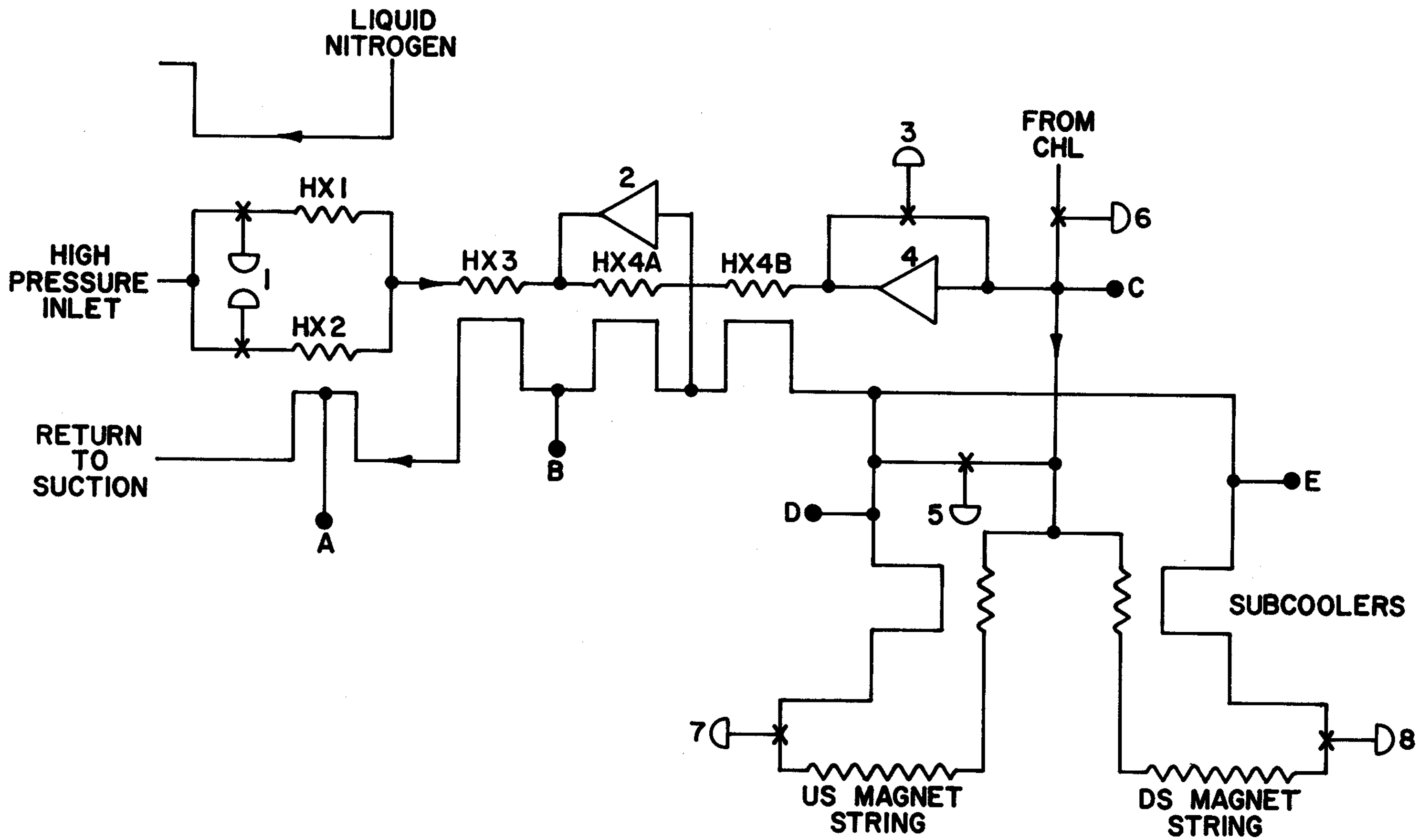

Fig. 12-1. Satellite system schematic showing process variables (letters) and control points (numbers).

