EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN-ISR-RF/80-30

CERN LIBRARIES, GENEVA

CM-P00043776

ISR BEAM MONITORING SYSTEM USING 'SCHOTTKY NOISE'
AND TRANSFER FUNCTION

by

J. Borer, J.Y. Hemery, J.P. Koutchouk, E. Peschardt, L. Vos

Paper presented at the XIth International Conference on High-Energy Accelerators, CERN, Geneva, 7-11 July 1980.

Geneva, July 1980

ISR BEAM MONITORING SYSTEM USING 'SCHOTTKY NOISE' AND TRANSFER FUNCTION

J. Borer, J.Y. Hemery, J.P. Koutchouk, E. Peschardt, L. Vos

CERN, 1211 Geneva 23, Switzerland.

ABSTRACT

Another way of monitoring the behaviour of particle beams in storage rings has been developed at CERN. It has been introduced and is in operation since 1972 in the ISR and has since been considerably refined. This non-destructive method is based on the beams' 'Schottky noise' spectra and on obtaining the beam transfer function (BTF) by additional noise excitation. The 'natural' Schottky spectra are used to monitor the momentum and the radial current density, the transverse frequencies (Q_H , Q_V) and the transverse emittance. The beam transfer function, or inverse stability diagram, is used to monitor: the 'working line', the beam stability and its optimization including active feed-back as well as non-linear structural resonances. The same instrumentation is used in cross-transfer function mode in order to monitor and to minimize the transverse and the beam-beam coupling. This non-destructive monitoring system is a powerful tool in the operation of storage rings. Its instrumentation, signal and data processing and operational uses are presented.

1. INTRODUCTION AND THEORETICAL BACKGROUND

This beam monitoring system uses two physical aspects of charged particle beams coasting in storage rings. Firstly, the stochasticity of the finite number of discrete charges with random azimuthal distribution and betatron transverse oscillations and secondly, the beam centre of mass response to a given transverse (or longitudinal) excitation.

The first aspect is called Schottky beam induced noise since it corresponds to the shot noise of free charges in an electrical current¹⁾. A single revolving proton passing a monitor produces dirac pulses in time domain which corresponds in the frequency domain to a spectrum of lines at all harmonics of the revolution frequency. The average over all particles having an energy distribution and hence a revolution frequency distribution, will produce the so-called longitudinal Schottky spectra.

The noise current I_n per instrumentation bandwidth Δf is¹⁾: $I_n^2 = 1/S \cdot 2e I_{DC} \Delta f$
 $I_{DC} = N$ nb. of protons and spread $S = h|\eta| \Delta p/p$ at the harmonic h . The squared longitudinal spectrum is therefore an image

of the N or current density as function of the momentum or radial position.

If, in addition, a particle has a transverse betatron motion, the signal obtained from a position sensitive monitor will be an amplitude modulated dirac pulse train. Averaging over all particles one obtains sidebands corresponding to the so-called transverse Schottky scans related to the betatron distribution $F(\omega)$. The frequency f_β of the transverse spectra are related to the 'working line' or tune diagram $Q(\Delta p/p)$. The magnitude or dipole density¹⁾ $D_{rms}(f_\beta)$ is:

$$D_{rms}(f_\beta) = \frac{\sqrt{e/2}}{2\pi R} \cdot A(f_\beta) \left[N(f_\beta) df_\beta \right]^{\frac{1}{2}}$$

where $N(f_\beta)$ is the number of particles per unit interval of betatron frequency, $f_\beta = (h \pm Q)f_r$ and $A(f_\beta)$ their individual rms transverse motion amplitude which is proportional to the beam emittance.

It should be underlined, from the instrumental point of view, that such incoherent Schottky noise signals are: proportional to $\sqrt{N}$ as well as $\sqrt{Af}$, very small, i.e. in the μV range and that the transverse sidebands are about 1/100 of the longitudinal spectra for ISR conditions.

The second aspect is the beam transfer function (BTF)²⁾ as obtained between an exciter and a monitor. Only the transverse case will be treated here because it is the most important one for the ISR from the stability point of view.

