Proceedings of International Collaboration on Advanced Neutron Sources (ICANS-VII), 1983 September 13-16
Atomic Energy of Canada Limited, Report AECL-8488

Proton Storage Ring (PSR) Diagnostics and Control System*

Peter Clout
Los Alamos National Laboratory
AT-3, MS H808
Los Alamos, New Mexico 87545

Summary

When any new accelerator or storage ring is built that advances the state of the art, the diagnostic system becomes extremely important in tuning the facility to full specification. This paper will discuss the various diagnostic devices planned or under construction for the PSR and their connection into the control system.

The PSR Control System

The PSR is a major new facility at LAMPF. The beamline, Line D, provides a short, high-intensity burst of protons to the Weapons Neutron Research (WNR) spallation neutron source. The nature of most of the experiments at the neutron source is such that the neutron pulse length determines the energy resolution. As beam is taken directly from LAMPF, this length also determines the total, time-averaged neutron flux and hence the signal-to-noise ratio of the experiments. Thus the setting of the existing WNR facility is a compromise between resolution and signal strength. The PSR will remove this compromise by accumulating LAMPF beam for up to 750 μs, a complete LAMPF cycle, and then delivering the accumulated charge with a time structure suitable for the experiment. The overall gain is dependent on the particular experiment, but usually it will be over two orders of magnitude. Figure 1 shows the PSR in some detail.

The existing controls for Line D and WNR consist of a single computer with ∿950 channels connected to it. The new PSR control system[1-5] will take over these channels and will add ∿1500 new channels. However, the controls problem does not scale with channels. The PSR adds a new dimension of complexity to the facility, and the machine physicists and the operators need much more help than the existing controls system on WNR can give. WNR has been operational for some years, and the PSR is due to take first beam in April 1985.

Requirements

The PSR control system's overall requirements are

- the system must provide the operator with full and responsive facilities for bringing on-line all the equipment that makes up the PSR;
- the system must automatically monitor equipment for normal operation and report exceptions to the operator;
- the system must present information to the operator about the current state of the PSR, or any selected section, in an easily understood form;
- the system must maintain a log of significant events; and
- the system must be flexible enough to add new equipments and channels easily, as well as to add new programs for operator interaction.

These requirements specify two kinds of processing required of the computers in the system. The first kind is single-word input/output (I/O) processing associated with reading values from and writing them to the interfaces connecting the PSR's equipment to the control computers. This task also will include simple routine conversions and range checks, and the magnitude of the task scales with the amount of equipment and number of channels. The second kind of processing relates to the provision for operator interaction, and the magnitude of this task scales with the number of operators and their activity.

The choice of microprocessors for the first task and a computer system for the second task is a natural one. To simplify the software development, the microprocessors and the computer were chosen from a compatible range and are Digital Equipment Corporation (DEC) LSI 11/23's running RSX 11S and a VAX 11/750 running VAX/VMS. Thus the LSI 11/23's are memory-only systems that are down-line loaded from the VAX 11/750.

The third requirement calls for not only a connection to all the power supplies, etc., but also

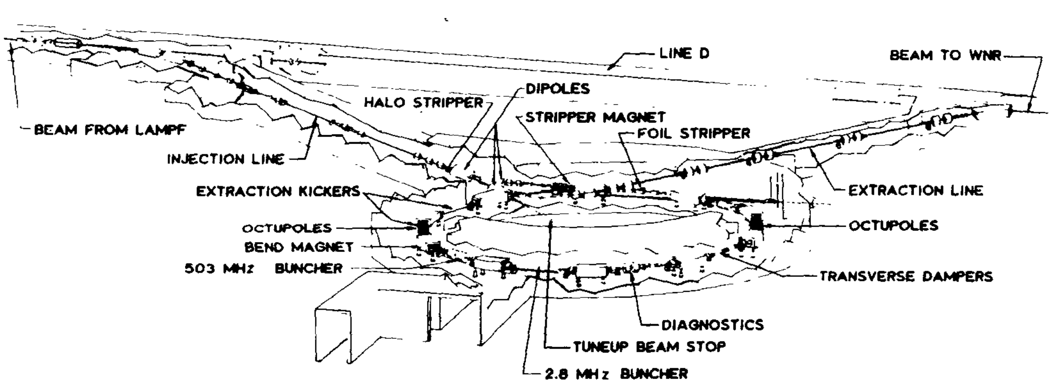

Fig. 1.
Proton storage ring schematic.

