CONTINUOUS TUNE MEASUREMENTS USING THE SCHOTTKY DETECTOR

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A continuous measurement of the betatron tune has been implemented in the SPS $p\bar{p}$ collider with hardware normally used for the detection of Schottky noise. Suitable values for the tunes and chromaticities are thus more easily achieved in a machine where the strong space charge effects of the two counter-rotating beams severely reduce the available space in the resonance diagram.

The basic idea is to monitor the frequency of one of the betatron lines, f_β, together with the revolution frequency and to deduce the tune ν according to the formula

$$f_\beta = (n + \nu) f_{rev}.$$

The betatron lines which naturally appear as noise signals adding incoherently, are strongly enhanced by exciting the beam at the required frequency with a kicker. The whole system then forms a closed loop in which an oscillator excites the beam producing a coherent signal at the Schottky detector, this signal providing the reference to lock the oscillator frequency. The excitation, 50 W at 10.7 MHz causes particle loss (~ 3%/cycle) and emittance blow-up (~ 10%/cycle) restricting the use of the apparatus to setting-up periods.

1. Introduction

The CERN SPS collider presently accelerates three bunches of protons, each with 10^{11} particles, and three bunches of antiprotons, each with 10^{10} particles, from an injection momentum of 26 GeV/c to a top momentum of 270 GeV/c. Four parameters of particular importance are the horizontal and vertical tunes and chromaticities. Indeed at injection the dense proton bunches suffer a large betatron frequency spread due to the influence of their own space-charge force, while the momentum-independent beam-beam interaction causes a strong tune spread in the weak anti-proton bunches. The two effects combine in such a way that the total spread occupies nearly all the space between the third and fourth integer resonances. As the momentum increases, the space charge effect on the protons decreases leaving more space in the tune diagram, but once in coast the available space is again reduced due to the need to avoid higher order beam-beam resonances (up to the 13th) which greatly reduce antiproton lifetime. Consequently the tunes must be controlled very carefully at injection and during the coast and with reduced requirements during the ramp. Moreover, to reduce the spread and keep the beams stable the chromaticity, at all times, must be brought as close to zero as possible whilst always maintaining a positive value. Measuring the tune using standard point by point techniques is very time consuming or restrictive in resolution, hence the interest in a continuous measurement which gives the tune over the whole cycle in only one cycle.

Further machine parameters of interest are as follows:

Nominal tunes at injection	$\nu h = 0.71$	$\nu v = 0.69$
during coast	$\nu h = 0.685$	$\nu v = 0.678$
Chromaticities during the rise $\xi_{H/V}$		$= 0.15$
during coast $\xi_{H/V}$		$= 0.08$
Revolution freq. at injection f_{rev}		$= 43.34734$ kHz
% f_{rev} change during acceleration		$= 0.0645\%$
Bunch length at injection		$= 4$ ns
at top energy		$= 2$ ns.

To set up this operation, one, two or three proton bunches and no antiproton are used on a repetitive cycle of 28.8 s length, the 26 GeV/c injection level lasting 19.26s, the ramp 5.22s and the 270 GeV/c flat top ~ 3s of which 1s is used for the squeezing of the two low beta insertions.

2. General description

The measurement has been implemented using the Schottky detector together with its associated directional kicker[1] and has been used operationally with one bunch of protons circulating in the machine. We recall that the frequency spectrum of a single bunch as seen at the output of the Schottky detector consists of lines at multiples of the revolution frequency, nf_{rev}, each line having a betatron sideband at νf_{rev} surrounded by synchrotron satellites (Fig. 1).