Coming back to the single revolving particle, this will respond when the exciting signal frequency corresponds to its betatron frequency. If the monitor signal is related to the exciter signal, the transfer function obtained is, at each resonance, equivalent to the response of a high Q tuned circuit with a phase rotation from $+90^\circ$ to -90° . But, since particles in the beam have a betatron distribution $F(\omega)$, their transfer function is that of a system with continuous distribution of resonators (Fig. 4). For frequencies below that of all the resonators the relative phase is

$+90^\circ$. For frequencies above, the phase is -90° , resulting in a smooth phase change of 180° across the sidebands. Such BTF is calculated from the displacement x of single particles with an excitation g and then averaged over the betatron distribution $F(\omega)$ ²⁾

$$\pm ID' = \pm \frac{1}{2 Q_0 \Omega_0 N} \int \frac{F(\omega) d\omega}{\omega - \omega_e} = \pm \frac{1}{2 Q_0 \Omega_0 S} ID$$

with : slow wave : - sign and $\omega_e = (h-Q)$,
fast wave : + sign and $\omega_e = (h+Q)$. $\Omega = 2\pi f_r$
index '0' at centre of distribution. The integral called the dispersion integral ID is well known¹⁾ and has been calculated for different $F(\omega)$ (Fig. 7). The BTF is therefore the inverse of what is known as the stability diagram $\frac{-1}{ID'}$ and $\frac{1}{ID'}$.

The transverse wall impedance effect on the beam has to be included and can be described as a feed-back through a passive network (Fig. 5):

$$Z = \frac{eIZ_T}{2\pi R_Y m_0} \text{ and } G = G_0 + Z\bar{X}/j$$

The resulting total BTF is then:

$$\frac{\bar{X}}{G_0} = \pm \frac{ID'}{1 \mp jID'Z}$$

which corresponds to the usual feedback control system formula.

From Nyquist, the stability criterion of the beam system is that:

$$Z \leq -j/ID' \text{ slow wave}$$

$$Z \leq j/ID' \text{ fast wave}$$

Fig. 6 summarizes the situation for a circular distribution $F(\omega)$. The reactive and resistive part are positive in the ISR. Negative values for the resistive part can only be obtained with active feedback. Only the slow wave is prone to instabilities and this at the bottom of the stack. The influence of $F(\omega)$ is also very important for the stability margin (Fig. 7). Coming back to Fig. 3, the instrumentation allows the measurement of $A(\omega)$ and $\phi(\omega)$ proportional to $\bar{X}/G_0$. The inverted function $1/A(\omega)$, $-\phi(\omega)$ contains all information allowing the calculation of: the stability margin under real operating conditions, the Z_T wall transverse impedance and active feedback negative impedance, and the betatron distribution from which the tune diagram or working line can be derived. From the instrumental point of view, it should be underlined that the beam response and

hence the monitor signal is proportional to N and is the coherent response of the beam centre of mass even if the exciter signal is noise of constant power spectrum. This fact allows the treatment of signals much higher than the Schottky beam and amplifier noise; even so, the disturbing signal to individual particles remains very small since it is proportional to $1/N$. This is the reason why this measurement technique does not produce any visible beam disturbance. Important: this measurement approach is only valid if the system is linear, which is true as long as the beam transverse motion remains small and the distributions are not modified.

2. INSTRUMENTATION DESCRIPTION

The first Schottky spectra observation system was implemented with swept spectrum analyzer. The high speed of present digital processing allows the on-line calculation of the fast Fourier transform of time domain samples. In comparison with a swept spectrum analyzer of the same IF bandwidth or resolution, an FFT instrument with n frequency channels represents n filters in parallel and the time needed for the average of noise spectra is reduced by n . With a dual channel instrument, the transfer function is calculated in amplitude and phase. This instrument having a bandwidth of 0-100 kHz and

the Schottky signals of interest being situated in a frequency range of 30 kHz to 100 MHz, a dual channel frequency shifter had to be developed and built. Its amplitude and phase characteristics must be constant across the band-pass and identical for both channels. One tenth of the FFT bandwidth has to be allowed for a steep attenuation (high-pass) in order to avoid frequency fold-over around 0 Hz. The frequency shifter block diagram and characteristics are given in Fig. 9. An input selector connects the desired signals from the preamplifiers to the inputs of the frequency shifter, whose central frequency setting is controlled by a synthesizer. The same signal controls also the central frequency of a tracking noise source of constant spectrum across 300 kHz, which is used for BTF measurements.

The same signal controls also the central frequency of a tracking noise source of constant spectrum across 300 kHz, which is used for BTF measurements.

