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BEAM TRANSFER FUNCTION MEASUREMENTS OF ACCELERATING BEAM IN THE FERMILAB BOOSTER

D. McGinnis, J. Marriner, V. Bharadwaj
Fermi National Accelerator Laboratory*

Abstract--Beam transfer function measurements were performed on accelerating beam in the Fermilab Booster with a network analyzer and a custom signal processing system. Since the Booster RF frequency slews from 30 to 53 MHz in 33 mS, an intermediate frequency processing circuit was built external to the reference and receive ports of the network analyzer. This circuit permitted resolution of 2.5 kHz synchrotron sidebands while the Booster RF frequency changed from 500 kHz in 15 mS.

I. INTRODUCTION

Presently, there is an effort at Fermilab to build longitudinal coupled bunch mode dampers for the Booster [1]. To determine the gain needed for the damper system, the transfer impedance of the pickup and kicker must be known. Also the delay and phase intercept of the damper system must match the beam response from pickup to kicker. These parameters can be measured using a network analyzer inserted in the damper system to measure the open loop gain as shown in Fig. 1.

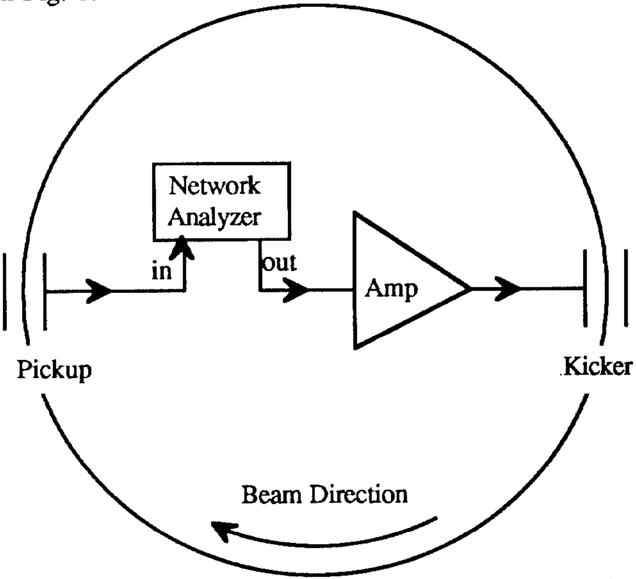

Fig. 1. Schematic of a network analyzer measurement for a circular accelerator.

The Booster accelerates protons from 200 MeV to 8 GeV in 33 mS. Since the machine circumference is 475 m, the revolution frequency must change from 360 kHz to 630 kHz in 33 mS. The revolution frequency for the last half of the acceleration cycle is shown in Fig. 2. A sketch of the beam transfer function at a given instant in the acceleration cycle is shown in Fig. 3. The spacing between the multipole lines is equal to the synchrotron frequency. After transition, which occurs about half way through the acceleration cycle, the synchrotron frequency is about 2.5 kHz and remains fairly constant until the end of the acceleration cycle.

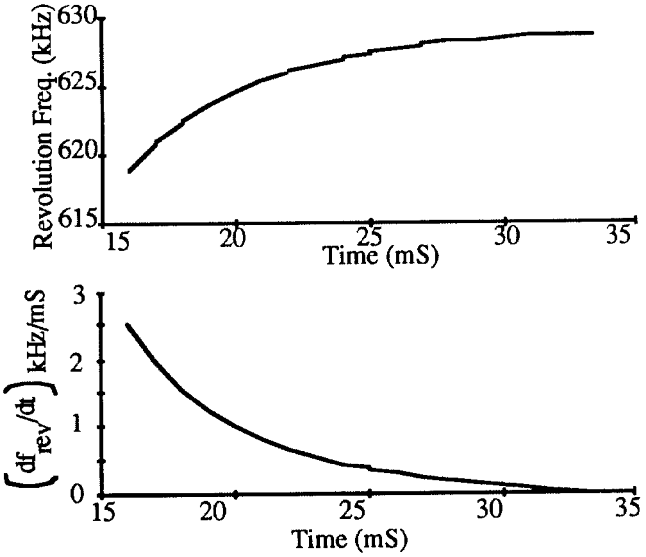

Fig. 2. Revolution frequency and rate of change of revolution frequency vs. time in the acceleration cycle for the last half of the cycle.

