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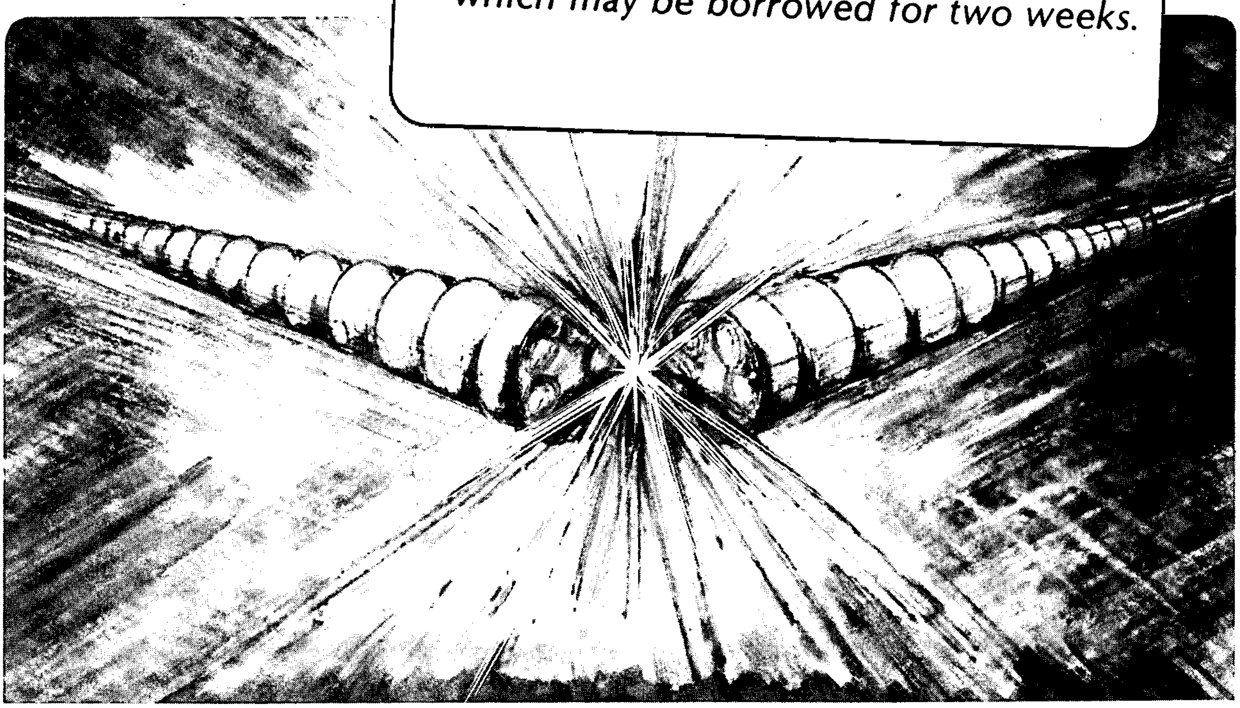

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ADVANCED LIGHT SOURCE (ALS) BEAM POSITION MONITOR*

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Introduction

The ALS is a third-generation synchrotron light source currently under construction at LBL. The accelerator complex will consist of a 1-2GeV electron storage ring, a 1.5GeV booster synchrotron, a 50MeV linac, and low and high energy beam transfer lines. Beam pickup devices and electronic instrumentation have been specified for the accelerator, and development of the beam position monitor (BPM) systems is well under way. Considerable effort has gone into the storage ring BPM system design in particular because of the need for very fast and accurate measurements. We meet the speed and accuracy requirements in the electronics with parallel processing and error correction techniques. A tuned receiver is provided for every beam position pickup, and for every array of four pickups there is a microprocessor controlling the measurement and recording data. In this paper we report on the requirements, design, and performance of the storage ring BPM system.

BPM Requirements

The ALS storage ring is 196 meters in circumference and has 96 locations for beam position measurement. At 72 locations the measurement is made near quadrupole magnets. The remaining 24 locations are at the entrances and exits of insertion devices. The ring is composed of 12 curved sections referred to as "sector arc chambers" and 12 straight sections. The BPM pickup electrodes are installed in the sector arc chambers only. Ten of the straight sections are reserved for wigglers and undulators. Beam from the booster synchrotron is injected into one straight section, and two RF cavities occupy another.