A very low noise broad band amplifier with good linearity has been developed for this equipment and its circuit is given in Fig. 10. It uses UHF silicon bipolar transistors and shunt feed-back to obtain an 'electronically cooled' input 50 Ω active impedance corresponding to a resistor at 70° K. This amplifier is used throughout the system as wideband amplifier. For transverse Schottky signal observation a 300 kHz bandwidth FET amplifier, with a differential tuned input circuit resonating with the

monitor electrode capacitance at 10.8 MHz ($n=34$), is necessary to obtain good S/N ratio with such low signals.

The horizontal and vertical monitors as well as exciters are of the diagonal splitted electrostatic type. They are used both for transverse Schottky spectra and BTF measurements. A gap, or coaxial transformer monitor is used for the longitudinal Schottky scans.

Numerous practical problems had to be solved to ensure proper and reliable operational characteristics. The system allows for automated BTF measurement from 2 to 80 MHz, for longitudinal Schottky spectra at 52 MHz and transverse ones at 10.75 MHz and this for ISR currents ranging from 10 mA (single pulse) to 60 A (stack).

3. COMPUTER SIGNAL PROCESSING

The system is connected to the ARGUS computer via a CAMAC crate containing a local processor (Ferranti ACC100) for hardware control. Schottky scan programs control the settings of the instrumentation, transfer the data and normalize them for presentation on display. They also calculate radial position and current density of the stack from longitudinal Schottky spectra and the Q value of the two stack edges from the transverse Schottky spectra whose magnitude is proportional to the local stack emittance.

BTF programs control the system settings, transfer the data and present them on the display. Its magnitude is a direct indication of the instability trend. Another program corrects the BTF data and calculates the stability diagram, the transverse impedance and the measured dispersion integral from which the transverse distribution $F(\omega)$ and the tune diagram or working line is derived³⁾.

4. OPERATIONAL APPLICATIONS

The evident application of the BTF is to monitor the stability margin and to control the betatron distribution by modulating the chromaticity in order to compensate for the reactive part of Z_T and optimize the stability. This accurate method is a step forward relative to the simplified stability criterion previously used : $I/Q < k \frac{F_Y}{|Z_T|}$ with Q' constant⁴⁾.

The BTF is also used to optimize the phase angle of the low frequency (20 kHz to 1 MHz) transverse feedback system⁵).

5. MONITORING SYSTEM USES FOR OTHER APPLICATIONS

Transfer functions can be measured in the longitudinal mode with a gap exciter, in the beam-beam coupling and V-H transverse coupling, etc. The transverse coupling transfer function has been found to be a very efficient means to measure the V-H coupling factor and hence to optimize its compensation. It has been calculated that the complex coupling coefficient is proportional to the coupling transfer function⁶⁾.

6. CONCLUSION AND ACKNOWLEDGEMENTS

This new way of monitoring the beam characteristic under real operating conditions was first implemented at the CERN ISR. Its history is interesting in many ways. It is another example of how theoretical concepts are being combined with instrumentation and experimental knowledge to provide a powerful tool that neither the theoreticians nor the experimenters could have dreamed of. It also shows how many people have contributed to this development. The progress steps from Landau damping, through the Schottky spectra measurement, to the stability diagram, with the name of most of the contributors, are given in Fig. 11. This BTF non perturbing diagnostic instrumentation has allowed improved ISR operating conditions and a boost in its performance (56.4 A) also made possible by the steadily improving vacuum system.

REFERENCES

- 1) H.G. Hereward, F. Sacherer, W. Schnell, B. Zotter, Theoretical Aspects of the Behaviour of the Beams in Accelerator and Storage Rings, Proceedings of First Course of the International School of Particle Accelerators in Erice, CERN-77-13 (1977).
- 2) J. Borer, A. Hofmann et al., Information from Beam Response to Longitudinal and Transverse Excitation, 1978 Particle Accelerator Conference, San Francisco.
- 3) Procedure for Obtaining Transverse Wall Impedance and Working Line from Transfer Function Measurements, this conference.
- 4) Transverse Beam Stability Optimization Based on Beam Transfer Function Measurements, this conference.
- 5) Compensation of the Resistive and Reactive Transverse Wall Impedance in the ISR with Feedback System, this conference.
- 6) Linear Betatron Coupling Measurement and Compensation in the ISR, this conference.