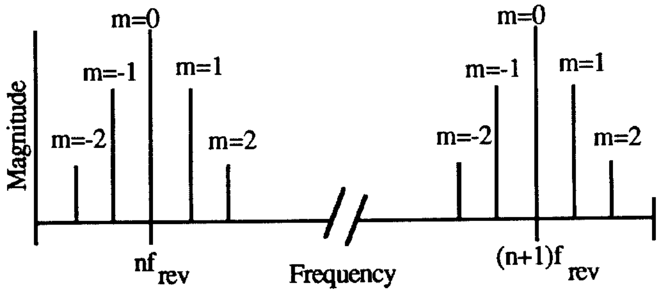

Fig. 3. A schematic representation of the magnitude of the beam transfer function for two neighboring revolution lines. m=0, ±1, ±2, ... indicate monopole, dipole, quadrupole, ... modes

The frequency scale of the beam transfer function shown in Fig. 3 will change during the acceleration cycle along a curve that is harmonically related to the frequency versus time curve of Fig. 2. The length of time that a network analyzer must dwell at a single frequency is inversely proportional to the resolution bandwidth of the network analyzer. Thus, if the resolution bandwidth is too low, the network analyzer will excite more than one multipole line for a given frequency. Expanding the frequency versus time curve in a Taylor series and keeping terms up to first order, it can be shown that in

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order for the network analyzer to excite only one multipole line, the following inequality must hold:

$$n \left. \frac{df_r}{dt} \right|_{t_0} < \frac{f_s f_{IF}}{2} \qquad (1)$$

where n is the harmonic number, f_r is the revolution frequency, t_0 is the time in the acceleration cycle when the measurement is taken, f_s is the synchrotron frequency, and f_{IF} is the resolution bandwidth of the network analyzer. For example, if n=84 (this is the harmonic number of the RF), f_s=2.5 Khz, f_{IF}=3 kHz, then the rate of change of the revolution frequency must be less than 44 Hz/mS. According to the second graph of Fig. 2, this condition does not occur until the last moment of the acceleration cycle.

II. MEASUREMENT THEORY

To remedy the situation described by Eqn. 1, the frequency of the network analyzer reference should track a harmonic of the revolution frequency. A circuit that provides such a reference is shown in Fig. 4. In this circuit, a portion of the low level RF of the accelerator is fed into the clock of a direct digital synthesizer. The direct digital synthesizer (for more information on the DDS circuit, see Ref. [2]) is programmed by the computer to provide a frequency output that is a fraction of the clock signal. (for example if the RF harmonic number is 84 and the DDS fraction is 16/84, the output frequency of the DDS is equal to the sixteenth harmonic of the revolution frequency.)

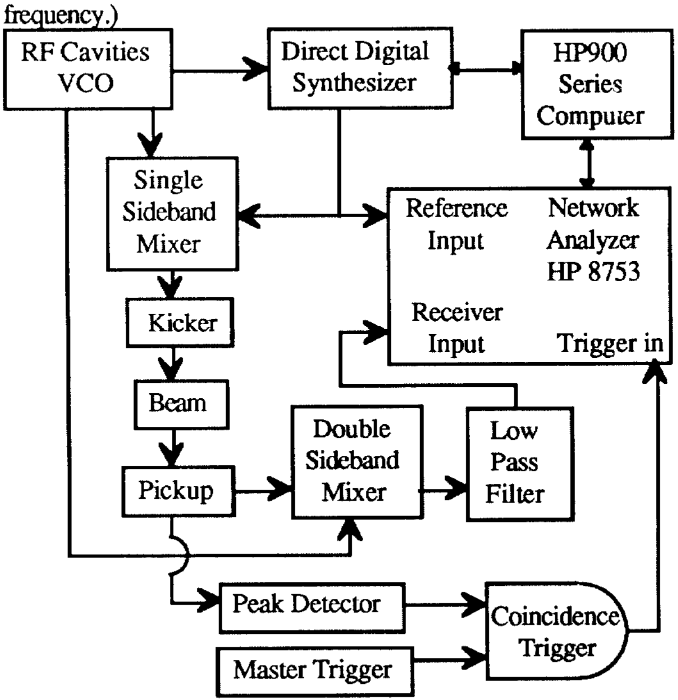

Fig. 4. Intermediate frequency processing circuit.