The position of the electron beam is measured continuously while it is stored and thus provides various accelerator systems with constant beam position information. For example, beam orbit distortions caused by insertion device gap adjustments must be measured and corrected as the device is tuned. Since the power density of some insertion device photon beams is sufficient to damage the vacuum chamber, the BPM system must report errant beam quickly. Bumps in the beam orbit are introduced at insertion devices to help stabilize the photon beams. The BPM system is employed here to insure that the local bump is truly local and does not impact other photon beam lines. In these cases a system bandwidth of 10Hz is adequate.

To be of use during storage ring commissioning, injection studies, and at other times when instant response is required, the BPM system must respond to a single turn of beam and should be able to store data from many turns. This is especially important with a low injection rate. The required bandwidth in this case is about 2MHz. Accuracy and resolution of 0.5mm are adequate for these high speed measurements.

With a stable stored beam the required resolution of the BPM system is 0.02mm. The required accuracy of the measurement is 0.03mm or about equal to the vertical rms beam size. These specifications are to be met for average beam currents ranging from 8mA (single-bunch) to 400mA (multi-bunch).

Beam Pickups

Storage ring beam is sensed by combined function electrostatic pickup electrodes (buttons) flush-mounted to the vacuum chamber (Fig. 1). The diameter of the buttons is 10mm (about twice the rms bunch length). This diameter was chosen to provide acceptable sensitivity to beam motion while at the same time coupling sufficient signal to the processing electronics. Larger pickups such as striplines are not suitable because a smooth bore is required in the beam pipe to avoid excitation of beam instabilities.

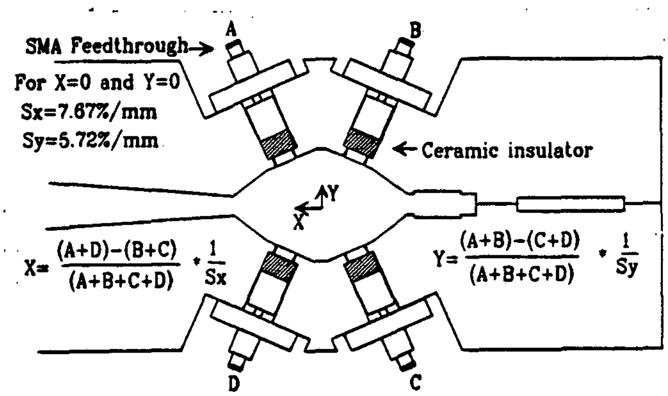

Fig. 1 Sector arc chamber showing button installation

The 10-meter sector-arc vacuum chambers are fabricated from large slabs of aluminum intricately machined for the beam aperture, magnets, photon stops, vacuum pumps, and the BPM buttons. Holes for the buttons are precisely placed in the chamber relative to survey points. A machined ceramic spacer positions the button in the thick chamber wall. The coaxial vacuum feedthrough attaches to the button via a spring loaded assembly with RF contacts. This provides the required beam signal connection while firmly holding the button against the ceramic spacer. The position of the coaxial feedthrough does not affect the button position. With this design we are able to accurately position and hold the button in the chamber wall.

For broadband RF measurements it would be desirable for a button to have zero length and to be supported by the center conductor of a constant impedance vacuum feedthrough. This would give us a beam pickup system with the fewest RF discontinuities and the smoothest frequency response. Since our measurement system is relatively narrowband (with respect to the span of the bunch spectrum) we chose to use non-constant impedance feedthroughs and relatively thick buttons. This gives us a mechanically robust system but one having high frequency resonances which are well within the beam spectrum.

Pickup Tests

The low frequency capacitance of the pickup assembly is about 20pF. This capacity in shunt with 50 ohms gives the button a high-pass response with a 3dB corner frequency of 160MHz. Impedance measurements at frequencies up to 3GHz show the button assembly to be capacitively reactive when measured from the feedthrough side. Measurements of the button impedance as seen from the beam side were made from 0.1 to 20GHz [1] and resonances were found at 5GHz and above. Calculations show the resonant impedances are not sufficiently high to adversely impact the beam. Moreover, none of the measured resonances can be driven sufficiently hard by the beam to damage the button structure.

