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REAL-TIME TUNE MEASUREMENTS ON THE CERN ANTIPROTON DECELERATOR

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A novel system for real-time tune measurement during deceleration of a low-intensity particle beam is presented. The CERN Antiproton Decelerator decelerates low intensity (2 x 10^7) antiproton beams from 3.5 GeV/c to 100 MeV/c. Because of the eddy-currents in the magnets, a tune-measurement during a pause in the deceleration would not be representative. One must thus be able to measure the tune in real time during the deceleration. The low intensity of the antiproton beam prevents the use of standard Schottky techniques, and swept Beam Transfer Function (BTF) measurements are too slow. A system was therefore developed which uses an M-shaped power spectrum, exciting the beam in a band around the expected frequency of a betatron side-band. Excitation at the betatron frequency, where beam response is highest, is thus minimized and measurements of BTF, and therefore the tune, can be made with much reduced emittance blow-up.

1 INTRODUCTION

The CERN Antiproton Decelerator (AD) decelerates low intensity (15 µA to 0.2 µA) antiproton beams from 3.5 GeV/c to 100 MeV/c. The low intensity in the AD results in very weak transverse Schottky signals from 0.5 pA/√Hz at 3.5 GeV/c down to 0.025 pA/√Hz for an uncooled beam at 100 MeV/c measured around 5.6 MHz (The resonance frequency of the pick-up (PU)). The Schottky signals are not large enough to measure the tune, so it is therefore necessary to use BTF-measurements. To measure the AD tune during deceleration without pausing (due to eddy-currents in the magnets, a paused measurement will not be representative) we needed a technique faster than a swept BTF (although swept BTF on plateaux has been used during the start up phase). A system was therefore developed which uses an M-shaped power spectrum, exciting the beam in a band around the expected frequency of a betatron side-band.

2 THE TUNE MEASURING SYSTEM

The system, see Figure 1, consists of the Schottky system, which measures the beam response, and the M-shaping filters that generate the stimulation. The Schottky system consists of a resonant PU and an ultra- low-noise pre-amplifier followed by a level adaptation system (to lift the signal over the quantization noise of the digital system). The amplified signal enters a Digital Receiver Board (DRX) after being analog to digital converted, where the data are hardware pre-processed in up to 8 Digital Down Converters (DDC). By this digital translation (down-mixing) the frequency window of interest is from DC and upwards. This will enable a Digital Signal Processor (DSP) perform the processing i.e. find the BTF. This is then passed on to the control system. The control system sets up the wanted analysis including the hardware control. The stimulation centre frequency is set as a factor n±q of the revolution frequency, where n is

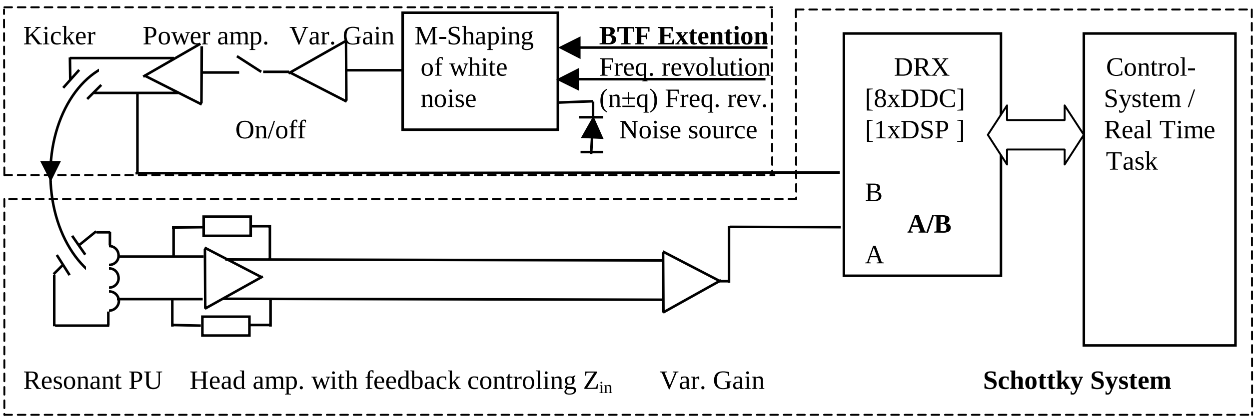

Figure 1: System block diagram.

the harmonic number chosen such that the frequency lies in the resonant range of the PU and q is the fractional part of the tune. The stimulation thus follows the expected betatron frequency during deceleration.

2.1 The Pick-up System

In order to avoid overlap of adjacent betatron side-bands at low momentum, the 1m long electrostatic PU is resonant at 5.6 MHz. The pre-amplifier has been designed so that, in a band around the resonance frequency, the Johnson noise from the losses in the coil is the dominant noise source of the system. To achieve the highest possible Q (low losses) of the resonant circuit, the PU has been designed with the coil inside the vacuum chamber. The total system noise density achieved is 0.9 pA/√Hz.