*Work supported by the US Department of Energy.

suitable, well-placed diagnostics in the beamlines and the storage ring that are connected into the control system. These diagnostics present extra challenges to the software designers because invariably they are more complex than power supplies, vacuum systems, etc. The second half of this paper will examine this aspect in more detail.

For many reasons, CAMAC was chosen as the interface system between the computers and microprocessors of the control system and the equipment of the PSR. This is also an excellent choice for the diagnostics because of the wide range of suitable CAMAC plug-ins available on the market. Nothing in the design of the software or hardware of the system precludes the use of other interfacing systems, for example, IEEE 488, where appropriate. A recent analysis of the software overhead, hardware costs, and performance showed that, given the communications needs of the system, a serial CAMAC system was the best choice for the communications between the VAX 11/750 and the LSI 11/23's.

Detailed Hardware Description

Figure 2 shows schematically the hardware of the system, which is located in several buildings. The computer-related items on the two operator consoles are six color-graphics displays with touch screens, twelve computer-assignable knobs, and a conventional computer terminal. The remainder of the console is taken up with oscilloscopes, TV monitors, and other dedicated instrumentation. Although the touch screens and color-graphics systems are commercial products interfaced to the VAX 11/750 Unibus, the programmable knob units are being constructed in-house and are interfaced through CAMAC modules. These devices make up the main hardware of the operator interface with the control system. The console consists of ten bays arranged to form two operator consoles and one single-bay alarm console.

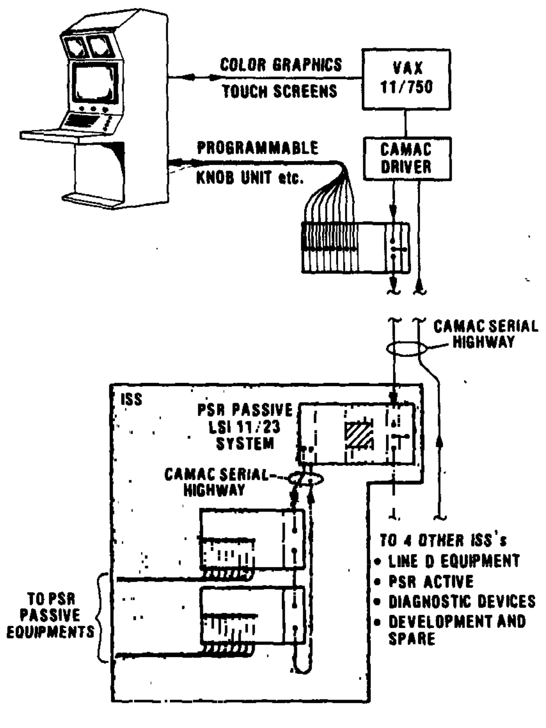

Fig. 2.
PSR Control system hardware.

The CAMAC driver on the VAX is a powerful interface with extensive direct-memory access (DMA) facilities, and it has a software driver under VMS, the VAX operating system. As can be seen in Fig. 2, the serial highway from the VAX 11/750 controls the CAMAC crates in which are mounted the LSI 11/23 microprocessors. One component of the LSI 11/23 system is a module that gives CAMAC access to the Q-bus of the LSI 11/23. It is this module and the DMA facilities of the CAMAC driver that allow the VAX 11/750 to keep databases up to date with minimum VAX software overhead and almost no LSI 11/23 software overhead. Both processors also are able to interrupt the other by CAMAC Look-at-Me (LAM) interrupts.