Since the buttons can be placed in the vacuum chamber with good precision we will make no attempt to measure their individual performance with wires or antennas. Placing wires in

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the curved chamber with the necessary precision would be very difficult. Instead, we rely on measurements made on a typical set of buttons in a 0.3 meter straight section of beam chamber.

Our test set consists of the beam chamber mounted to a moveable X/Y stage. A vertically mounted wire is installed in the chamber and terminated in its characteristic impedance to minimize reflections. We drive the wire with a network analyzer and measure the signal coupled to the buttons as the X/Y stage is moved. The high frequency coupling impedance to a centered wire is about 0.1 ohm. X and Y sensitivities to small displacements of a centered wire are shown in Fig. 1. These measurements were made at 500MHz.

With the wire accurately positioned in the center of the chamber the calculated position (using equations in Fig. 1) showed an offset of 300um in X and Y. We found this to be due to small differences in button capacity. Differences in feedthrough and coaxial cable insertion losses result in similar offsets as do physical displacements of the buttons. This would seem to justify testing every BPM station with a wire. Instead, a method was developed for determining these offsets by external measurement [2]. The wire was removed from the test chamber and transmission measurements made between buttons at 500MHz. It was necessary to extend the network analyzer dynamic range with external amplifiers to achieve the desired resolution and stability for this measurement because the attenuation between buttons is about 100dB. When we applied gain correction coefficients to the position equations and re-measured a centered wire the offsets were reduced to less than 30um.

When the storage ring buttons and cables have been installed the button-to-button measurements will be made at all stations. These data will not only help remove BPM offset errors but will be useful in the future should we suspect faulty cables, feedthroughs, or buttons.

BPM Electronics

Signals from the buttons are sent about 30 meters in high quality coaxial cables to instrumentation racks outside the shielded area. The button signals are short pulses (less than 50ps), a few volts in amplitude. Dispersion and loss in the cable lengthen the pulses and reduce their amplitude. These pulses, still quite short, are delivered to tuned receivers (Fig. 2) described below.

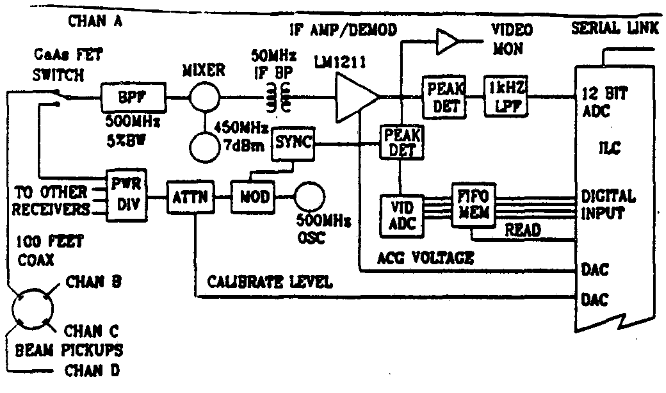

Fig. 2 BPM electronics, 1 of 4 channels.

The receivers are tuned to 500MHz, the 328th harmonic of the ring revolution frequency. The accelerator cavity frequency is also 500MHz. There will be from 1 to 250 bunches in the ring in arbitrary patterns. The ring will not be completely filled because some time must be allowed for ion-clearing. The bunch spacing will vary from 2ns for multi-bunch patterns to 656ns for a single bunch.

The button signal spectrum for a single bunch will contain harmonics of the 1.52MHz revolution frequency with nearly constant amplitude to well above the S band. Any of these harmonics could be used for beam position monitoring, however the higher harmonics should be avoided because their amplitude is strongly dependent on bunch length. Also, it is probably wise to avoid frequencies above beam pipe cutoff because of propagating fields.

If all 328 beam buckets could be uniformly filled, the button signal spectrum would have lines spaced at 500MHz, and the revolution frequency lines would disappear. With 250 bunches spaced at 2ns and a dead time of 150ns the revolution frequency and its harmonics will appear in the spectrum, but the cavity frequency and its harmonics will appear much stronger. We chose the center frequency for our receivers as 500MHz because the amplitude of any lower beam harmonic is strongly affected by the bunch fill pattern. The next attractive frequency would be 1GHz, but it is generally more costly to process higher frequency signals.