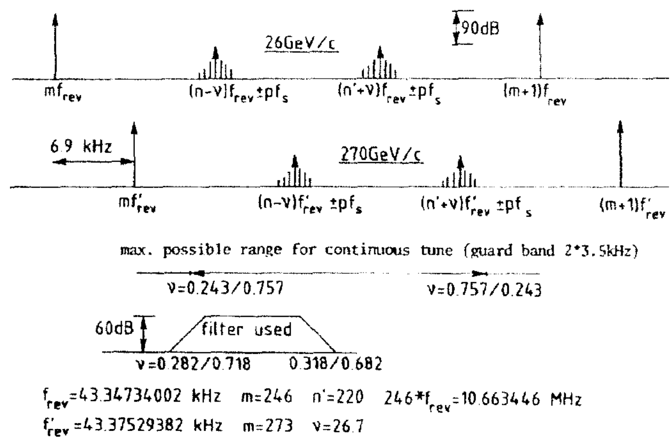

Fig. 1 Single bunch frequency spectrum from Schottky detector

The betatron sidebands and their satellites are essentially formed by the incoherent addition of the signal from each particle, the total power per line being $\propto$ N the number of particles, whereas the revolution frequency lines are formed by the coherent superposition of the particle signals, i.e. power $\propto N^2$. With 10^{11} particles a typical signal to thermal noise ratio for the betatron line is ~ 20 dB with the longitudinal line ~ 90 dB higher after 40 dB rejection obtained by centring the detector.

To measure the tune it is sufficient to measure a betatron line harmonic frequency, that is to say $f_\beta = (n'+\nu)f_{rev}$. To enhance this line the bunch can be excited coherently by means of a signal at a frequency $(n'' + \nu)f_{rev}$ applied to the kicker. The rotating bunch samples this signal at the revolution frequency and produces an excited spectrum where all the betatron lines falling in the range from d.c. to ~(bunch duration)$^{-1}$, that is to say including $(n' + \nu)f_{rev}$, are enhanced.

The coherent signal taken from the Schottky detector is filtered to reject the longitudinal lines at m f_{rev} adjacent to $(n' + \nu)f_{rev}$ and used as the reference for a phase lock loop which locks a voltage controlled oscillator (VCO) to the frequency

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$(n' + \nu)f_{rev}$. The output of the VCO, possibly shifted in frequency by $(n'' - n')f_{rev}$, is the signal used to excite the beam.

The control voltage of the VCO is proportional to the tune at constant momentum. A separate measurement of the revolution frequency allows the tune to be deduced as the momentum increases with acceleration.

3. The hardware

(i) The Schottky detector. This detector has been described previously[1]. It consists of two 3 m long moveable plates in the vertical or horizontal plane which are resonated at 10.7 MHz by an air-cored coil, the 3 dB bandwidth being ~ 2 f_{rev}. For this particular type of operation, the vertical and horizontal plates are set permanently ~ 55 mm apart to accommodate the beam at injection. The signal strength obtained for the betatron line is ~ 1.5×10^{-17} Watts/line for 10^{11} particles.

(ii) The directional kicker. These kickers (see Fig. 2) have been installed in the machine to allow preferential excitation of either the proton or antiproton beams in the horizontal or vertical plane. Each consists of two 80 cms long parallel electrodes spaced at a sufficient distance from the wall to produce a 50 Ω impedance when excited differentially. At each end a 50 Ω feedthrough connects the electrode to the signal source and load. With a power of 50 W per plate a kick of 5×10^{-8} rad is produced at 26 GeV/c.

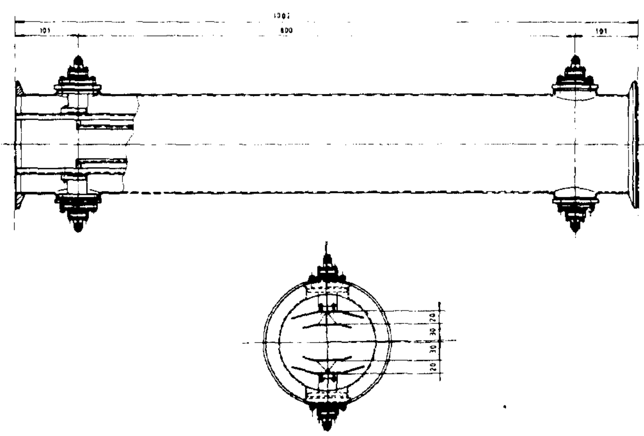

Fig. 2 Vertical directional kicker

(iii) The electronics. A block diagram of the circuit is given in Fig. 3. The signal from the Schottky detector, ~ 10.7 MHz, is filtered by a quartz filter of bandwidth ±4.2 kHz and centre frequency 10.67988 MHz. This filter rejects the coherent longitudinal lines centred at 246 f_{rev} and 247 f_{rev} by ~60 dB. During acceleration, both these lines move by 6.9 kHz; this clearly restricts the maximum filter bandwidth allowed and consequently the tune values for which a continuous measurement can be made, in this case to tunes in the range 0.243 to 0.757. The 8.4 kHz bandwidth filter further restricts this range to 0.68 → 0.72. The signal, after amplification, is sent to the main control room where it is used as the phase lock loop reference. A voltage-controlled oscillator provides the signal at 10.7 MHz which is compared in phase with the reference, the phase error being amplified and used via a correction network to control the VCO frequency.

