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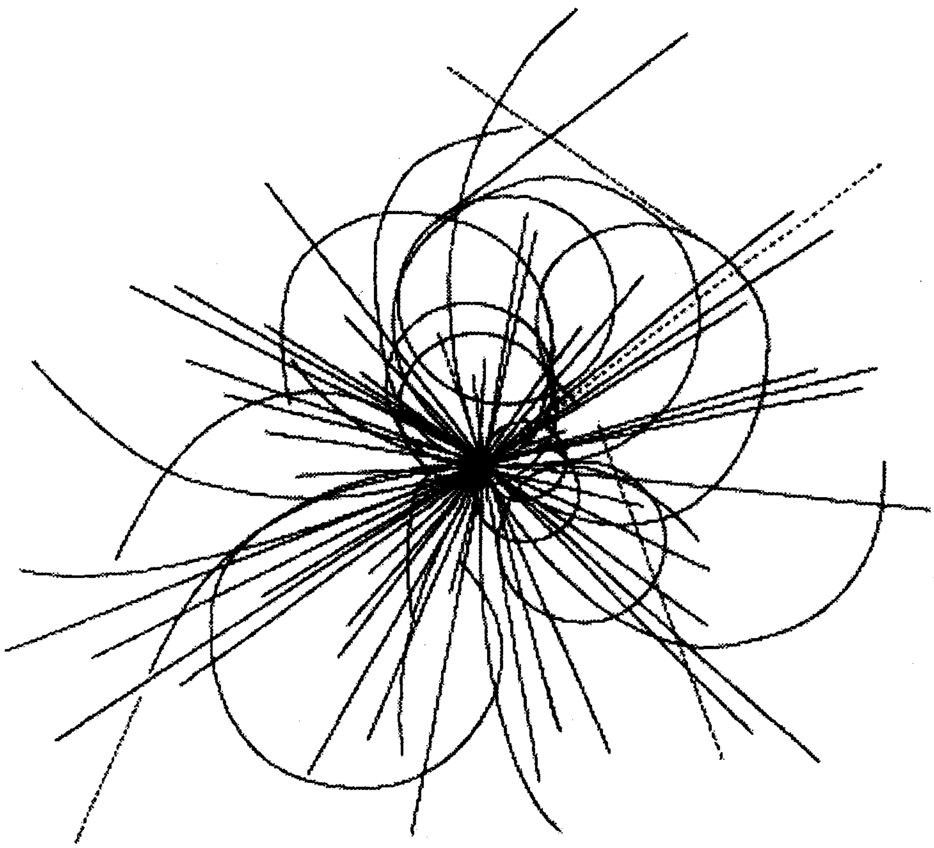

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BEAM INSTRUMENTATION AND PRECISION TIMING EQUIPMENT FOR THE SSC ACCELERATOR COMPLEX

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INTRODUCTION

This article is intended to provide an introduction to the beam instrumentation systems and the precision timing system of the SSC Laboratory. The Beam Instrumentation Department of the SSC Accelerator Systems Division is responsible for the design of these systems for the Collider rings and the injector accelerators. Status and plans are briefly described.

The signal sensors and low level signal processing electronics of the beam instrumentation systems are the eyes and ears into the world of the proton beam. Situated between that invisible beam and the accelerator operator, they monitor and measure the behavior and performance of the otherwise intangible protons as they are guided and accelerated through the Linac and the injector synchrotrons, and finally stored in the Collider rings.

The precision timing system provides the vital time references required to synchronize critical accelerator hardware functions, beam manipulations, and data acquisition over the geographical extent of the Supercollider complex. Several fundamental timing signals are distributed over dedicated fiber optic networks. Special programmable electronic modules process the timing information to provide precisely timed outputs to control the many accelerator systems and devices.

BEAM INSTRUMENTATION

Monitoring and controlling the beam of protons through acceleration and storage requires measurement of a variety of beam parameters. Additionally, peak accelerator performance is achieved only with a thorough understanding of the "as built" machine. The most sensitive probe of the behavior of the accelerator magnet and RF systems is the beam itself, and the instrumentation systems provide the tools for measuring beam response. Parameters to be measured and the respective systems to be designed include: the quantity of protons - beam intensity monitors; transverse location of the beam within the evacuated beam tube - beam position monitors (BPMs); transverse beam size and distribution - profile monitors; loss of beam particles due to scraping, misalignment, or instabilities - beam loss monitors (BLMs); and temporal distribution of particles in the beam - wideband current monitors.