Instrumentation and low level electronics in the ALS are packaged in Eurocard bins. The BPM electronics are contained in shielded size 3U plug-in modules 200mm deep. A custom made five-layer backplane interconnects the modules. The multi-pin DIN connectors mounted on the backplane include coaxial inserts for connections requiring shielded cable.

Four receivers are used to amplify signals from one BPM station. This permits high speed measurement but causes problems with accuracy because the receivers do not have identical gain. A single 10V digital-to-analog converter (DAC) sets the gain of the four receivers as beam intensity changes, and even though we can equalize the gains at some particular setting, we observe tracking errors as the gain is adjusted. We compensate for these errors by measuring the gain differences in the four channels with calibration signals. Switches disconnect the button signals and connect the receiver inputs to a calibration signal source. This is done every time receiver gain is changed.

Band-pass filters in the RF module ring at 500MHz in response to the short beam pulses. The ringing time for a single pulse is about 50ns which provides a sufficient number of cycles for measurement. When pulses arrive at 2ns intervals, the filter output reaches a steady state condition in about 100nS. Signals from the four filters are heterodyned to 50MHz and amplified in separate intermediate frequency (IF) modules. A 450MHz surface acoustic wave (SAW) oscillator provides the local oscillator (LO) input to the four mixers via a buffer amplifier and four-way power splitter.

We are using the LM1211 broadband demodulator integrated circuit in the IF modules. This device contains a gain controlled amplifier and a quasi-synchronous amplitude detector. The detector bandwidth is in excess of 10MHz which is sufficient for single turn position measurements even in the booster synchrotron. The video output of the LM1211 consists of pulses 0 to 3 volts in amplitude. These pulses are processed in the IF module to go into three paths:

1. A video buffer makes the signal available for external processing and monitoring.

2. A peak-detector, sample and hold, and low pass filter smooth the signal for digitization in 13 bit analog-to-digital converters (ADC). With computer averaging this low frequency beam signal provides the resolution and accuracy we require with a stable stored beam. The averaging is helpful only if there is no coherent interference.

3. Another video buffer drives the input of a fast digitizer via a resettable peak detector. There are four video digitizers contained in two of the plug-in modules. These 8 bit ADCs are triggered at the ring revolution frequency to convert beam signals for temporary storage in first-in first-out (FIFO) memory. There is sufficient memory for 1000 measurements. One set of FIFOs takes data at the revolution frequency. Another set can be triggered at a slower rate for a longer history of beam position.

Synchronization pulses and calibration signals are generated in the timing module. In addition to the various digital timing signals required in the bin, this module generates the pulsed RF signal used for calibration. The output of a 500MHz SAW oscillator is pulse modulated by either a 50ns or a 500ns gate generator to simulate single or multi-bunch beam. The level of the modulated RF is controlled by a programmable attenuator over a 40dB range. When not needed the oscillator is switched off to prevent interference with beam signals.

The BPM electronics are controlled and monitored by the intelligent local controller (ILC) [3], another module in the bin. The ILC is a 16MHz computer with 64 Kbytes of RAM, 4 channels of 13 bit analog input, 4 channels of 16 bit analog output, and 24 channels of bit I/O. An RS-485 serial interface connects the ILC to the accelerator control system.

The four low frequency beam signals are digitized in the ILC by a 13 bit ADC with multiplexed inputs. The conversion rate of the ADC is about 10kHz. When four channels have been read and averaged 20 times the effective digitizing rate is less than 100Hz but well above the 10Hz requirement. Currently digitizing is asynchronous to the beam signal. The ILC has interrupt capability so it is possible to control the time when conversion takes place if desired.

The ILC has four +/-10V DACs. One is used to control the gain of the IF amplifiers. The level of the calibration signal is controlled by another. The remaining DACs supply bin output signals for X and Y beam position at 1V/mm. These are useful for external low frequency beam position monitoring.