When liquid from the CHL is not used, the percentage of helium flow through the liquid-nitrogen precooler (HX1) is adjusted by valves (1). The settings of these valves are controlled by the temperature of the return gas measured in the middle of HX2. The nitrogen level in HX1 is controlled by its own level detector. The gas-engine speed (2) is now servoed from the temperature at point B.

The primary JT valve (3) and bypass valve (5) can be controlled from point C. The JT is used primarily during failure of the wet engine and the bypass valve is used during cooldown or unstable operation.

The nitrogen system has three servo loops. The first maintains the liquid level in the first heat exchanger HX1. The other loops control the cooling in the nitrogen shield in the two magnet strings fed from one service building by maintaining a constant output temperature at the nitrogen outlet.

Most routine control, adjustment and monitoring will be done from the main control room using the general-purpose serial CAMAC facilities. The refrigeration system will also require the development of flexible closed-loop control that is local to a given satellite and development of the interactive local control station for use in the initial debugging and in performing operational adjustments.

Experience thus far has indicated that it is desirable to implement the closed loops using a dedicated intelligence module housed in the local CAMAC crate. The present scheme calls for monitoring about 60 channels of analog information and control of as many as 11 closed loops. This system could easily be extended to provide local generation of tolerance alarms, resulting in a significant reduction in the number of devices that the main system would be required to scan.

12.6 Vacuum Monitor and Control

A CAMAC-based vacuum controller will be implemented at each of the 24 service buildings to collect vacuum data and to exercise control of valves and pumps associated with insulating vacuum and section valves in the bore tube. The controller will continuously scan all its local transducers and calculate the average vacuum readings at the service building. During normal operations, the average reading and the local high and low will be sent to the central system. This scheme will greatly reduce the communications workload that exists in the current Main-Ring system, where each individual reading is returned to the central computer for house-average calculation. Any out-of-tolerance readings will be flagged to allow localizing trouble conditions. Upon request of an operator, all individual readings will be made available via block-transfer facilities for display.

The controller will be able to sequence events to establish and maintain desired insulating vacuum and to operate the electropneumatic section gate valves in the beam tube. In the event of a partial or catastrophic vacuum loss, the controller should respond immediately to prevent propagation of the problem.

An interlock will be supplied to the refrigeration system to indicate sufficient vacuum for start of cooldown and a beam permit will be generated to indicate that all section gate valves in the bore tube are in the full-open position. A temperature input is desirable to allow turning off appropriate pump stations once cryopumping dominates.

A manual control panel in the service buildings will allow local readings of individual transducers and operation of individual pumps and valves. The controller will respond to a manual operation if established vacuum is not jeopardized. Any illogical request will generate a warning and will be performed only if a separate manual override is set.

12.7 Quench Detection and Snapshot

If possible, it is best to detect a beam problem and fire the abort before the magnets quench, so that recovery time can be minimized. In order to detect such problems continuous monitoring of various beam parameters is necessary. For instance, beam position and tune should be kept within allowable limits and beam losses kept below the level sufficient to trigger a quench. Local continuous monitoring of all beam-position detectors could generate an abort trigger if any signal exceeded the allowable limit. If all the position information is stored in a local memory that is frozen at the time of the abort trigger, then in effect a "snapshot" is taken. The information can be recalled to the central computer and analyzed in terms of necessary corrections to the trim-dipole wave forms before another pulse of beam is attempted. Note that corrections are used throughout the acceleration cycle and must be set properly at every level of excitation.

There will also be instances when a quench occurs but no previous indication of malfunction or mistuning has been detected. In this case, the cause of the quench may have occurred considerably earlier in time and the snapshot of various quantities must be monitored over sufficient time to give an indication of cause, be it caused by beam, insufficient refrigeration or a weak magnet.

Thus the time from the initiation of a quench to its detection is the fundamental time constant of the system. Presently two control techniques are being investigated. The first technique calls for data from all pertinent devices to be collected for a time extending backward from the time the quench is detected to the time of the start of a quench. A second scheme that anticipates quench propagation calls for collection of data both before and after a quench or abort.