Acquiring measurements requires interaction with the beam particles themselves or their associated electromagnetic fields. As a result, most beam instrumentation systems include sensors which must be an integral part of the beamline vacuum system. Monitors that interact directly with the particles nearly all need mechanical actuators to allow remote insertion and withdrawal from the beam path. Electromagnetically coupled monitors must have coupling loops or electrodes within the beam vacuum or a vacuum tight insulating "window" to the fields associated with the beam. Nearly all instrumentation devices require

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vacuum sealing electrical signal feedthroughs. In some cases multi-pin connectors are appropriate and in many other cases coaxial feedthroughs with controlled high frequency performance are demanded. Beam loss monitors, sensitive to radiation penetrating the beam tube walls, are the exceptional devices which generally do not interface to the vacuum system. In all cases, the sensors must provide a long useful lifetime in the radiation environment of the beamlines. Front-end low level processing of the instrumentation signals is typically done in the tunnel niches in the HEB and Collider rings and in surface level equipment buildings for the conventional injector machines.

Intensity monitors and wideband current monitors are an assortment of electrical current transformers designed to measure microamperes to hundreds of milliamperes with bandwidths ranging from DC to several gigahertz. A beam position monitor consists of one or two pair of electrodes in the vacuum, electronics to determine the relative amplitude difference between signals from opposing electrodes over a large dynamic range, and necessary interconnecting cabling as much as several hundred meters long. Transverse beam size and profile measurements, which will be among the most difficult and challenging, utilize a variety of techniques ranging from thin wires or grids to synchrotron light, ionization, and transverse probe beams of electrons or neutral ions. Accurate determination of beam sizes as small as 100 microns must be made in the high energy machines. Beam loss monitors are typically ionization chambers or solid state radiation detectors located outside but near the beam tube.

Many parameters, including beam current, profile, and temporal distribution, are adequately determined by measurements made at only one or a small number of points around each ring. Since each machine has different beam aperture requirements, beamline space constraints, and/or measurement range and resolution requirements, devices to determine these parameters are most often one of a kind mechanical designs. These instruments frequently are complex, precision assemblies with positioners or actuators designed for remote control. Commercial concerns with the capability to economically design and fabricate such custom assemblies would find the most interest in these types of beam instrumentation components.

Beam position and beam loss measurements are required to be made at many locations, more or less regularly spaced around each ring. These are the instrumentation systems that would be attractive to businesses interested in quantity production items. The sensor mechanics and the electronics for each of these types of systems number in the three thousand range.

Beam Position Monitor Systems

The position monitor sensors (usually just called BPMs) are approximately 20 cm long and 10 cm diameter in all rings. They consist of one or two pair of electrodes in the vacuum around the beam line, acting as antennae to the beam. The BPMs for each accelerator have unique aperture requirements and unique external mechanical interfaces and constraints. In the LEB and MEB, they are room temperature devices. In the HEB and Collider they are located in the cryogenic spool pieces and must operate at 4^{o} K. The total number of BPMs is approximately 2650; of these, 2250 are 'cold' and 400 are 'warm'. Mechanical reliability of the 'cold' BPMs is critical, since failure requiring repair or replacement means days of downtime for warm-up, repair, and cool-down.

The electrical center, the axis on which the beam must travel to impart equal signal to opposing electrodes, of BPMs installed in each ring must ultimately be known relative to the ideal nominal beam line to an rms. accuracy of better than 1.0 mm in the LEB and 0.2 mm in the Collider. Positional stability over lifetime and temperature is important. This must be accomplished by an economical combination of manufacturing tolerance, electrical measurement, mounting, and installation survey.

Vacuum tight coaxial electrical feedthroughs pass the signals through the BPM body. In the superconducting machines, these feedthroughs must survive numerous temperature cycles and perform reliably for 25 years. Special coaxial cables exhibiting good high frequency transmission characteristics, low heat conductance, and high radiation resistance are required to carry the signals from the cold BPMs through the insulating vacuum to the cryostat wall. Another feedthrough is used there to bring the signal finally out to atmosphere. Over 17,000 high quality coaxial feedthroughs and 8,000 of the special cables are required.

Coaxial cables of RG8 or flexible solid copper shielded type shall carry the signals from the BPM in the radiation environment to the signal processing electronics in the niches of the superconducting machines or to the surface buildings in the warm machines. Over 600 kilometers of such cable is required.

