MEASUREMENT OF COHERENT QUADRUPOLE OSCILLATIONS AT INJECTION INTO THE ANTIPROTON ACCUMULATOR

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Abstract

In beam transfer between the $\bar{p}$ accumulator and other rings, good transverse matching between rings is required to conserve low emittance. To check on this with proton beams, a quadrupole pick-up was installed in the accumulator. This responds to the coherent beam envelope oscillations after injection, at second-order betatron frequencies $(n \pm 2q)f_0$. (Strong components at the revolution harmonics, caused by misalignment and electrical unbalance, are filtered out and second-order components caused by missteering are minimized by carefully compensating the coherent dipole oscillations). The signals are digitized and the following analysis discriminates between horizontal and vertical signals (with slightly different frequencies) and measures their amplitude and phase. The associated problems and result of the measurements are discussed.

Introduction

Observation of transverse quadrupole mode instabilities in the CERN Antiproton Accumulator (AA), [1] with an improvised resonant pick-up, stimulated interest in quadrupole oscillations and prompted the installation of a purposely designed detector. Now the measurement sensitivity has been significantly increased, facilitating observation of the instabilities and enabling measurements of coherent quadrupole oscillations of injected beams to be made. The latter provides a means of optimizing the matching of the injection and ejection transfer lines.

This paper will detail aspects of the system design in addition to discussing the data acquisition and analysis.

Detector Design Requirements

The theory of measurement of the multipole coefficients of a charged beam using electrostatic or stripline detectors, and the basic measurement limitations, are developed in references 2 through 5. In these papers it is shown that there are severe practical limitations on the accuracy with which multipole coefficients can be measured. The principal problems arise from, firstly, the quadrupole signal from the pick-up has an additional component, at the same frequency, which increases with the square of the beam's transverse displacement due to dipole oscillations, and secondly the quadrupole signal is normally very small compared with the common mode signal at the revolution frequency. There are two ways of minimizing the errors produced by the first problem, namely, reducing the dipole oscillation until its contribution is negligible or measuring this oscillation and, after calculation, subtracting the dipole contribution. This latter technique is not simple and has not been necessary for the AA application. For the second problem, the revolution frequency can be reduced by good common mode rejection and if the quadrupole frequencies to be observed are sufficiently far away, then strong filtering of the revolution frequency can also help.

A simple pick-up design was chosen using four flat plate electrodes. A more complicated design with a linear response to the quadrupole moment would be less sensitive and the attainable system accuracy could hardly justify the complications.

In addition to the quadrupole signal, this pick-up is also required to supply horizontal and vertical dipole signals. These signals are used for coherent dipole oscillation measurements at injection and in the near future will be used for a new transverse damper system [6]. They will replace the existing signals taken from the beam position monitors reducing significantly the noise injected on the stack via the damper kickers.

The four electrodes are connected to independent vacuum feedthroughs allowing the dipole signals to be obtained. The electrodes are 515 mm long and 25 mm wide and spaced at 35 mm, which is as close as possible for the machine 25π mm.mrad acceptance. The electrodes were made narrow and strengthened by spinal ribs to minimize the inter-electrode capacitance which can significantly reduce the sensitivity to quadrupole signals.

The range of output signals from this pick-up with 50 cm of 50 ohm cable connecting each feedthrough to the signal treatment box is as follows:

- for a central beam of 2×10^{11} particles in a bunch 20 ns long the voltage on each electrode is ~10 V/peak,
- for similar beam conditions the peak dipole signal is ~750 mV/mm but the output linearity has a very restricted range,
- at the other extreme a beam of 10^{10} particles centered in the pick-up but with a quadrupole distribution of ± 1 mm produces a quadrupole signal of approximately 12 μV.

Signal Treatment

The dipole damper imposes the greatest requirements on the frequency range. The lowest dipole mode to be damped occurs around 460 kHz and a linear phase response to 30 MHz is necessary demanding a bandwidth in excess of 50 MHz. The lowest frequency quadrupole mode is just under 1 MHz.

Using the standard approach of differential amplifiers or impedance buffers to measure these signals with their large common mode excursions would be difficult and inevitably noisy. It was therefore considered better to use wide-band hybrid transformers. Normally, wide-band hybrid transformers work at low impedances (50-100 Ω), but with a low electrode capacitance this would give a very high low-frequency cut-off, (tens of MHz). The pick-up sensitivity and low noise would be quickly sacrificed by working at low impedance.