The VCO output is also used indirectly to provide the excitation signal. Because of the crosstalk between the cables which carry the excitation (50 W) and the detected signal (~10^{-17} W) the excitation is shifted in frequency by one revolution frequency line to place it outside the filter bandwidth.

The phase of the VCO is fixed by the loop with respect to the detector reference signal. For a given frequency the phase at the kicker can be adjusted to increase the beam excitation. Frequency changes, 6.9 kHz due to the momentum change during the ramp plus changes due to tune variation, combined with the delay in the excitation loop ~ 150 µsecs mainly due to the quartz filter, cause phase shifts greater than 2π which must be compensated if the excitation is to remain coherent. This ensures that the signal is not reduced to its natural level.

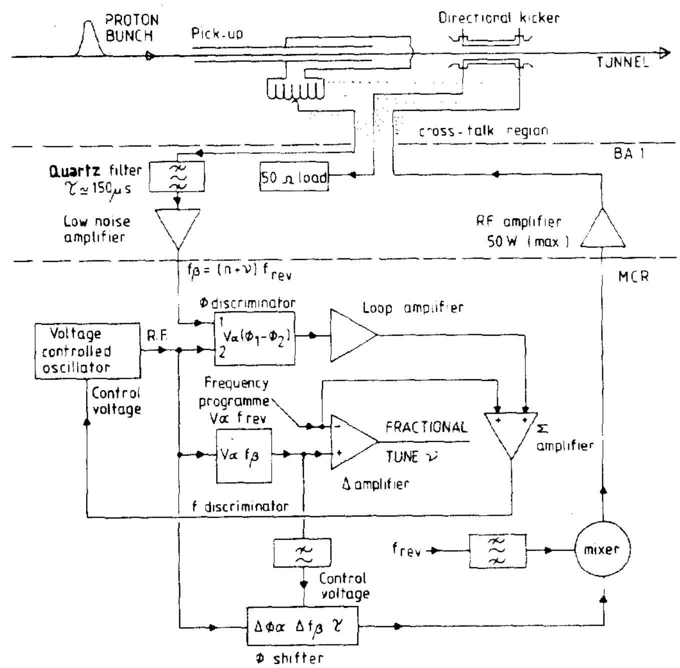

Fig. 3 Block diagram of continuous tune scan system

To do this a phase shifter is inserted in the excitation path; its control voltage, proportional to f_β, is derived directly from a frequency discriminator working on the output of the VCO and applied via a low-pass filter necessary for loop stability.

A signal proportional to f_{rev} is available from the main RF accelerating system and this is subtracted from the discriminator signal ($\propto f_\beta$) to give the direct measurement of tune.

4. Operational results

When setting the machine up with three proton bunches the injection oscillations of the second and third bunches perturb the operation of the loop. In addition the excited signals from these additional bunches, which are spaced at 1/3 intervals around the ring, add coherently with a phase shift ($\propto \nu$), producing in general a reduction in signal strength compared to a single bunch signal. Consequently, it is better to work with only one bunch of protons in the machine. The coupling in the SPS is rather strong so that both h and v lines are present on one detector signal and any kicker will excite either plane if the frequency is chosen correctly. This is convenient since one system can measure ν_h or ν_v simply by choosing the free running frequency of the VCO. However, difficulties arise when the tunes become very close or actually cross: the loop tends to jump from one to the other in an arbitrary fashion, although this in itself can be a diagnostic tool. The problem disappears if the coupling is compensated, but in this case two systems are needed to measure both tunes. A typical result for the ν_v line is given in Fig. 4.

