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Tune Measurement in the NSLS Booster Synchrotron*

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Abstract

The NSLS booster synchrotron can accelerate an electron beam from approximately 80 to 750 MeV in 0.7 sec. The betatron tunes can change during acceleration by as much as 0.1 units, causing beam loss as they cross resonance lines. Precise measurements with a conventional swept spectrum analyzer have always been difficult because of the rapid variation of tune as the magnets are ramped. We are now using a system based on a Tektronix 3052 digital spectrum analyzer that can obtain a complete frequency spectrum over a 10 MHz bandwidth in 200 μsec. Betatron oscillations are stimulated for the measurements by applying white noise to the beam through stripline electrodes. We will describe the instrumentation, our measurements of tune as a function of time during the acceleration cycle, and the resulting improvements to the booster operation.

I. INTRODUCTION

The injector for the electron storage rings at the National Synchrotron Light Source (NSLS) is a 77 - 750 MeV synchrotron called the booster [1]. It has a 28.35 m circumference and a 0.7 Hz repetition rate. The lattice consists of four superperiods, each containing two combined function bending magnets and two horizontally focusing quadrupoles. The vertical tune is determined primarily by the gradient in the bending magnets and the horizontal tune by the quadrupoles. Eight small, air-core trim quadrupoles are provided at positions in the lattice with large values of the vertical beta function for fine adjustment of the vertical tune. Each family of magnets is powered by its own programmable power supply.

The booster performance has always been very unstable. The electron current could vary by a factor of ten from one acceleration cycle to the next. It was known from measurements with a conventional spectrum analyzer that at a given point in the acceleration cycle, the betatron tunes could vary by as much as 0.1 on succeeding cycles. It was also known that injection required a tune just below the half-integer resonance. Apparently, the beam was lost when the horizontal tune wandered close to the half integer.

Because a conventional spectrum analyzers may need at least 20 msec to measure a frequency spectrum, it was always hard to see the rapid tune changes that occurred in the booster during acceleration. The spectra were distorted as the spectrum analyzers swept slowly through the measured frequencies and the number of points that could be measured while the beam was accelerated was small.

To understand the problems with the booster a way was needed to rapidly measure the tunes during a single acceleration cycle. Real time display of the results was desired to aid in adjusting the magnet ramps. This paper will describe a system based on the Tektronix 3052 Digital Signal Processing system [2], an instrument that can measure a complete frequency spectrum from 0 - 10 MHz in a time of 200 μsec, to simultaneously measure the horizontal and vertical tunes in the NSLS booster throughout the acceleration cycle [3].

II. TUNE MEASUREMENT SYSTEM

A. Spectrum Analyzers

Accelerator tune measurements are often made with a swept spectrum analyzer. This consists of a tunable bandpass filter whose center frequency $\omega_0(t)$ is swept over the frequency range of interest. The center frequency can not be changed by an amount equal to the bandwidth of the filter $\delta\omega$ in a time less than $O(1/\delta\omega)$ without distorting the spectrum. Additional time may also be needed by the instrument to process the data after the sweep is completed. In a rapidly cycling accelerator like the NSLS booster, the tunes can change appreciably during the sweep time which can distort the spectra and make them hard to interpret.

The Tektronix 3052 Digital Signal Processing System uses 1024 bandpass filters operating in parallel to obtain a frequency spectrum. All of the filters simultaneously measure the signal within their passbands to produce the entire frequency spectrum in one shot. The Tektronix 3052 takes 200 μsec to measure a complete spectrum over a 2 MHz range to a resolution of 1/800.

A Fast Fourier Transform (FFT) spectrum analyzer operates in the time domain by sampling the incoming signal and then performing an FFT numerically to calculate the frequency spectrum. This technique is commonly used to measure accelerator tunes in the 100 KHz range but, for the 5 MHz spectral range required for the NSLS booster tune measurements, the FFT technique would be dominated by the numerical processing time, and could not be used.

B. System Details

Electrostatic pick-up electrodes are used to measure the beam position in the NSLS booster synchrotron. The betatron tune appears as sidebands on the harmonics of the revolution frequency. Because coherent betatron oscillations do not usually appear spontaneously, it is necessary to stimulate the beam with a driving force to provide a large enough signal to measure the tune. This is done by applying a deflecting field to the beam with a set of stripline electrodes.