To obtain high impedance hybrids, the transformers should have many turns on large area, high μ cores but these factors conflict with the required high frequency response. The main limitation came from the inter-winding capacitance and optimum results were obtained by stacking 3 small high μ ferrites and limiting the number of turns to 10+10:14. The final arrangement is shown in Fig. 1. The input impedance achieved is 1.5 kΩ giving a low frequency cut-off of 1.1 MHz.

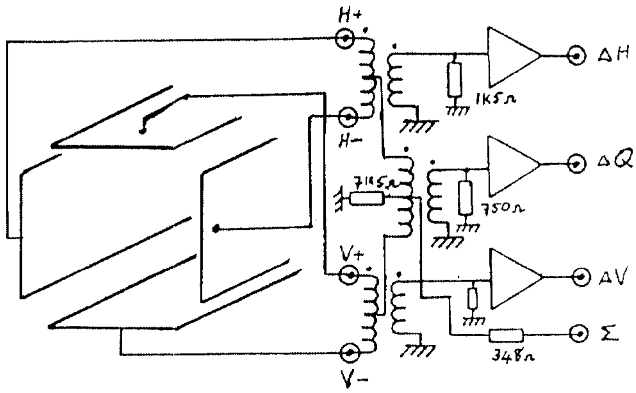

Fig. 1 - Quadrupole pick-up electrodes and hybrid circuit.

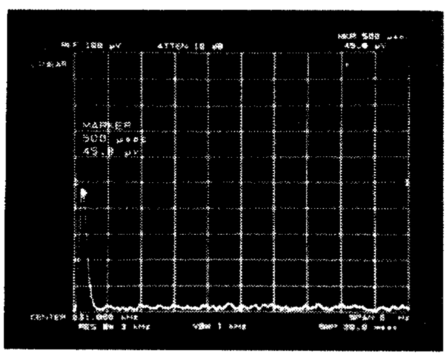

Fig. 2 - Evoluton of quadrupole coherent oscillation at injection.

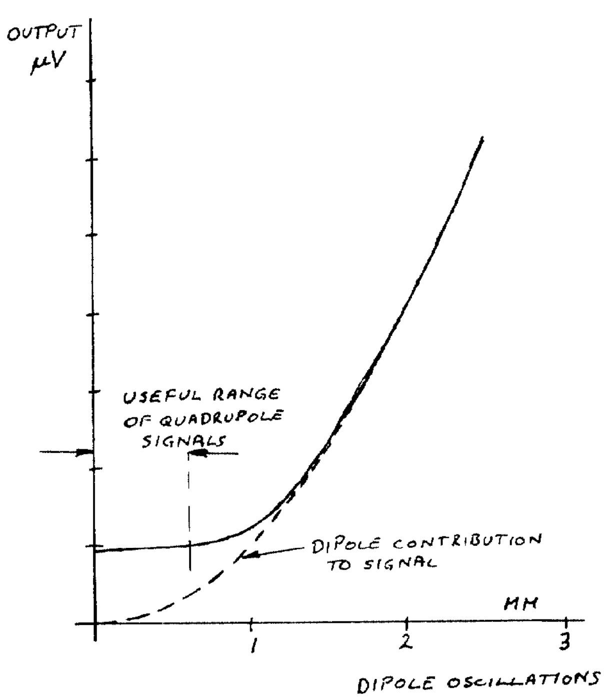

Fig. 3 - Increase in quadrupole signal with dipole oscillations.

First Measurements of Coherent Quadrupole Injection Oscillations

The first measurements were made using two spectrum analysers tuned to the calculated quadrupole frequencies $(-4+2Q_H)f_0$ and $(-4+2Q_V)f_0$. By triggering the spectrum analyzers at injection, the evolution of the quadrupole coherent oscillation could be followed (Fig. 2). The importance of the transverse position was determined by deliberately missteering both horizontally and vertically. Typical results are shown in Fig. 3, from which it can be seen that data on the quadrupole oscillations is valid only when the dipole oscillation is less than ±0.5 mm.

Using this technique, quadrupole signals were measured at different magnet currents for both direct and reverse injection into the AA machine. Optimum settings were found giving smaller quadrupole coherent oscillations.

The range of voltages measured during these studies, with beam intensities around 2×10^{10} p, corresponds to detector levels of 8 to 325 μV. Unfortunately the common mode rejection of the high impedance hybrids is inadequate for eliminating the revolution frequency signal in the quadrupole channel for which only 30 dB of rejection is obtained. When measuring with a spectrum analyzer this component is not a problem but, for display on an oscilloscope, it had to be filtered by 40 dB. The signals have been amplified and made available on a digitizing oscilloscope where their amplitude is in the range 5 to 250 mV r.m.s. The revolution frequency content is 20 mV r.m.s.