The 24 channels of bit I/O in the ILC can be configured for either input or output on three ports. One input port is used to read the FIFO data from the fast digitizers. The remaining I/O lines are used to address FIFOs, control the calibrator, set the fast digitizing rate, do internal handshaking, and handle external halt requests.

On the bench we control the ILC with a PC/AT personal computer and a serial link via an interface module in the AT. The ILC contains a database with names specific to the task at hand. This database is stored on board in battery backed up RAM. At the outset the equipment designer is given an ILC which is basically a data acquisition front-end for the AT and not a stand alone computer. The BPM electronics are fully exercised by the ILC but all calculations take place in the AT. We develop our code with Microsoft QuickBASIC, a relatively friendly environment for the occasional programmer. Once we have the hardware and software working together well we will give the code to programmers who will translate it into the language necessary for the ILC microprocessor. This method of operation has the advantage of directly involving the equipment designer in software development.

Performance

As yet the BPM electronics have not measured real beam. We can report laboratory results only.

We do not have pulse generators with the high repetition rate, short pulse length, and high amplitude necessary to simulate all bunch patterns of the beam in our test chamber. We simulate two conditions; a single bunch rotating at 1.524MHz and all bunches uniformly filled.

To simulate single bunch beam we use pulse generators with pulse lengths of 60ps at 3.5Vpk and 300ps at 30Vpk. The amplitude of these pulses is not sufficiently high to simulate peak beam current in the high impedance wire in our test chamber so we drive the receiver inputs via broadband power dividers and attenuators.

We simulate multi-bunch beam in the chamber by driving the wire with 500MHz RF. We choose an RF level equal to the magnitude of the 500MHz harmonic of the bunched beam. For ease of calculation we assume the ring is uniformly filled with 328 bunches 28ps long and 2ns apart. The beam frequency spectrum consists of lines 500MHz apart spanning many GHz with equal amplitude. For an average current of 0.4A in the ring, the peak amplitude of the first harmonic is twice the average, i.e., 0.8A. The rms value of this current is 0.57A. With coupling impedance of 0.1 ohm the 500MHz component of the button signal is 57mV. Assuming a cable loss of 6dB at 500MHz, the signal at the receiver input is about 25mV. This calculation provides a reference value for the maximum signal anticipated at the output of the receiver band-pass filter.

To simulate real beam conditions we pulse modulate the RF and drive the wire via a 10W amplifier and isolator. Fig. 3 shows a 10mV peak, pulse-modulated RF signal at a button output and the detected video at the receiver output.

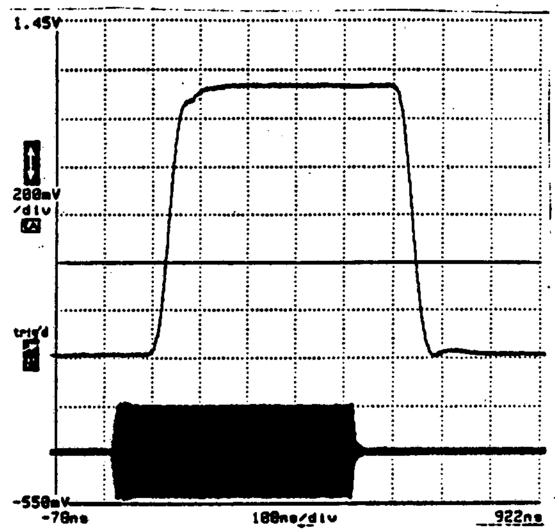

Fig. 3. Receiver RF input (10mV pk) and video output.

Conclusion

With this button signal level we achieve +/-10um resolution when twenty low frequency measurements are averaged. If we use signals from a power divider instead of the chamber the measurement resolution improves to a few micrometers. The dynamic range of the measurement system is about 50dB. Gain compression in the mixer sets the upper limit and noise in the IF amplifier sets the lower limit. We meet the accuracy specifications if the system is allowed to re-calibrate when signal levels have changed. Non-linearity in the IF amplifiers and detectors can cause rather large errors if re-calibration is not done. Averaging twenty measurements requires one second with the AT controlling the ILC. With a math co-processor installed and the ILC running on its own we should attain our 10Hz goal.

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