There are five such LSI 11/23's planned, including one for development, and each will have a serial highway of its own to connect its CAMAC crates. These crates hold the CAMAC plug-ins that connect to the equipment of the designated area for the LSI 11/23. A watchdog system in each LSI 11/23 crate will ensure that if a fault occurs in the LSI 11/23, the run permit for the PSR will be dropped within 1 s. The LSI 11/23 and its associated CAMAC system is termed an Instrumentation Sub-system (ISS); the "PSR Passive" ISS is the shaded area in Fig. 2.

Presently, there is one LSI 11/23 allocated to act as the "Diagnostics" ISS. However, some diagnostic devices are better placed on the CAMAC serial highway of the VAX and controlled directly by the VAX. Another diagnostic is in fact controlled by an 8085 microprocessor, and this communicates directly with the VAX like any ISS.

Data in the System

In the control system, data exist in one of four forms. Binary data are used to represent two-valued inputs and outputs, such as on or off. Analogue integer data represent I/O values that are covered by an integer in the range -32 000 to +32 000. Analogue real data are used for all other single-valued channels. Finally, analogue vector channels are used where an array of integers is required, for example, to specify a waveform. Each of these forms can be in a number of different types:

- Interface units--the value in primary SI units at the front panel of the CAMAC or IEEE 488 unit.
- Hardware units--the bit pattern read or written across the I/O bus.
- I/O units--hardware units modified to a legal PDP/11 and VAX/11 data type (the form in which data are stored in the run-time database).
- Engineering units--value in meaningful units to an operator; for example, pounds per square inch, amperes, degrees Celsius.
- Physics units--value converted to a higher level unit that in some cases is a more meaningful indication of the physics of the process; for example, tesla.
- Process units--high-level units that cannot directly translate to a single I/O channel, for example, tune.

Not shown on the diagram of the software, Fig. 3, is that the conversion between I/O units and engineering or physics units is carried out by a conversion module. This module has coded into it the various required algorithms and has access to the run-time database to obtain the parameters needed for each conversion.

Detailed Software Description

The overall software has been broken down into a number of modules, each having a well-defined function

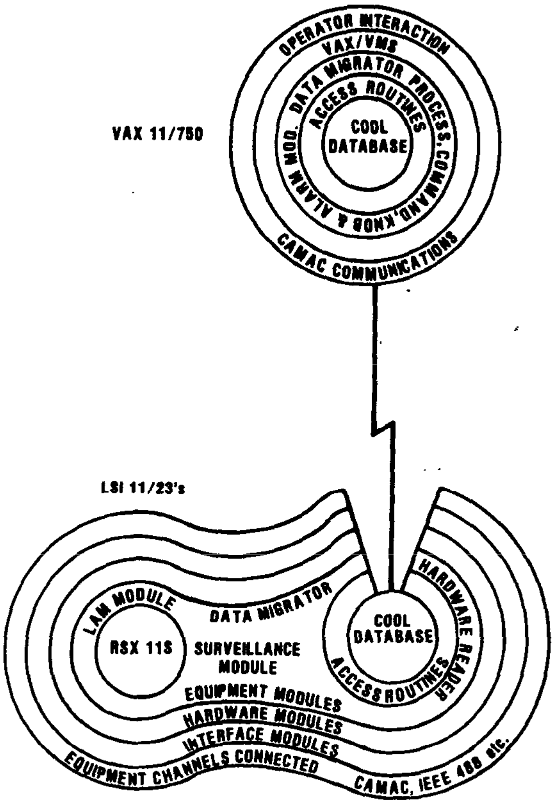

Fig. 3.
PSR control system software.

and a clear interface to the rest of the system. In fact, the modularity of the software reflects that of the hardware, allowing ease and flexibility in making changes. The modules are defined so that

- one or more modules make up a program or task;
- ideally, each module should be less than one month's work to code and test; and
- the intermodule interface is chosen to isolate future changes.

The first step was to isolate in a single database all information that relates to the individual equipment and its associated channels. The information in this database is held in an ASCII file established and maintained using a DEC product, DATATRIEVE. DATATRIEVE allows easy maintenance of a database and easy-to-use sorting of the data and report writing.

