SSRL Beam Position Monitor Detection Electronics*

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Abstract

As part of a program to improve its orbit stability SSRL is redesigning its detection electronics for its beam position monitors (BPMs) [1]. The electronics must provide highly reproducible positional information at the low bandwidth required of an orbit feedback system. With available commercial technology, it is now possible to obtain highly resolved turn by turn information so that this electronic module can also be used to measure beam dynamics. The design criteria for this prototype system and performance of the analog section of the processor is discussed.

1 INTRODUCTION

SPEAR is a 3 GeV electron storage ring used for synchrotron radiation. It was originally built as an $e^- - e^+$ collider for high energy physics, and its BPM detection electronics was designed to differentiate between the signals from the two particles. All of the BPM inputs are multiplexed into one large switching matrix and processed by one set of electronics. We are redesigning the electronics to improve processor speed, dynamic range, and resolution. In addition to providing highly resolved positional information under normal operation, the system must be able to detect low current orbits for injection studies, etc.

Table 1: SPEAR BPM Parameters

Energy	E	3	GeV
Radio Frequency	$\mathrm{f_{RF}}$	358.54	MHz
Harmonic Number	h	280	
Revolution Frequency	$\mathrm{f_{rev}}$	1.2805	MHz
Nominal Beam Current	$\mathrm{I_{nom}}$	10–100	mA
Number of BPMs		40	
Resolution		10	μm
Channel Isolation		>80	dB
Detector SNR @$\mathrm{I_{nom}}$	SNR	>126	dB/Hz
Dynamic Range		40	dB

2 BPM SIGNAL SPECTRUM

The periodic nature of the beam in a storage ring means that the signal spectrum on a BPM will be periodic. The spectrum of the 'reference particle' is a sequence of signals at the harmonics of the fundamental frequency, $\mathrm{f_{rev}}$. The amplitudes of the individual harmonics are determined by the frequency response of the pickup electrode. For a bunched beam of many particles in many buckets, the spectrum becomes slightly more complex. Although the locations of the frequencies do not change, their amplitudes now depend on bunch shape and fill pattern. In all cases, the amplitudes of the harmonics incident on the BPM are multiplied by the Fourier transform of the bunch length. For multiple bunch fills, the signals from the various bunches add coherently and modulate the amplitudes of the harmonics with the Fourier transform of the bucket fill pattern. Since the ring can only contain a finite number of bunches (the harmonic number, h), this modulation repeats with $\mathrm{f_{RF}}$. In particular, all harmonics of $\mathrm{f_{RF}}$ carry the information of the DC current of the beam. These are the only harmonics of $\mathrm{f_{rev}}$ guaranteed to be non-zero for arbitrary fill patterns.

The spectrum at each harmonic is almost, but not quite a pure frequency. Transverse oscillations of the beam give rise to amplitude modulation of the BPM signals and create betatron sidebands around the $\mathrm{f_{rev}}$ harmonics. Longitudinal oscillations give rise to phase modulation and synchrotron sidebands.

3 RF SIGNAL PROCESSING

The periodic nature of a storage ring determined our choice of a harmonic processing system that detects the power in an appropriate frequency bandwidth. Since we determine the beam position by the difference over sum technique, we multiplex the signals as early as possible to minimize errors in the signals due to electronic variations. Our RF processing is designed to provide a high quality, narrow bandwidth signal for our $\mathrm{f_{IF}}$.

3.1 Processing Frequency

For the reasons given above, we process a harmonic of $\mathrm{f_{RF}}$. The decision as to which harmonic to process was a tradeoff of engineering considerations. SPEAR has several BPMs near the RF cavities, where the evanescent fields from these cavities provide a strong beam-independent signal at the RF, so we rejected processing $\mathrm{f_{RF}}$. Although our BPM buttons are more sensitive to the higher beam frequencies, we chose the second RF harmonic, 717.08 MHz, for two reasons. First, our signal processing electronics will be housed in the control room, typically 100 m from the buttons, and attenuation due to the cable length greatly increases with frequency. Second, the size of our beam pipes gives a typical vacuum chamber cutoff frequency of about 1 GHz. Discontinuities and structures in the vacuum chamber support higher order modes at these frequencies that contaminate the fundamental signal on the BPMs produced by the image charges of the beam.