Accommodation of one or both techniques demands an accelerator-wide philosophy of data collection that can yield analytically coherent snapshot information. Questions remain as to what is a realistic time constant for each of the various subsystems and also as to what rate of sampling is required within this time constant.

The quench-detection interface module should have a circular buffer capable of storing half-cell voltages for a period of 1 s prior to a quench to 10 s after. The data can be used to reconstruct primary and secondary quenches for analysis and to cross-check the quench-detection monitor itself.

12.8 Abort Trigger

The abort trigger system consists of an input panel in each service building that accepts triggers from a large number of different types of control units, for example, power supplies, quench detectors, beam-position detectors, loss monitors, and so on. Each trigger input and its time of occurrence will be recorded in a digital status module. The information can then be transferred to the central system to determine which alarm or alarms generated the abort, and their order of occurrence.

An or-ed output of all activated triggers is used as an input to the abort-trigger-system communications link. This link makes use of a dedicated cable which runs from service building to service building around the ring. A circulating pulse on this cable is used as a "heart beat" or "keep-alive" signal to the abort kicker; when the heart-beat pulse disappears, the abort kicker is fired. The use of a dedicated abort-trigger system communications link results in a delay of only a few turns before the information to trigger a beam abort is transmitted from any service building to the abort kicker at C0.

12.9 Correction and Adjustment Elements

The present correction element package consists of 180 trim dipoles, quadrupoles, sextupoles, and a large number of skew quadrupoles and octopoles. The dipoles are independently powered and require 180 independently driven but synchronized waveforms. The other correction elements will be powered in series strings utilizing up to eight power supplies per type of correction element; they also demand up to an order of magnitude higher precision. The description of the dipole function generators will consequently emphasize the potential operational problems in using so large a number of independent waveform generators.

12.9.1 Dipole function generators. The correction-element power supplies require a versatile ramp generator. The detailed shapes of the time-varying excitation currents of the dipoles are not known *a priori*, but must be determined during commissioning and operation. On the other hand, the basic functional service provided by the correction elements is relatively straightforward and well-defined and the associated waveforms are not expected to be unduly complex.

The design of the waveform generators has been guided by the following design requirements, operational characteristics, and viewpoints:

(i) It is desirable and possible to characterize each of the 180 waveforms by a small number of parameters. Specifically, each waveform can be parameterized by a sequence of thirty-two (or fewer) piecewise linear segments.

(ii) User-oriented software facilities, available at a control-room console, will be used to set up, generate, validate, and manipulate the parameters of the various waveforms. These parameters will then be downloaded to the local function generators, which will develop the required waveforms without further interaction with the main control room until a modification is required.

(iii) Continuous diagnostic and monitoring features are necessary to ensure the reliable operation of the waveform generators and power supplies. These features will be provided by incorporating self-checking facilities into the design of the function generators. These continuously active, self-checking features should allow the central control system and the control-room operator to ignore the normal operation of the correction-element package, but should provide the operator with information on abnormal or out-of-tolerance conditions.

(iv) The waveform generators should provide facilities for accommodation of changes in the main-supply excitation curve and facilities for entering and leaving the storage mode and for tuning the elements while in that mode. A B-dot clock with a frequency controlled by the main guide field could possibly be used in conjunction with the ramp generators to ease the complexity of changing ramp times and flat-top lengths. The first-order field dependence of the correction could then be removed explicitly from the waveform curves. The relative merits of the real-time clock vs. B-dot clock are yet to be assessed and the following discussion uses a a real-time clock for simplicity of description.

(v) A temperature-stable, bipolar, 12-bit digital-to-analog converter (11 bits + sign) is adequate for providing the required accuracy and tolerance.

These functional characteristics of the waveform generators could be realized with a design technique using either random logic or microprocessor-based local intelligence. The two techniques would be comparable in performance and flexibility; the preferred implementation technique in this case would undoubtedly be determined by the economics of specific designs.

The function generators will be packaged as CAMAC modules and be housed in new CAMAC crates located in each service building.