From this database is generated a machine efficient, run-time Control (COOL) database. It is this database that exists in main memory of the VAX 11/750 and the LSI 11/23's, and that which the programs reference. As an example, the address of a CAMAC plug-in will take several ASCII characters in separate fields in the ASCII database from which the run-time database generation program will produce packed binary addresses. The format of the packed address will be defined by the CAMAC coupler, so that it can be used directly at run-time. The run-time database generation also will produce any data tables required by individual programs or tasks. Thus the generation of a new database will at least mean relinking much of the system.

Figure 3 shows schematically the system's software layers. Generally, the LSI 11/23's act as intelligent I/O controllers to the VAX 11/750, enabling the VAX 11/750 to carry out operator-requested functions.

At the center of the VAX 11/750 software is the COOL database that is referenced through access routines to isolate the detailed structure of the database. On top of the access routines come all the other modules of the system.

The Command Module is responsible for the interaction with the operator to assign knobs or start specific operator-interaction programs. It is also responsible for keeping track of console resources. This is the module that comes up first at the console when the system is started.

The Knob Module is responsible for accepting knob assignments, taking knob input, and making the corresponding changes in the COOL database. It also maintains the one-line display on the knob unit.

The Alarm Module is responsible for maintaining the alarm screen and the log of significant events. Each channel, soft or hard, will have three sets of limits associated with it. Warning and alarm limits are self-explanatory, but the log-by-exception limits are less clear. These define a delta so that when an input channel is more than this delta from its last logged value, the new value is logged with the time and date. For control channels, these data are maximum range, normal range, and maximum rate of change.

The Data Migrator ensures that the varying data and the flags that indicate changes are kept current between the VAX 11/750 and the individual LSI 11/23's. For this the CAMAC system is used as described above.

Although all the above are single modules, the Process Modules are many and varied. It is here that the expansion takes place, and the system is tailored to the particular needs of the PSR. Selected Process Modules are started by the Command Module on the request of the operator. The running Process Modules have full access to the graphics devices on the console and the COOL database, which includes the last inputs from the touch screens. Thus they have full information on the state of of the PSR and full control of the PSR equipment. It is in the Process Modules that the flexibility of the system exists.

The next layer of the software is the operating system, VAX/VMS, through which goes all communication with the real world. For this purpose, VAX/VMS includes the I/O drivers added for CAMAC and the Lexidata color-graphics system.

Finally comes the Operator Interaction and CAMAC communications layer, which represents the main functions of the VAX 11/750.

There are two fundamental differences between the VAX 11/750 software layout and the LSI 11/23 software layout. The first is that the RSX 11S operating system is used only for task management and not for I/O management. This gives rise to the double-centered representation of the software. The second difference is that, as shown, the VAX 11/750 has direct access to the LSI 11/23 COOL database. This is a simplification in some respects, because the VAX 11/750 Data Migrator has control access to the Data Migrator in the LSI 11/23 to ensure that the LSI 11/23 takes action on the changed data.

Input channels are handled differently from output channels by the ISS. Two software modules, the LAM Module and the Hardware Reader, are responsible for ensuring that the COOL database input-channel data in the ISS are up-to-date. The LAM Module does this for I/O plug-ins that are interrupt or LAM based, whereas the Hardware Reader does the updates on a timed basis. All the other software modules access input data from the COOL database.

The Surveillance Module is responsible for checking input data against specified limits and reporting exceptions to the Alarm Module in the VAX 11/750 through the COOL database.

All changes to be made to equipment parameters must be made through an Equipment Module, which is a separate program for each set of equipment. This module can check input channels in the COOL database and apply the change in a manner specific to that equipment. This allows checks to be programmed into the system to ensure safe and correct operation. The Equipment Module also implements soft channels. These channels do not relate directly to a single hardware channel, but to two or more channels in a specific way. A simple example might be the on-off control of an equipment where a single soft on-off channel might be translated by the equipment module into a pulse output on one of two binary output channels.