3.2 Signal Multiplexing

The main purpose of the BPM system is to provide highly resolved information about the orbit of the beam. For our vacuum chamber size, resolution of 1 micron beam motion means a variation in the difference signals of about 50 ppm from the 4 buttons of each BPM. The design of the electronics attempts to minimize the potential for systematic errors that could prevent high resolution measurements. Therefore, we have multiplexed as much of the button processing as possible. The current system multiplexes all BPM buttons into a single processor. We will initially commission the new processor with this same arrangement, but then may build more processors to decrease the overall system sampling time.

The BPM signals are multiplexed at the input. Since this is the only part of the circuitry that is not common to all of the buttons, we desire the technology with the most consistent and repeatable characteristics. We favor GaAs FETs over PIN diodes because of the independence of the FET video impedance with respect to signal level. Standard isolation per switch at our processing frequency is less than our desired 80 dB, so our design cascades absorptive switches to achieve the desired isolation. Our 80 dB isolation specification relates to buttons from different monitors;

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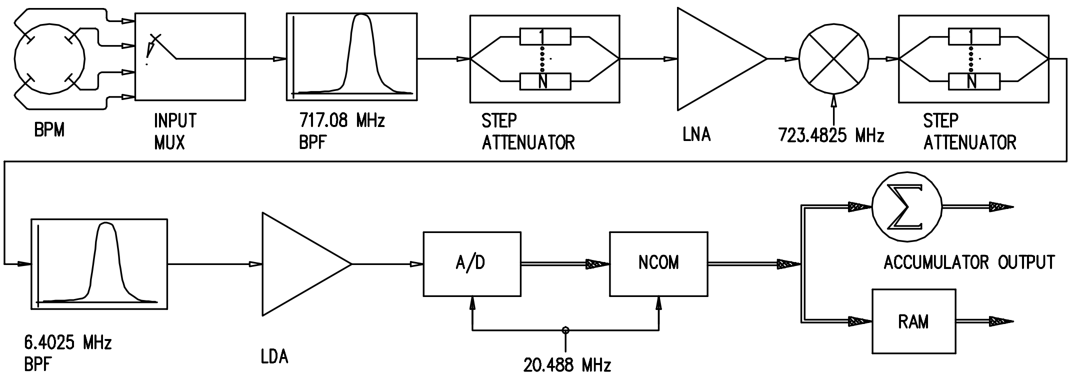

Figure 1: Processor Block Diagram

one 60 dB switch in series should provide sufficient isolation between buttons from a single BPM. Initially, the switches will all be placed in the control room and will be cascaded to provide one final output for the processor. We will also study the feasibility of placing the switches in the ring. If they can be adequately shielded from the radiation, the multiplexer will then require only one high quality signal cable from each BPM to the control room. The only signal paths that will vary from button to button from one BPM will then be a short cable from the button to the multiplexer and the switches themselves. If the switches are placed close to the buttons, we may need to put some inexpensive bandpass filters at the inputs to limit the instantaneous voltage on the switches.

3.3 RF Conditioning

The processor will heterodyne the RF signal down to an f_{IF} of 6.4025 MHz, where its amplitude will be measured. A dielectric resonator band pass filter, a 5 section Chebyshev filter with a 1% bandwidth and 7 dB insertion loss at 717.08 MHz, limits the out of band input power. In order to condition this signal for a 10 dBm image reject mixer, its power level is limited to a maximum value of -10 dBm. We use a combination of a FET step attenuator and a low noise, fixed gain amplifier to keep this level in range. Measurements show that, for our normal operating range of currents, we will always have a -10 dBm signal at the input of our mixer. We chose a fixed gain amplifier and attenuator arrangement because of its overall lower noise figure than that of a variable gain amplifier. We chose a step attenuator over a voltage controlled variable attenuator because we require the more constant attenuation provided by the digital control rather than the fine adjustment offered by variable control. The operating values of the input power were chosen to be well below the amplifier 1 dB compression point and the mixer 3rd order intercept in order to maximize linearity of the system.