Signals from the BPMs will be a train of sharp bipolar pulses approximately one nanosecond long with a 16 nanosecond repetition period. Each pulse train may range from a burst of as few as 10-20 pulses to a continuous stream depending on the distribution of particles in the machine. The pulse amplitude may vary from less than 0.1 volt to greater than 20 volts in proportion to the instantaneous beam current. Over this range of operating conditions, the processing electronics must extract beam position information by determining the normalized amplitude difference of signals from opposing electrodes. The signal processing bandwidth must be several megahertz. We anticipate this electronics to be constructed in VXI or VME format with analog signal processing, video digitizing, and memory on a single board. About 2,650 channels of such electronics required. Reliability of the electronics is of concern since much of it will be housed in the tunnel niches which are not normally accessible. However, in most instances, there is considerable redundancy provided by the large number of channels.

The mechanical BPMs for the Linac and LEB have been designed in-house and are in prototype fabrication. Within the coming several months we expect to solicit bids for production. MEB BPM design is scheduled to begin soon. To date, a few prototype Collider BPMs (HEB units will be quite similar or perhaps identical) have been fabricated and a current design is complete. That design has been provided to the spool piece contractors, Martin Marietta and Westinghouse, to produce 'build to print' units to include in their first prototype spools. A performance spec is in the final stages of preparation to contract for engineering services to improve manufacturability and reduce cost of the current design. A decision has yet to be made as to whether production BPMs will be supplied to the spool vendors as government furnished equipment or be contracted directly as a part of the spool production. Development contracts for 'cold' feedthrough, cryostat wall feedthrough, and 'warm' feedthrough designs are in place. A performance specification for the special coaxial cables used inside the cryostats has been written and will soon be released for solicitation of proposals. The BPM mechanical budget is approximately $6 million dollars.

The development, design, and qualification work on the Collider BPM, feedthroughs and cables must be completed this year in order to stay in tune with the 1994 spool piece production schedule. Preliminary development and design of the BPM electronics is underway in-house at this time. In parallel, a specification is being written for the electronics to obtain assistance in areas of manufacturability and reliability. The BPM electronics budget is also about $6 million dollars.

Beam Loss Monitor Systems

The beam loss monitor system to be provided by the Beam Instrumentation Department shall be used for accelerator commissioning, operational, and diagnostics purposes. It does not form any part of the personnel radiation safety system, though it does play an important role in accelerator technical equipment protection. The system will be capable of sensing and locating small beam losses for the purposes of monitoring loss patterns, identifying potential aperture restrictions or obstacles in the beam tube, tuning the machine for the cleanest possible operation, and triggering a controlled abort of the beam when the potential for losses that may lead to equipment damage or high irradiation of accelerator components is sensed. By providing a monitor to reduce operational beam losses within the tunnel to a low level, residual radiation induced into accelerator components that require access for maintenance can be minimized.

The beam loss monitors (BLMs) are expected to be gas filled ionization or proportional chambers or perhaps solid state radiation detectors. They are distributed more or less uniformly around each accelerator, mounted to the tunnel walls, magnet stands or similar location. The BLMs must exhibit properties including radiation resistance, high and stable sensitivity to radiation signals, low noise or dark current, wide dynamic range, low maintenance and high reliability. Approximately 3500 BLMs and associated electronics channels are required.

Development and design work has begun for both the sensors and the electronics. It is likely that a small number of BLM development contracts will be placed within the next two years. Assessment of the suitability of gas filled chamber type detectors as used at Fermilab and Brookhaven National Laboratory is now underway. Investigation is also ongoing into the possible use of mercuric iodide and other materials for a solid state detector.

BLM electronics must be suitable to process small signal currents expected from the sensors over a dynamic range of 10,000:1. For purposes of accelerator equipment protection from large beam losses, a response time on the order of ten microseconds is required . Each channel must have sufficient memory to provide a postmortem record for analysis purposes of beam aborts. As with the BPMs, we anticipate the electronics to be constructed in VXI or VME format with analog processing, digitization, and memory on a single board. Reliability of the electronics and sensors is of special concern since failure to trigger necessary beam aborts may result in severe magnet damage and each abort caused by false alarms will result in hours of unacceptable machine downtime.