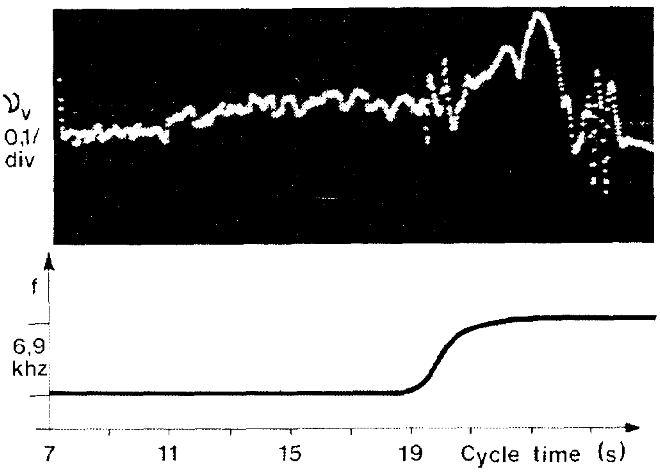

Fig. 4 Vertical tune and frequency change along acceleration cycle

The ν variation is seen to be large, ±0.015 in total, large variations occurring up the ramp and during the low β squeezing. In order to check the calibration of the system the region of low β squeezing was chosen and here a point-by-point measurement was made and is given in Fig. 5, together with an expanded continuous measurement. The agreement is very good. The next stage would be to trim the ν values but this has not yet been attempted for lack of time.

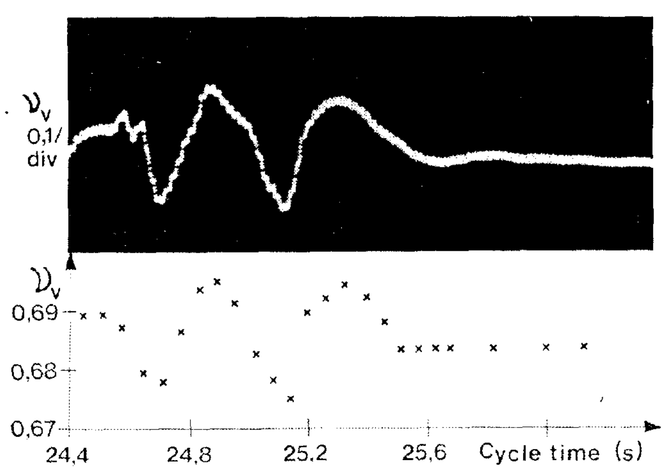

Fig. 5 Continuous and point by point comparison in the low-β squeezing region

The vertical chromaticity measurement is shown in Fig. 6. Here three scans are made with the beam in the nominal centre and then with a radial offset of ±4mms.

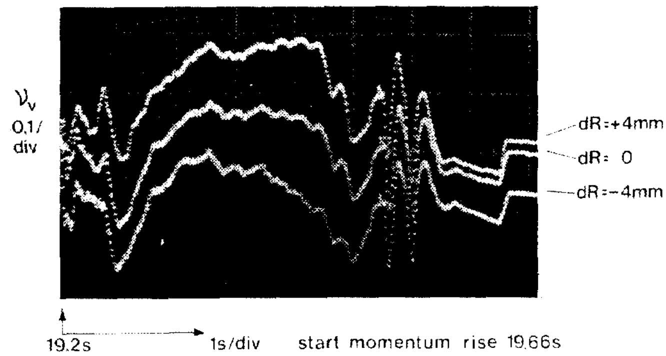

Fig. 6 Tune scans for different radial positions giving the chromaticity

Operation of the device has shown up two results which restrict its use to setting-up periods. First a small but continuous intensity loss is observed along the cycle accompanied in the second place by a blow-up of both transverse profiles. Typical orders of magnitude are 3% total loss and 5% transverse profile blow-up (10% emittance increase) for a continuous excitation of 50 W on the kicker. This effect may be the result of the Landau damping mechanism seen when a sinusoidal driving force is applied to a broadband population of oscillators. The particles continuously lost are those just on resonance with the external excitation, whereas the increase in emittance is the result of the residual oscillation of the whole beam. This explanation becomes quantitative for the transverse blow-up by assuming the realistic value of 10 Hz for the amplitude dependent width of the Schottky line. The transfer of transverse blow-up from one plane to the other is due to the strong transverse coupling.

5. Possible future developments

At the moment the maximum range of ν values continuously observable during the ramp is restricted to $0.243 \leq \nu \leq 0.757$ by the longitudinal line rejection coupled with the frequency swing at 10.7 MHz. The range can be increased by lowering the detector central frequency to reduce the swing. For example, by lowering to 5 MHz, the total tune range available is increased to $0.15 \leq \nu \leq 0.85$ provided a suitable set of filters is available.

Acknowledgements

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Reference

1. A transverse Schottky noise detector for bunched proton beams, T. Linnecar and W. Scandale, IEEE Transactions on Nuclear Science Vol. NS-28, No. 3 June 1981.