4 IF SIGNAL PROCESSING

Our f_{IF} was selected so that, using available commercial technology, we could digitize it directly without sacrificing the resolution of our IF signal. Proper selection of frequency within this range gives us highly resolved, wide bandwidth signals with a minimum of processing overhead.

Recent technological advances have produced monolithic 20 MHz, 12 bit A/Ds at reasonable prices. Therefore we tried to select our f_{IF} below 10 MHz, the frequency above which the A/D performance starts to roll off. The lower f_{IF}, however, the harder it is to reject through filtering the mixer image of the desired frequency. Our RF bandpass filter rejects this image at the input by $\sim$40 dB, but by using an image-reject mixer, we reduce the IF image by another 30 dB. We chose f_{IF} to be 6.4025 MHz as a reasonable compromise where very high quality commercial video opamps and digitizers are available while good image rejection is still possible with simple circuitry.

4.1 Digital Considerations

For any BPM system which is used to control the beam, one needs to digitize the information at some point and pass it on to other elements of the control system. Available technology now makes it reasonable to digitize the signal at the IF. This allows great flexibility in terms of selecting signal bandwidths to optimize SNR, response time, etc., for various applications. In particular, in addition to providing the information needed for our low-bandwidth orbit feedback, this technique allows us to use this processor to detect, with high accuracy, single turn phenomena for machine physics studies. By digitizing the IF, we also have a system with only one non-linear component, the mixer, thereby improving our system linearity.

Since our digital signal processing starts with the IF, we have chosen it, and hence the mixing frequency, to optimize this processing. When Fourier transforming band-limited data, the signal is assumed to be a portion of an infinitely periodic signal. For signals with arbitrary frequency content, this periodic assumption 'contaminates' the transform with non-existent frequency components that are needed to make the sample periodic. To minimize this problem, a 'window' is applied to the data which de-emphasizes the ends of the data sample. This windowing also contaminates the data, but hopefully less than an unwindowed sample. The signals we measure, however, are extremely periodic and we have access to the ultimate system clock, f_{RF}. By making use of this periodicity, we can choose to sample a signal that is periodic with respect to our clock, so that this signal truly is a portion of an infinitely periodic signal. With this method, we get a faithful frequency decomposition of the signal without windowing. Since our signal is coherent while noise is incoherent, N samples per revolution will increase our SNR by $\sqrt{N}$. Therefore, we chose our digitization frequency as $16f_{rev}$, or 20.488 MHz.

When a perfect periodic signal is digitized, the output codes will have a periodic fixed quantization error. To minimize this error, the digitizer should sample the signal at as many values as possible. This means that the periodicity of the sampler should be as relatively prime as possible to the periodicity of the signal. Based on the criteria of image rejection, analog signal fidelity, periodicity, and digital fidelity, we chose $5f_{rev}$, 6.4025 MHz, as our f_{IF}.

4.2 IF Analog Conditioning

The remainder of the analog processing optimizes the signal for the digitizer. A lumped element band pass filter at 6.4 MHz passes the output of the mixer. This filter needs only act as an anti-aliasing filter for the digital processing that follows, with the nearest aliased frequency of f_{IF} at 14.0855 MHz. We set its bandwidth to $\sim f_{rev}$, since we want the ability to observe signals change that quickly. (In fact, we have been very conservative in all of our analog filtering specifications. Since each revolution harmonic carries the same spectral information, we are detecting synchronously with the ring RF, and the button response is essentially constant over the small bandwidths we are considering, the only contamination we would get from aliased signals is a uniform increase or decrease in the detected signals of all buttons. The major danger in this is that two signals may be exactly out of phase and cancel, but contamination on the order of $\sim$40 dB would not affect our detection resolution.) In the IF we again use a combination of a digital step attenuator and fixed gain amplifiers. Although there are variable gain video opamps with the same noise performance as fixed gain opamps, we are more confident in keeping the system gain constant with the step attenuators. We use a low distortion, low noise amplifier to boost the IF signal to the 1V nominal input value desired by the digitizer.