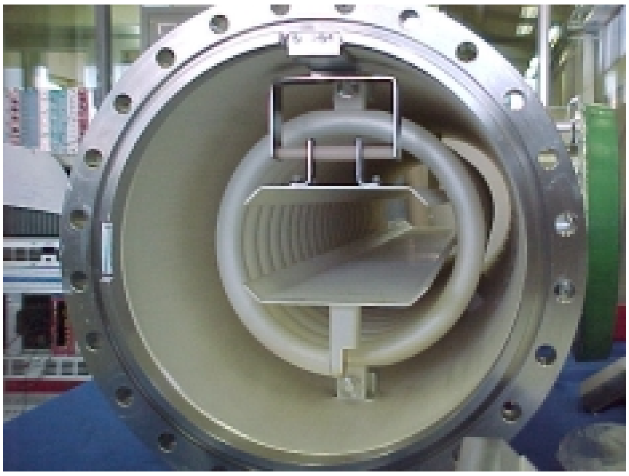

Figure 2: The resonant PU

The high Q resonant circuit is detuned by a feedback around the pre-amplifier, making the input impedance appear like a 350 Ω resistor working at a temperature of less then 13 K. Detuning the resonant circuit makes the PU broad-banded enough to always have a betatron sideband in the low noise part of the response from 5.3 MHz to 6.2 MHz. The details of the feedback and noise calculation can be found in ref. [1], describing the longitudinal Schottky system with which this system was developed in parallel.

Since the coil ends are fixed to the PU plates at opposite ends, a relatively big signal compared to the Schottky signal (max. of a few mV for the AD intensity) is generated at the beam revolution frequency. This is due to the beam time of flight through the PU. Therefore a high dynamic range of the system is needed.

2.2 The BTF Stimulation

A betatron sideband is like a parallel LCR-resonant circuit, in the way that it is most sensitive to stimulation at the exact resonant frequency and that it will make a 180° phase shift when passing through the resonance. To see the whole of the response the stimulation has to be increased more and more as one moves away from resonance. The blow-up of the beam emittance is given mainly by the stimulation power at the beam resonance frequency [1]. The blow-up rate is given by:

$$\frac{d\varepsilon}{dt} = \frac{\beta_0 \omega_0^2}{4\pi} \left(\frac{eL}{2md(\beta c)^2} \right)^2 \frac{S_p(f_n)}{2\pi} \qquad (1)$$

Here β_0 is the beta function at the kicker, ω_0 the angular revolution frequency, L the length of the kicker, d the distance between the kicker plates, m the particle mass, βc particle speed and $S_p(f_n)$ the power density at the betatron frequency.

Table 1: The expected blow-up rates for the AD, with β_0 =7.55 m, L=1 m and d = 0.15 m.

Momentum [GeV/c]	$S_p(f_n)$ [V^2/Hz]	$S_p(f_n)$ [dBm]	β	ω_0 [rad/s]	dε/dt [μm/sec]
2.0	$5x10^{-4}$	-20	0.905	$9.35x10^6$	0.08
0.1	$5x10^{-6}$	-40	0.106	$1.09x10^6$	0.06

Table 2: The measured blow up in the AD due to a 50 kHz wide M-shaped (6 dB depth) noise of density S_p.

Momentum [GeV/c]	$S_p(f_n)$ [V^2/Hz]	$S_p(f_n)$ [dBm]	β	ω_0 [rad/s]	dε/dt [μm/sec]
2.0	$5x10^{-4}$	-20	0.905	$9.35x10^6$	0.14
2.0	$5x10^{-3}$	-16	0.905	$9.35x10^6$	0.30
2.0	$5x10^{-3}$	-10	0.905	$9.35x10^6$	0.82

Table 1 and 2 show respectively calculated and measured blow-up rates in the AD. The measured blow-up at 2 GeV/c agrees within a factor 2 the calculated value.

Using an M-shaped power spectral density gives a blow-up corresponding to the power in the centre of the M, while it still gives a good beam response over a broad spectrum. See Figure 3.

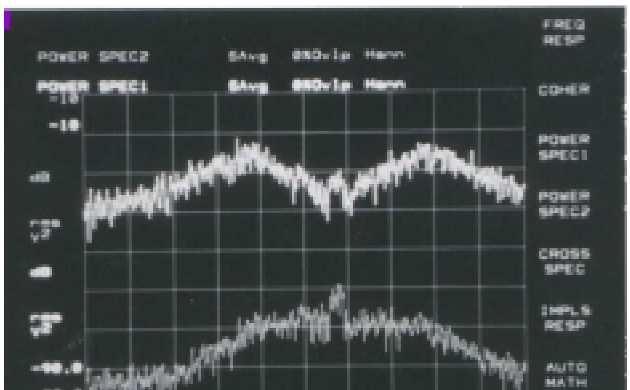

Figure 3: An M-shaped power spectrum (upper trace) and the corresponding flat beam response.

Dividing these two complex spectra gives the BFT, shown in Figure 4. From this, the resonant frequency is found and the tune is calculated.