Because of the limited frequency range of the DDS circuit (The one used for this paper is the QUALCOMM Q0310 Evaluation Board which has a maximum frequency range of 25 MHz.), the DDS output is mixed in a single sideband mixer with the RF VCO output to provide a frequency that is (84 - $DDS_{fraction}$)*f_{rev}. A single sideband mixer is necessary so that only one RF harmonic is excited. To keep the frequency swing in the reference leg small so that the network analyzer will not lose phase lock, the DDS output is also used for reference leg of the network analyzer.

The mixed-up signal is then applied to the beam via the kicker and the response is detected by the pickup. To make the received signal frequency the same as the reference frequency, the pickup signal is mixed down with the low level RF signal where the high frequency component of the mixing product is eliminated by a low pass filter.

Since the reference frequency of the network analyzer is not constant during the measurement, the network analyzer is placed in the Continuous Wave (CW) mode and the amplitude and phase of the ratio of the pickup signal to the reference is displayed as a function of time throughout the accelerator cycle. To trigger the network analyzer at the proper time in the cycle and trigger only if there is beam in the machine, the pickup signal is peak detected and a coincidence gate is formed with the accelerator clock.

The measurement described above is performed for only one fractional revolution harmonic. To obtain the response as a function of the fractional revolution harmonic, the computer must increment the fraction, a new batch of beam must be injected into the accelerator, and the network analyzer must be re-triggered. This procedure will yield satisfactory results if the operating conditions of the Booster remains stable during the measurements. Experimentally, this has been found to be the case. However, for extra conditioning, the response for a given fractional revolution harmonic can be averaged for a number of beam batches before changing the fraction. This averaging also has the added benefit of reducing signals caused by beam instabilities the are not phase related to the kicker signal.

Since the DDS frequency will not track a multipole line exactly during the acceleration cycle, the width of a given multipole line must be large enough so that the crossing of the DDS frequency through the multipole line will take long enough to fill the IF filter of the network analyzer. By expanding the frequency versus time curve in a Taylor series and keeping terms up to first order, the requirement on the synchrotron line width can be written as:

$$\frac{\Delta f_s}{f_s} > \frac{2\left(\frac{1}{f_r}\frac{df_r}{dt} - \frac{1}{f_s}\frac{df_s}{dt} \right)}{f_{IF} + \frac{1}{f_s}\frac{df_s}{dt}} \qquad (2)$$

Near transition, which is at 18 mS in the Booster, the right hand side of Eqn. 2 will approach 100% because the synchrotron frequency goes to zero. However, after about 21 mSec into the cycle, the synchrotron frequency reaches 2.5 kHz and remains fairly constant for the rest of the cycle so that the right hand side of Eqn. 2 is well under 5%.

III. RESULTS

Figs. 5-7 show the results of a network analyzer measurement performed on accelerating beam in the Booster during the last 15 mS of the acceleration cycle. The network analyzer was uncalibrated so the magnitude of the results is unnormalized. The beam intensity was 1x10^{12} protons. The number of points along the time axis is 26. The number of revolution fractions is 220. For this measurement, the number of averages at each revolution fraction was 10. With the Booster operating at a repetition rate of about 4 seconds, this measurement took about 2.5 hours to complete. The measurements were centered around the 74th revolution harmonic. (the DDS fractions were centered around 10/84.)

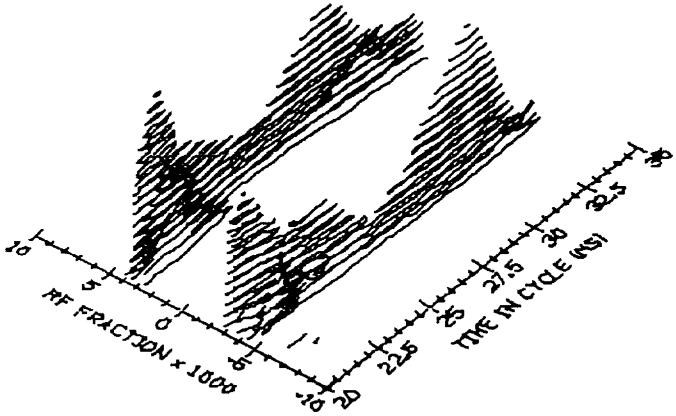

Fig. 5. The linear magnitude of a network analyzer measurement as a function of the DDS RF fraction and time in the acceleration cycle. The RF fraction axis is centered around the 74 revolution harmonic.