4.3 IF Digital Processing

We digitize the data at a high rate to improve the SNR of the system, but it would be very expensive to keep and process the entire Nyquist bandwidth. From a beam dynamics point of view, all desired information is stored within a bandwidth of f_{rev}. Further, since this system is not designed to look for coupled bunch modes, it is not clear what information we would ever need to investigate that happens faster than f_{rev}. We therefore use a digital mixer, the Harris HSP45116 numerically controlled oscillator/modulator (NCOM), to beat our f_{IF} down to baseband once per revolution period.

The NCOM takes as input the stream of 12 bit digital words from the A/D, internally multiplies them with the sine and cosine of f_{IF}, accumulates them 16 samples at a time, and then outputs 16 bit words that represent the amplitudes of the quadrature components (I&Q) of f_{IF} during the previous f_{rev} period. (Its rejection of the other harmonics passed by the anti-aliasing filter is $\sim$90 dB.) An AMD29240 32-bit microcontroller accumulates these amplitudes and stores them in DRAM. This sum is the filtered value of f_{IF}, the width of which is determined in software by the number of samples taken. The digital sum is then passed along, in real time, to subsequent processors for orbit calculations and corrections.

The microcontroller will also handle the low level control of the switches and attenuators, and communicate with the rest of the crate via high level commands, which will determine the BPMs that are sampled, the sampling order, and periods. This programmability of the microcontroller allows us to change sampling periods to minimize errors by coordinating the sampling period with, for example, the period of the synchrotron or betatron frequency. The microcontroller can even implement a phase-locked loop on the NCOM that can independently keep the Q signal of each button zeroed to reduce the amount of data needed to transfer to the control system during normal operation.

Although the electronics are primarily designed for orbit measurement that can be used to correct for slow beam motion, the digitization of the IF and the flexibility of the microcontroller allow for accurate single turn information to be output from the electronics. When such information is desired, the microprocessor can be programmed to acquire a large buffer full of turns, then download it to another processor for computations. Because of our choice of processing frequencies, we are able to have a large enough bandwidth in our IF filter to allow turn by turn motion to be observed. One can observe the betatron oscillations by measuring the turn-by-turn amplitude modulation of the data, and can observe the synchrotron oscillations by measuring the phase modulation.

5 SYSTEM TIMING

The timing generation of the system is straightforward. To generate the synchronous signals for our clocks and local oscillators, we divide down either f_{RF} or $2f_{RF}$. Switching of electrodes will all be done at increments of the revolution period and the processor will sample each electrode for multiples of this fundamental period. These values can, of course, be dynamically changed through software. We plan to package this controller in a format that will interface to a VME environment. Once this decision is finalized, we will use standard interface logic to connect the processor to the control system.

6 SYSTEM TEST RESULTS

We were able to test a prototype version of the analog portion of the processor during SPEAR's 1994 run by parasitically observing signals from one BPM with 55 mA of current in the machine. At this current we required 29 dB attenuation in the signal path to set our IF signal at the 1V level desired by the A/D, so that our measured analog path SNR will hold down to $\sim$2 mA. For a 10kHz RBW, our signal measured $\sim$70 dB above the noise floor at the IF output. Our signal was clean enough to see the amplitude and phase oscillations on the beam. If we need a greater SNR, we can trade off with the current system dynamic range. We saw no evidence of any problems due to processing at a harmonic of f_{rev}. Direct feedthrough of f_{IF} was $\sim$58 dBc, which we feel can be further reduced by addition of appropriate filters. The other noticeable product, probably a mixer IMD was $\sim$65 dBc. As discussed earlier, neither of these should be a problem.

We are continuing our development of the processor. Improving commercial technology makes possible increasingly better isolation per multiplexing switch, so we are evaluating new products before we make our final choice. We must still input this signal into the digital processor and program the controller, but based on the results of the beam tests, this work can be done on the bench.

7 REFERENCES

[1] R. Hettel, J. Corbett, D. Keeley, I. Linscott, D. Mostowfi, J. Sebek, and C. Wermelskirchen, "Digital orbit feedback control for spear," in *IEEE PAC Conf. Proc.*, AIP, 1995.