All access to the I/O plug-ins by the LSI 11/23's is through the Hardware modules and the Interface Modules. These modules are designed to hide the differences between, for example, I/O plug-ins of similar function but different detailed design. Thus the code in an Equipment Module need only reflect the type of I/O, not the details of the actual I/O plug-in used. The Hardware Module also has no need to know the details of how the I/O bus is connected to the computer, but rather it issues calls in terms of the I/O bus (CAMAC, IEEE 488 etc.) to the Interface Module that localizes the code reflecting the actual connection of these buses. To illustrate: if a pair of wires bringing a 0- to 10-V signal to a CAMAC plug-in were to be moved to a similar IEEE 488 unit, all that would need changing would be the run-time database.

Diagnostics Interfacing for the PSR

Beam-Position-Monitor System

This system has already been described in some detail elsewhere.[6] It consists of a large number of detection units with an rf multiplexer system to select the unit of interest. The output of the multiplexer is then processed by rf signal-processing electronics that provides an X- and Y-position signal to two fast analogue-to-digital converters as well as a beam-present signal. Some further linearization of the signal is then required before the two X- and Y-positions of the centroid of the beam are obtained.

The detectors used consist of four pickup plates equispaced around and just inside the beam pipe. As such, they do not intercept the beam and so give a nondestructive read-out of the beam position.

To control the timing and sequencing of data acquisition and take account of the operating modes of the PSR, a microprocessor system has been implemented based on an Intel 8085. This has two control ports. One is an RS 232 port that allows an exerciser to operate the system locally for initial setup and trouble-shooting. The second port is a 16-bit parallel port connected to the VAX 11/750 computer. This second port is implemented with commercial 16-bit FIFO I/O CAMAC units. In addition, there are separate signals to allow the 8085 to interrupt the VAX to indicate that there is a message in the input FIFO and to allow the VAX to initialize the 8085. Thus, rather like the LSI-11/23's, the comunications are CAMAC based although they are message orientated. The 8085 therefore can be looked on as a single-purpose ISS as far as the hardware is concerned.

When it comes to the software, the Process Module that is called by the operator to handle the beam-position-monitor system communicates directly with the system through the CAMAC driver in the VAX. Messages have been defined that cause the 8085 to set the various delays and multiplexers and collect position data. When all the requested data are collected, the 8085 places a message in the input FIFO and sets a CAMAC LAM so that the Process Module in the VAX will be started, will read the data, and will present it to the operator.

The high speed of the ADC's allows the collection If a large amount of data from a single detector during one cycle of the PSR. However, the delays involved in resetting the multiplexers and the associated delay settings preclude taking data for more than one detector in a single cycle, and thus some of the commands to the system can take from a considerable fraction of a second to several seconds to complete, depending on the repetition rate of the PSR as well as on the actual command.

The current status of the beam-position-monitor system is that the final details of the timing and the VAX interface are being worked on, and it will then be ready for installation.

Beam-Profile Monitors - Harps

The harp units consist of an X-Y grid of wires that is placed in the beam-transport lines. The current on each wire is proportional to the integrated intensity of the beam along the wire. Thus, measuring the charge collected in one cycle of the PSR on all the wires gives an X- and Y-profile of the beam. The resolution of this profile depends on the spacing of the wires, and the sensitivity depends on the thickness of the wires and the noise in the electronics.

The harps will perturb the beam, especially in the injection line where they will cause the beam to be partially stripped from H^- to protons. For this reason, the harps are introduced into the beam only when a measurement is needed. In the storage ring itself, the high circulating charge precludes the use of harps.

The read-out of harp wires will be by specially constructed multiplexers. The input stage of the multiplexers has a sufficiently high impedance that over a cycle of the PSR it will integrate the accumulated charge. After a cycle of the PSR, the multiplexers will cycle through the 32 X and 32 Y wires and provide an output voltage and trigger pulse for an ADC to digitize the beam profile. This ADC will be operated by the diagnostics ISS and the results will be migrated to the VAX in the normal way. In this case, commands to insert a harp, make a measurement, adjust the gains of the ADC, etc, will be normal output or control channels to the ISS.