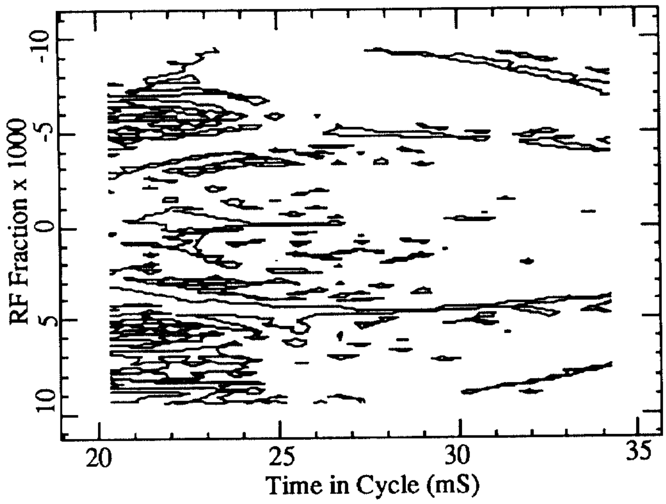

Fig. 6. The 90° phase contours of the network analyzer measurement shown in Fig. 5.

Figure 5 is a three dimensional contour plot of the beam transfer function versus time in the cycle and fractional revolution frequency. As seen in Fig. 5, the only part of the response that is greater than the noise floor is a set of dipole lines located near the revolution fraction = ±0.004. This revolution fraction coincides with a synchrotron frequency of 2.5 kHz. Figure 6 shows a phase contour of the response for 90°. Because the phase contour correlates well with the magnitude contours shown in Fig. 5, it is very likely the the signal received by the network analyzer is indeed due to the signal sent out by the network analyzer. Figures 7a-c are the response versus revolution fraction at a single instant in the acceleration cycle. These figures clearly show the dipole response of the beam. Also Figs. 6 and 7a show a slight hint of the quadrupole lines.

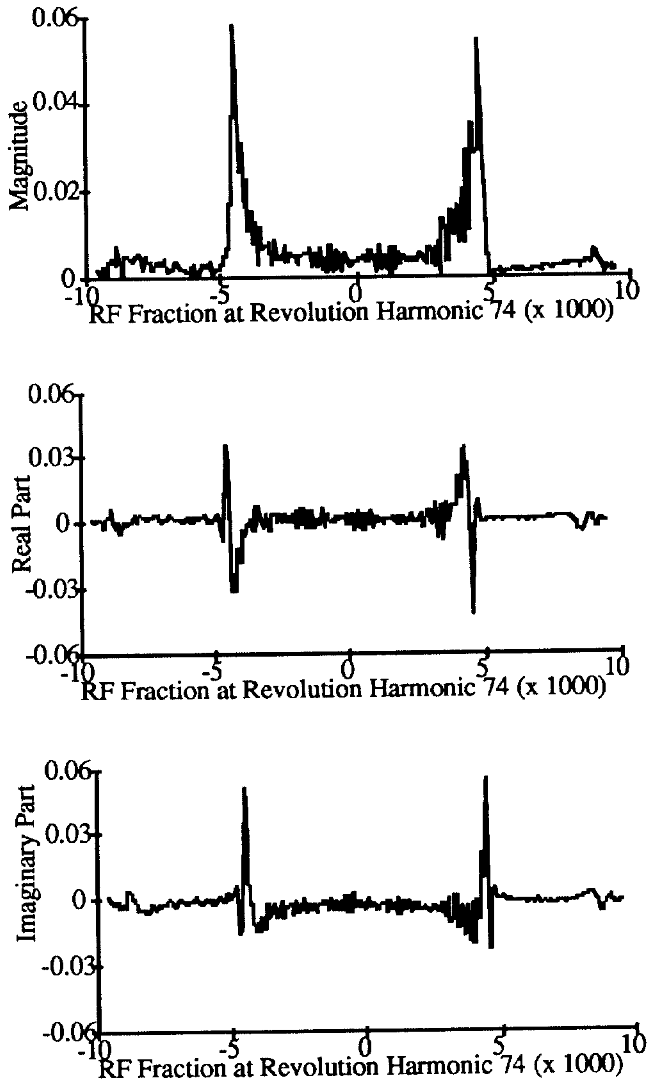

Fig. 7a-c. The magnitude, real, and imaginary response of the network analyzer measurement at a single instant in time centered around 31.5 mS into the acceleration cycle.

IV. ACKNOWLEDGEMENTS

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