The schedule for these devices is somewhat relaxed as compared to the BPM mechanics since the BLMs are expected to be relatively fragile components and among the last items to be installed in the tunnels. Significant quantities are not expected to be needed before mid 1995. The budget for BLMs including sensors and electronics is over $2 million dollars.

PRECISION TIMING SYSTEM

Operation of the SSC accelerator complex requires synchronization between many different systems and devices with widely varying time precision over a large geographical region. The magnetic cycles of the different accelerators must play out relative to each other with millisecond fidelity; transfer of beam from one synchrotron to the next requires 100 picosecond accuracy between the RF systems of the respective rings as well as nanosecond accuracy of fast pulsed kicker magnets. The Precision Timing System will be composed of a fiber optic distribution system for the required time base signals, a means of encoding resets or markers onto the time bases, and an electronic receiver or clock module to keep time per the time base, to respond to the resets, and to generate outputs as programmed via the Global Accelerator Control System.

The main timing references for the accelerators are the utility company power line, which is highest frequency external interface to the accelerators, and the RF or revolution frequencies of the beam particles as they orbit around each synchrotron. The nominal 60 Hz power line provides a suitable time base for the synchronization of the power supplies and magnet cycles. The revolution frequencies, and multiples thereof, provide necessary time bases for beam control and manipulation operations. The revolution frequency of particles in any one synchrotron is a function of the machine circumference and the time varying parameters of beam energy and magnetic field strength. At any given instant, there is no direct correlation between the frequencies of any two synchrotrons; yet within relatively narrow windows of time, transfer of beam from one machine to the next must be made under stringent conditions of frequency and phase match. A mechanical analogy might be a multigear transmission in which synchronization must be achieved at the time of shifting, not simply to mesh the gears but also to align a specific tooth on one gear with another specific tooth on the next. In addition, the geographical extent of the accelerator systems requires careful attention to and control of timing signal time-of-flight delays.

A global time base with information related to the power line frequency and machine cycle resets will be distributed throughout the entire accelerator complex. In addition, each synchrotron will have distributed around it the respective RF time base with the revolution frequency information contained. This RF time base is also required at the RF control point of the next lower energy machine to facilitate the beam transfer synchronization. The RF time bases are nominally 60 MHz with some variation from one synchrotron to another; the LEB RF frequency for instance sweeps from 47 to 60 MHz during that machine's 50 millisecond acceleration cycle. All distribution systems must provide a high degree of point-to-point signal transit time determinacy, requiring a dedicated purpose system. Active feedback control of signal transit delays is expected to be required along some segments of the distribution networks to compensate for temperature and aging effects. The respective time bases must be made available at each niche or surface equipment building for each accelerator. Studies are underway to determine suitable reset or marker coding schemes to understand the impact on timing system jitter and noise.

A general purpose clock module, dubbed the Universal Timing Module (UTM), is being designed to serve as a receiver and decoder of the time base signals. It needs to consist of 60 MHz counters, control logic, and an interface to the control system. The control system provides a 'schedule' which programs the outputs of the UTM. The outputs shall be TTL and/or ECL pulses or gates for direct timing control of hardware devices and data acquisition systems. Somewhere in the range of 2,000 UTMs are expected to be required. Prototype modules, likely to be less than full-featured, are now well into the design stage for Linac applications where they are needed by the end of this year. Larger quantities demanding near full performance are required for the LEB in early to mid 1995. VXI format is planned for the initial boards.

The budgeted value of the entire precision timing system including fiber optic systems and electronics is approximately $7 million dollars.

SUMMARY

Considerable work on many components for the beam instrumentation and precision timing systems is underway with industrial participation on levels ranging from systems engineering, to detailed design, to prototype and soon production fabrication. Much effort yet remains to establish final requirements definitions for many aspects of the systems before detailed design and production contracts are ready to be placed. Specifications for beam instrumentation equipment often converge only late in the accelerator design stage. This is because the instrumentation is frequently subjected to spatial limitations imposed by less flexible beamline components such as magnets and RF systems, and also because many instrumentation performance requirements are intimately dependent on planned and desired accelerator operational flexibility which the accelerator designers and physicists are understandably reluctant limit early in the design.

To abide by the current schedule calling for Collider operation before the year 2000, initial contracts for BPM fabrication and electronics design will need to be in place by the end 1993. The total budgeted cost for design, procurement, fabrication and test of all beam instrumentation and precision timing systems for the entire injector and Collider complex is approximately $50 million dollars.