Compensation of Quadrupole Oscillations

The transfer line for antiprotons from the accumulator to the PS machine is 400 m long and contains as many as 45 quadrupoles. Good betatron matching between the two rings is therefore not easy to obtain, but it is important for conserving the low antiproton emittance obtained by cooling.

We measure the mismatch by observing the coherent quadrupole oscillations in the AA of protons transferred in the opposite direction. The signals are acquired by computer from the digital oscilloscope. A FFT spectral analysis (using a half-sine window) shows up the lowest frequency components at $2qf_0$ and $(1-2q)f_0$ for the two planes. Since q (the fractional part of Q) is near to 0.25 in both planes, these 4 frequencies are not much different (Fig. 4). Careful compensation of the linear coupling between the two planes by means of a skew quadrupole is required to remove components at $(q_h+q_v)f_0$ and $(1-q_h-q_v)f_0$.

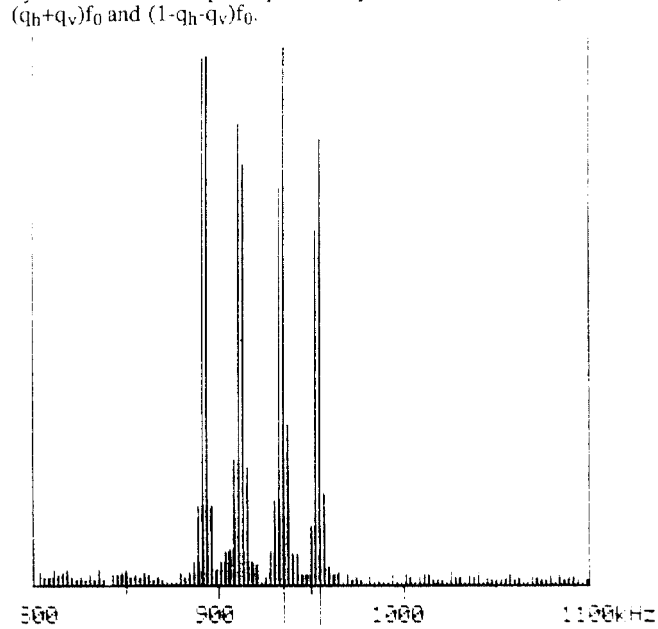

Fig. 4 - The four frequencies obtained by spectral analysis.

To remove the mismatch by trial and error as described above is surprisingly difficult. Therefore, for each plane the sine and cosine components of the $2qf_0$ component are measured with respect to the injection time, and two quadrupoles in the transfer line are adjusted to cancel both. For each plane, we use two quadrupoles that are focusing in that plane. The horizontal and vertical corrections are not entirely decoupled, but sufficiently so for a rapid convergence.

How much each quadrupole must be varied to cancel both components is first established by a calibration. Each quadrupole is changed in turn by a known amount and the resulting change of the sine and cosine components is measured. By inverting the 2×2 matrix so obtained, we can deduce the changes needed to cancel both components simultaneously. This process is, strictly speaking, only valid for small changes, whereas the measurement errors require reasonably large ones. A compromise was found that leads to convergence after a few measurements and corrections.

The calibration and correction sequences are programmed and executed automatically when required. The program also compensates the dipole oscillations (measured simultaneously in a similar manner) and only accepts those pulses for the quadrupole measurements that show a dipole amplitude less than 0.3 mm.

For discriminating the different frequencies a signal record extending over about 380 periods (400 μs) is used; a total of 2048 samples is acquired. The data from the first 5 μs must be rejected because of high noise content from particles lost during the first few turns. For measuring the phase with respect to injection, only the first quarter of the time record is used. This appears to minimize the fluctuations of the phase measurement; if a longer record is used, the result becomes too sensitive to errors in the frequency measurement.

The result of these measurements was a reduction of the quadrupole oscillations (mainly in the horizontal plane) by about a factor 3. The remaining components are of the same order as the fluctuations in the measurement. By calibration, using a known dipole perturbation, we conclude that the emittance increase due to mismatch must now be smaller than a few percent.

Conclusions

The passive high impedance hybrid circuit allows detection of very small quadrupolar differential signals in the presence of strong common mode signals. Detection of phase and amplitude of coherent vertical and horizontal quadrupolar oscillations at injection permits measurement and automatic correction of transverse mismatch.

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