Loss Monitors

These monitors are designed to study the beam spill at various positions along the transport lines and storage ring. The actual monitors are mounted on the walls of the tunnel and consist of 1-pint cans filled with Nuclear Enterprises scintillator 235A viewed by an RCA 4552 phototube. The amplifier electronics has two outputs. The first allows the loss to be seen on an oscilloscope as a function of time and the second is connected to a gated analogue to digital converter so that the loss as a function of time can be recorded by the Control System. This will be done by the diagnostics ISS and the result then is migrated to the VAX in the normal way.

Activation Protection Monitors

These monitors are the same as the Loss Monitors but the electronics differ. The amplifiers have a longer time constant than the Loss Monitors and the output is compared with a preset trip level. If the level is exceeded, the output will activate a fast-protect system so as to either stop injection or rapidly dump the stored beam, depending on the time and location of the trip. The fast-protect system is quite separate from the control system, although the control system is able to read out the inputs that caused a fast-protect trip. Each new cycle of LAMPF and the PSR will attempt to reset fast protect. The Activation Protection electronics provides a dc output that is proportional to the average loss expressed as a percentage of the trip level. The Activation Protection monitors are used to regulate the spill budget of the facility. As such, each monitor will be set to a trip level appropriate to its location.

Phosphor Screen

One insertable phosphor screen will be installed in the region downstream of the injection-line stripper magnet before the injection point. At this point, the beam is a neutral hydrogen atom beam. Read-out of the phosphor screen is by a television camera, and thus no read-out to the control system is planned. The screen will be inserted by command from the control system, however.

Energy Measurement

The energy acceptance range of the PSR, $\Delta p/p$, is less than about 0.1%, requiring stabilization of the energy of the beam from LAMPF. At 800 MeV, the protons and H^- ions are not fully relativistic, traveling at about 0.8 c; thus, a time-of-flight measurement can be used to determine the energy. This requires two pickups with a time measurement made as a bunch traverses between them. A flight path between the pickups of about 100 m is needed, assuming a 100-ps time resolution. Quite standard commercial CAMAC units are able to achieve this; therefore, the energy measurement in this case would be a simple input channel on the diagnostics ISS. Another approach being studied is to partially strip the beam with a laser. The stripped electrons have an energy of about 0.5 MeV and can be deflected out of the beam and energy analyzed with an electrostatic analyzer. This approach is somewhat more complex but it does not rely on the bunch structure of the beam.

The last approach for measuring the energy is to use the injection line and/or the storage ring as a magnetic spectrometer. In this case, existing beam-position-monitor detectors provide the read-out.

The present beam from LAMPF has no stringent requirement on absolute energy. On the short term, it has been observed to vary by 0.5 MeV from its nominal 800 MeV. This variation is within the acceptance of the PSR, but closer control is desirable. Long-term variations of up to 10 MeV have been seen, and clearly these are outside the acceptable limits. One solution to reduce the fluctuations is by controlling the phase of the last rf tank of LAMPF. This would be a feedback loop from the energy measurement through the diagnostics ISS.

Quadrupole Moment Detector

The quadrupole moment detector uses the same design of pickup as the beam-position-monitor system, but processes the signal in a different way to generate the X- and Y-widths of the beam, which then give the quadrupole moment. The pickup will be placed in a straight section of the ring rather than inside the quadrupoles as are the position-monitor pickups in the ring. The output voltage of the pickups will be read by a gated ADC attached to the CAMAC system of the diagnostics ISS. The result is a single-valued channel migrated to the VAX in the normal way.

Frequency Monitor

The frequency monitor in the ring consists of a simple pickup inside the pipe with a fast spectrum analyzer to analyze the signal detected. As the spectrum changes with time, a real-time spectrum analyzer is required. The signal can be observed simply with the CRT of the analyzer, but the system is much more versatile if the frequency spectrum is read into the control system. This will allow reading the spectrum as a function of time as well as further processing of the information. As with the beam-position-monitor system, such an instrument will be connected directly to the VAX.