With a conventional swept spectrum analyzer, an amplified signal from a tracking generator is used to drive the beam at the frequency being measured. A sustained response is only possible at the frequency of one of the beam's normal modes of oscillation; i.e. at one of the revolution harmonics or the betatron tune sidebands. The position signal is then connected to the input of the spectrum analyzer and the betatron tune lines are seen as a response of the beam to the deflecting signal.

Measuring the betatron tunes with a multiple receiver spectrum analyzer like the Tektronix 3052 or by FFT techniques is slightly more complicated. Because all of the frequencies in the range of interest are observed simultaneously, it is necessary to stimulate the beam at all of

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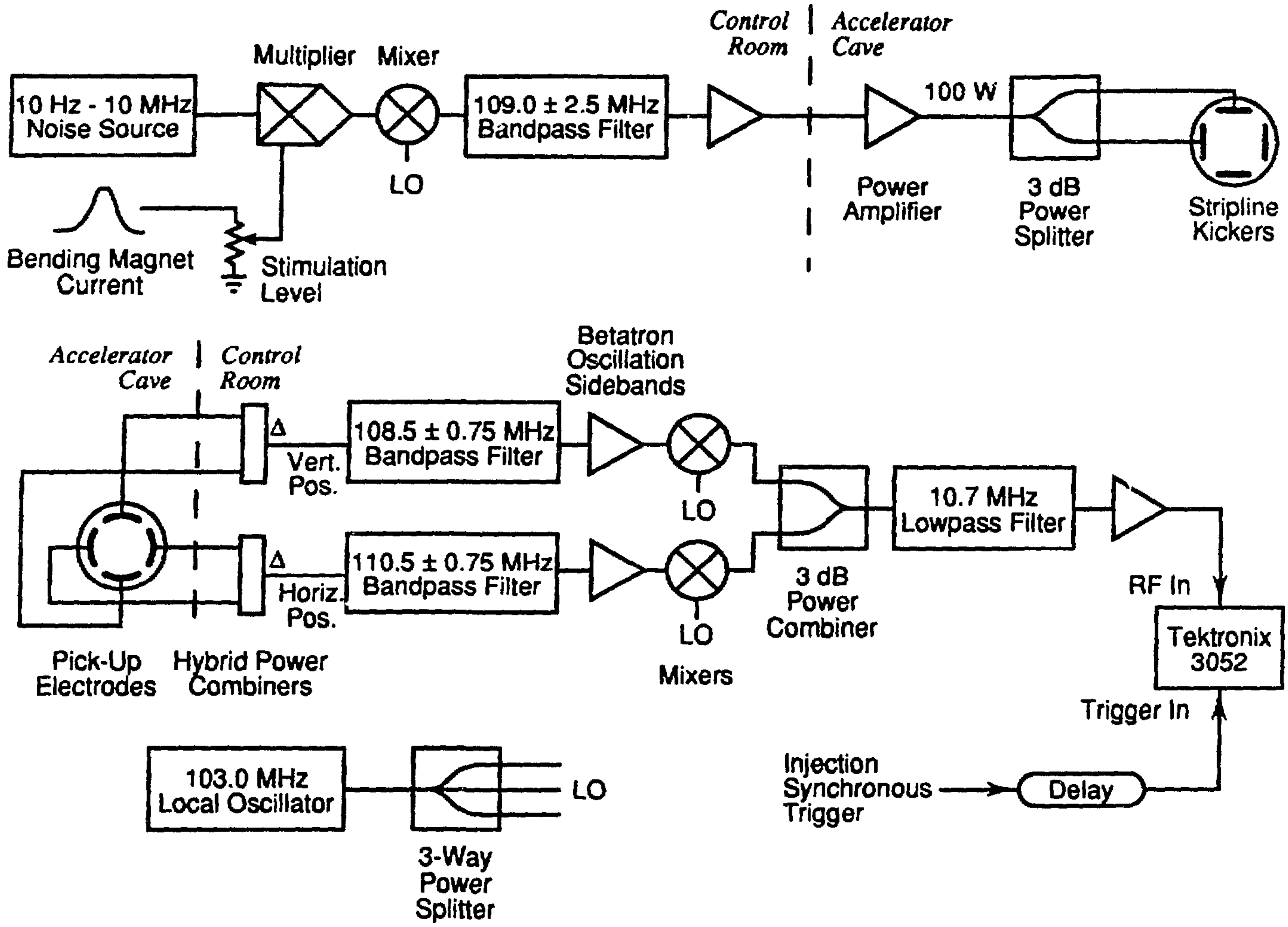

Fig. 1. NSLS booster tune measurement system block diagram.

the frequencies of the band simultaneously as well. This can be done by applying the signal from a broadband noise generator to a deflecting electrode.