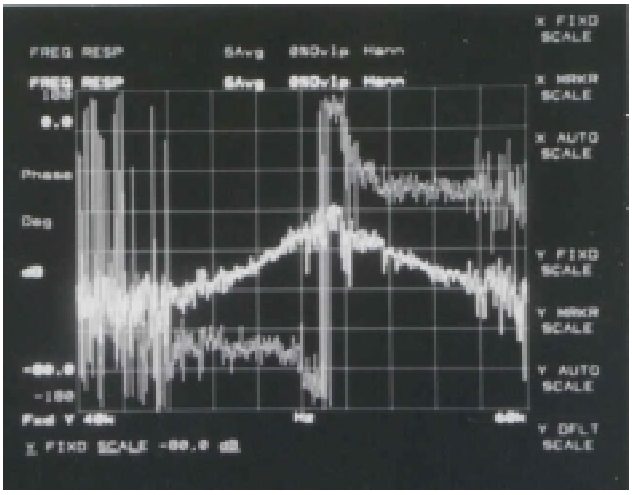

Figure 4: The BTF magnitude (centre trace) and phase.

The frequency range in which the measurement is valid is seen from the noise levels of the signals on the magnitude and phase plots in figure 4. A correlation calculation performed in the DSP will extract this as well:

$$\gamma^2 = \frac{G_{xy} \cdot G_{xy}^*}{G_{xx} \cdot G_{yy}} \qquad (2)$$

$G_{xy}= F_y \cdot F_x^*$ is the cross spectrum, F_x is the stimuli frequency spectrum and F_y the beam response spectrum, * marks the complex conjugate, G_{xx} is the stimuli power spectrum and G_{yy} the beam response power spectrum.

If there is a good correlation in the measurement, the correlation coefficient γ will be 1, if not it will be 0 se Figure 5. The usable frequency range can be changed by changing the M-width and keeping the power level constant at the centre. The data processing to be implemented is in preparation [3].

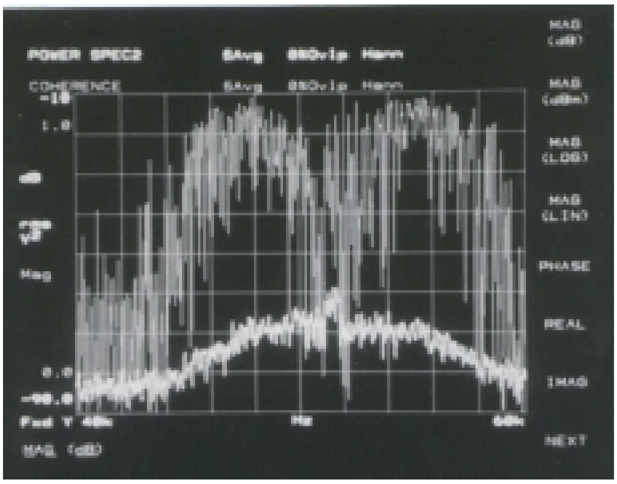

Figure 5: Top curve is the calculated γ i.e. correlation.

The measurements in Figure 3, 4 and 5 were done, as a proof of principle using analog down-mixing and a commercial FFT analyser at 2 GeV/c with $2x10^7$ antiprotons, an M-width of 10 kHz with a power spectral density of -30dBm at the M-centre. Each spectrum is an average of 5 beam stimulations of 40 ms. The ramp of the M is 6 dB/octave from the shoulder frequency of 5 kHz and down towards the centre to at depth of -24 dB. The small spike in the centre (Fig. 3 upper trace) is due to an imperfection in the prototype M-shaping circuit. The duration of each measurement was given by the FFT analyser frequency resolution. As can be seen from formula (1) the blow-up rate that is a product of the stimulation is proportional to the power given to the beam; thus if less frequency resolution is needed, one can stimulate in a shorter time, with more power, to get the same beam response. It is essential to be fast when measuring during deceleration, since the duration of the measurement defines the time resolution on the q value.

2.2.1 The M-shaping

The M-shaping is made using switched capacitor filters [4] in order to make the M-width a fixed fraction of the revolution frequency that changes during deceleration. The cut-off frequencies are made 1/20 of the filter control frequency, and additionally a divider is introduced in order to get smaller fractions of the revolution frequency when needed.

White noise is filtered by a low-pass filter and by a band-pass filter (2^{nd} order giving the 6 dB/octave on the inner ramp of the M). The two parts are then added with a switchable gain for the low-pass filtered signal to determine the depth of the M. The shaped noise is then mixed up to the expected betatron frequency, where the positive and negative image makes up the M.

During set-up of the accelerator the M will be kept wide to allow measuring tunes deviating a lot from those expected. When the accelerator has been set up, the tunes will correspond to the expected ones and the system can monitor the tune without causing significant beam blow-up.

3 SYSTEM STATUS

The Schottky part of the tune measurement system is ready, but the S/N is too poor to measure the tune. The BTF analysis is expected integrated in the system during the summer of 2001.

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