Satellite Detector

The chopper's function is to prepare the time structure of the H^- beam to be accelerated by the linac so that it suits the particular operating mode of the WNR/PSR facility. Satellites are defined as bunches or parts of bunches appearing before or after the desired bunch. They could arise if the chopper does not deflect the beam sufficiently or if it is incorrectly phased. Thus, a satellite detection system is essential to adjust the chopper. The satellite detector consists of a foil that can be inserted into the beam in the transport line between the end of LAMPF and the storage ring. The flash of γ-rays is recorded with a fast detector as a function of time to obtain the time structure of the injected beam with respect to the chopper frequency. A time-to-digital converter in the ISS CAMAC will be used to store the information in the control system.

Ring Profile Monitor

For a ring profile monitor, two ideas are currently being discussed, but so far no actual design or construction has been started.

One idea is to have a gas curtain across the beam. The interaction of the protons with the gas will produce electrons in proportion to the proton density. These electrons then can be imaged, using suitable electrostatic or magnetic lenses, into a two-dimensional detector. The distortion of the image due to the potential well of the proton beam means that further processing is necessary to reconstruct the true profile.

The second idea is to pass a wire rapidly through the beam, collecting the current on the fly.

Both of these ideas need considerable development and they are unlikely to be available for some time.

Current Monitors

These will be ferrite toroids with the beam acting as the primary winding. The secondary winding will have about 100 turns, the output of which is then amplified and passed through a voltage-to-frequency converter. A gated scaler as part of the diagnostics ISS will then measure the beam charge for the gate period. The injection line current monitors will be an existing LAMPF design. The ring monitor cannot be highly inductive and so a wall current monitor will need to be developed. For the extraction line, the behavior of the LAMPF monitor needs to be investigated for peak currents of up to 46 A.

Conclusion

The basic design philosophy for the PSR control system has been presented, together with those aspects specific to the diagnostics of the PSR. Each of the diagnostics currently being considered or implemented has been briefly described, together with the planned implementation of the interface to the control system where appropriate. The development of the diagnostics for the PSR is limited by resources but is driven by the need to understand the operation of the machine in order to reach full design current. First beam for the PSR is scheduled for April 1, 1985 with a tune-up period of about 18 months to full current.

Acknowledgments

This work reports the contributions of many other people to the PSR project. S. Bair, A. Conley, R. Ford, M. Fuka, and N. Greene all contributed significantly to the design and implementation of the control system. E. Higgins and F. Wells were responsible for the beam-position-monitor system and R. Hardekopf and A. Jason together are responsible for the remainder of the PSR diagnostics. I would also like to acknowledge the many helpful suggestions made at the proof stage by R. Hardekopf and A. Jason.

References

1. P. Clout, "Proton Storage Ring Instrumentation and Control System, Overall Philosophy," Los Alamos National Laboratory, Accelerator Technology Division, Group AT-3, PSR Technical Note 47 (February 1980).

2. P. Clout, "PSR Control Console, Conceptual Design Document," Los Alamos National Laboratory, Accelerator Technology Division, Group AT-3, PSR Technical Note 88 (June 1981).

3. P. Clout, "PSR Instrumentation and Control Data Base System," Los Alamos National Laboratory, Accelerator Technology Division, Group AT-3, PSR Technical Note 106 (May 1982).

4. P. Clout, "Proton Storage Ring Instrumentation and Control System, Signal Connection Manual," Los Alamos National Laboratory, Accelerator Technology Division, Group AT-3, PSR Technical Note 108 (November 1982).

5. P. Clout, S. Bair, A. Conley, R. Ford, M. Fuka, and N. Greene, "The Proton Storage Ring Control System," IEEE Trans. Nucl. Sci. 30, Vol. 4, p. 2305 (1983).

6. E. F. Higgins and F. D. Wells, "A Beam Position Monitor System for the Proton Storage Ring at LAMPF," IEEE Trans. Nucl. Sci. 28, Vol. 3, p. 2308, (1981).