A block diagram of the NSLS booster tune measurement system is shown in fig. 1. Horizontal and vertical tunes are measured simultaneously. The beam positions are obtained by subtracting the signals that are induced on pairs of electrostatic plates using hybrid power combiners. Deflecting forces are applied to the beam by signals on horizontally and vertically oriented stripline kickers. Both the position detectors and stripline kickers are most sensitive at frequencies near 100 MHz so we measure the betatron tunes at the upper sideband of the tenth harmonic of the 10.58 MHz revolution frequency. We heterodyne these signals down to the 0 - 10 MHz range of the Tektronix 3052.

The stimulating signal is obtained from a noise generator with a flat frequency spectrum from 10 Hz to 10 MHz. To provide a constant excitation at all beam energies, the noise source is scaled by a signal proportional to the current in the dipole magnet which, in turn, is proportional the beam energy. The signal is then mixed with the 103 MHz signal from a crystal controlled oscillator, the components in the 103.0 ± 2.5 MHz band are selected, amplified, and applied to the horizontal and vertical kickers.

From the design of the booster and from previous measurements with swept spectrum analyzers, we knew that the fractional horizontal tune was between 0.4 and 0.5, and the fractional vertical tune was between 0.2 and 0.3. At the sidebands of interest, these correspond to frequencies near 110.5 MHz for the horizontal tune and 108.5 MHz for the vertical tune. We filter the signals from the position detectors at these frequencies to avoid saturating the electronics with extraneous noise. The horizontal and vertical betatron sidebands are separately mixed with a signal from the 103 MHz local oscillator, combined, and the difference signal is selected by a 10.7 MHz low pass filter. The result, containing the horizontal and vertical betatron tune information, is applied to the input of the Tektronix 3052.

After receiving a trigger corresponding to the injection of the electrons into the booster, the 3052 begins to collect a frequency spectrum every 200 μsec. Every r^{th} spectrum is saved, where r is an integer that can be set by the user, and 501 spectra can be saved in the instrument's internal memory. A false color image showing the horizontal and vertical tunes as a function of time after injection is displayed after each booster cycle. An example of a color spectrogram can be seen in reference [3].

C. DATA ANALYSIS

The 3-D plots that are produced by the spectrum analyzer can be used for tuning the booster, but for analysis it is useful to extract 2-D plots of tune vs. time or horizontal vs. vertical tune. This information is extracted using the Motorola 68030 based, single board computer that is incorporated in the Tektronix 3052. The program is written in the "C" language.

Tunes are extracted from the raw data by a simple peak finding algorithm following exponential smoothing of the data at nearby frequencies to remove narrow-band electrical noise. (This is described in more detail in reference [3].) An ASCII file containing the the horizontal and vertical tune as a function of time is written to the spectrum analyzer's hard disk where it can later be examined or transferred to another computer via an RS-232 interface for further analysis. Performing the initial data reduction within the spectrum analyzer has the advantage of reducing the amount of data transmitted. Fig. 2 shows a plot of the horizontal and vertical tune during a typical booster acceleration cycle.

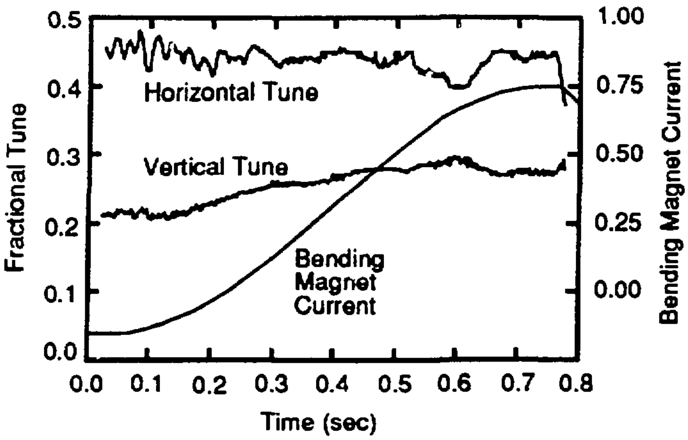

Figure 2. Horizontal and vertical tunes in the NSLS booster as a function of time during the acceleration cycle. Also shown is the booster bending magnet current which is proportional to beam energy.