12.9.2 Quadrupole, sextupole, and octopole generators. The description of the quadrupole and octopole power-supply systems in Section 7 summarizes the rigid tolerances that are required for these elements. The use of high-precision A-to-D and D-to-A converters is mandatory; greater attention to noise and isolation protection is necessary. For these reasons, it is clearly desirable to package the A-to-D and D-to-A converters with the power supply.

With this modification, the function generators for the dipoles, described above, would also be adequate for the quadrupole, sextupole, and octopole power supplies. The use of totally digital techniques both to parameterize the waveforms and to generate the required voltage set-point is easily extended to the required 16-bit precision.

12.10 Position Detectors

A horizontal position detector is located at the upstream end of each horizontally focusing quadrupole and a vertical detector at each vertically focusing quadrupole. These detectors are electrostatic.

The electronics of the system consists primarily of an rf multiplexer to switch among signal input pairs, and a beam-position processor unit which uses amplitude-to-phase conversion and phase comparison to obtain the position information independent of intensity. A trigger box senses when beam is present, especially for first-turn information and an interface module will contain memory to store the information as a function of detector and time. Typically, signals from nine detectors come to each building. Extra channels are available for test signals and additional detectors. Provision will be made so that a special single-bucket processor can be inserted between the multiplexer and position processor. In the $\bar{p}p$ mode, the single-bucket processor will be necessary in order to produce appropriate oscillating signals for the position processes. It may utilize gating of p and $\bar{p}$ buckets and shock-excited ringing circuitry.

The beam monitors will have two modes of operation, single-turn and closed-orbit. The single-turn operation will be used at injection time to measure position and intensity on the first turn as a function of azimuthal location. Information from a few successive turns will be helpful in minimizing coherent oscillations produced by injection errors. A minimum of one detector per house can be measured on each beam pulse. Minimum intensity requirements are approximately 5×10^9 protons over a 0.6-μs time. If a full turn of beam is injected, it appears to be possible to read as many as five detectors per house by rapid switching of the multiplex channels. Thus a full set of horizontal or vertical position information might be obtained in a single beam pulse. Here intensities of the order of 10^{11} protons are necessary. In either case, information on subsequent turns could also be read. At the conclusion of single-turn data taking, the beam-position detector (BPD) will revert to the multiturn mode of operation. Sequential scan of all detectors in a house will be established, with data averaged over 10 turns per channel and a full scan every 2 ms.

Data from the single-turn and closed-orbit modes will be stored separately in a local memory in the interface module. Fixed space will be allotted for the single-turn data and circular memory for the closed-orbit information. Memory size will be sufficiently large to permit meaningful snapshotting of the system data in the event of an abort or magnet quench. In event of an abort or quench, updating of the local memory will cease and all stored information will be transferred on command to the central computer for analysis.

The BPD will provide programmable discrimination capabilities to sense large position errors and provide alarms and abort-triggers. In addition, BPD information can be used to make single-turn plots, closed-orbit plots, and real-time position plots available to the operator, as in the present Main Ring system.

12.11 Loss Monitors

Loss monitors will be installed at all quadrupoles and other special locations to monitor time-dependent losses throughout the cycle. The magnets are more susceptible to quenching from losses at higher energies and abort discrimination levels of the monitors should therefore be weighted as a function of magnet excitation (possibly by use of a B-dot clock). Loss-monitor signals will be integrated over two distinct time intervals. The first will be of the order of 1 ms to detect fast losses and the second of the order of 100 ms, to detect slow or quasi-dc losses. The two times are necessary because the superconducting magnets have different sensitivities to losses with different time dependences (see Section 13). The integrated outputs will be compared against differently weighted discrimination thresholds and, as with the position detectors, an alarm or abort trigger can be generated. During extraction, it is possible that the extraction rate could be slowed if too high a loss level is sensed.

There will be approximately 10 loss-monitor inputs per service building. Inputs will not be multiplexed but rather will go directly into the processor unit, which will provide integration, sampling, digital conversion and alarm discrimination.

The loss-monitor processor (LMP) is almost identical in concept to the beam-position detector interface module. Sufficient memory should be available to store loss-monitor history preceding aborts or magnet quenches, as well as provision for transfer of information to the central computer at its request.