III. RESULTS AND DISCUSSION

Together with the tune data, fig. 2 shows the booster bending magnet current, which is nearly proportional to the electron beam energy. The horizontal tune fluctuates at a frequency of approximately 60 Hz at low energy. The oscillation is caused by an instability in the regulation of the bending magnet power supply at low currents. The tune at any given time in the cycle also tends to vary from one cycle to the next due to slow drift in the power supply. On some cycles, the variation is enough to carry the peaks in the horizontal tune across the half-integer resonance causing beam loss. This explained an instability in booster operation that had been seen for many years but only incompletely understood.

In the long term the problem with the tune variation will be cured by replacing the booster power supplies [4] but for now, the instability was fixed in another way. A program had already been started to increase the energy of the linac that serves as an injector for the booster from 77 to 116 MeV. Observation of the tune instability provided impetus for completing the linac upgrade. At 116 Mev, corresponding to a time of approximately 0.15 sec in fig. 2, neither the rapid fluctuations nor the cycle to cycle variation in the horizontal tune are as severe. We used the same bending magnet ramp as for 77 MeV injection but delayed the injection time until the magnet currents reached the 116 MeV values. Booster operation is now much more stable, The cycle to cycle variation in the electron current is now less than 10%

More recently, a new digital feedforward system [5] was connected to the bending magnet power supply to improve the low frequency response. This corrected the remaining cycle to cycle tune variation. Because the new feedforward system changed the regulation of the power supply, it was necessary to adjust the magnet ramp to compensate. This was easily done, using the tune measurement system to monitor the tune in real-time. Similar adjustments in the past took weeks of work with a swept spectrum analyzer.

Fig. 3 shows a plot of the vertical tune as a function of the horizontal tune in the booster, derived from the mean data in fig. 2. Also shown are the resonance lines in the region plotted. As the beam is accelerated, it crosses the fourth order resonance $4q_y=1$ and later skirts back and forth along the third order resonance $q_x+2q_y=1$ but never crosses it. Although the the fourth order resonance apparently does not effect the beam, the third order resonance does. This explains why the booster beam was lost if the vertical tune was increased. Raising it will carry it across the resonance line.

The vertical tune in the booster is controlled largely by the trim quadrupoles. Their power supply can only produce a limited current and can not be scaled with beam energy during the entire acceleration cycle. This explains the increase in vertical tune seen in fig. 2. The lack of control of the vertical tune has always been a problem: if the vertical tune is too low injection suffers but if it is too high the third order resonance is crossed. Now that the tunes were measured precisely, a new trim quadrupole power supply will be installed to correct the problem.

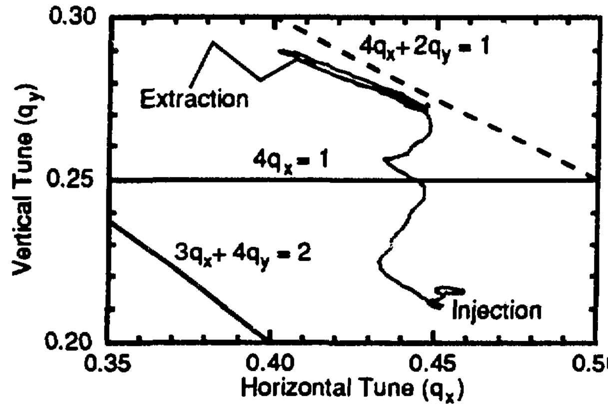

Figure 3. Horizontal vs. vertical tune in the NSLS booster obtained from the data in fig. 2, smoothed to eliminate rapid oscillations. The third and fourth order resonance lines in this region of the tune plane are indicated.

IV. ACKNOWLEDGEMENTS

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V. REFERENCES

[1] J. Galayda, L. Blumberg, R. Heese, J. Schuchman, and A. van Steenbergen, *I.E.E.E. Trans. Nucl. Sci.* **NS-26** (1979) 3839.

[2] Tektronix Federal Systems Inc., P.O. Box 4490, Beaverton, OR 97076, USA.

[3] E.B. Blum and R.J. Nawrocky, *Nucl. Inst. and Meth. A*, to be published.

[4] R. Olsen, J. Dabrowski, and J. Murray, Conf. Rec. of the 1992 IEEE Nucl. Sci. Sym. and Med. Imaging Conf., 572.

[5] R. Olsen, J. Dabrowski, and J. Murray, "Control System for the Booster Power Supply Upgrade", these proceedings.