LONGITUDINAL SHOTTKY SIGNAL MONITORING FOR PROTONS IN HERA

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Abstract

Stable longitudinal behavior of the protons is an important feature for future HERA operation. Specific diagnostic tools must be developed for this reason. In this case a standard wall current monitor is used to detect a beam signal from the incoherent motion of the protons due to both coasting beam and synchrotron oscillations during luminosity operation. This will be helpful to understand the process of coasting beam production in HERA. The coherent rotation harmonics from the bunched beam are strongly suppressed to enable amplification of the Schottky signal. The signal processing will be described and measurements at HERA will be presented.

Table 1: Longitudinal Parameters for Protons in HERA

Beam Energy	$cp = 920\,GeV$
Revolution Frequency	$f_0 = 47.3\,kHz$
Harmonic Number	$h = 4400(1100)$
RF Frequency	$f = 208(52)\,MHz$
RF Voltage	$V_c = 580(100)\,kV$
Momentum Compaction	$\eta = 1.3 \times 10^{-3}$
Synchrotron Frequency	$\nu_s = 37\,Hz$
Bunch Length FWHM	$\tau = 1.2 \ldots 1.8\,ns(10\,h)$
Longitudinal Emittance	$\epsilon = 0.6 \ldots 0.85\,eVs$
Number of Protons/Bunch	$N_b = 7 \times 10^{10}$
Number of Bunches	$n_b = 180(220)$

1 INTRODUCTION

Two rf systems are used to capture and accelerate the proton beam in HERA. Both systems apply fast feedback for stable beam operation. Table 1 lists the longitudinal parameters at high energy. The longitudinal emittance growth during the luminosity run is mainly due to intra-beam scattering. At the same time the acceptance around the bucket becomes populated with coasting beam causing background disturbances for the experiments. The process behind this is not understood so far. In HERA 180 proton bunches are circulating at a distance of $(220 \times f_0)^{-1} = 96\,ns$. Every eleventh bucket is empty and a $1\mu s$ gap for a dump kicker is empty too. Therefore even with equal bunch charges the spectrum measured using a wide-band pick-up has strong coherent revolution harmonics which can obscure the small Schottky signal arising from incoherent particle motion both inside the bunch and from the coasting beam. To achieve the resolution for Schottky signal detection one needs first a pick-up with sufficient sensitivity for an acceptable S/N ratio. But additionally it is important to suppress the revolution harmonics which decreases the dynamic range.

2 DETECTOR CONCEPT

The Schottky signal from bunched and unbunched beams in a circular machine has a periodic time structure. Therefore it is convenient to concentrate on the frequency domain for signal analysis. The full spectral information is inside a band surrounding every harmonic of the revolution frequency. For unbunched beams the power spectral density decrease with the harmonic n until they are overlapping and the Schottky current depends on the square root of the total number of particles N [1]:

$$\Delta f(n) = nf_0\eta\frac{\Delta p}{p} \;\; , \;\; I_{RMS} = 2ef_0\sqrt{\frac{N}{2}} \;,$$

where $\Delta p/p$ is the beams' momentum spread.

Bunched beams have symmetric sidebands of the particle synchrotron frequencies [2] [3]. In a small frequency band the Schottky current can be approximated by

$$I_{RMS}^{n,k} = 2ef_0\sqrt{\frac{N'}{2}}J_k(n\omega_0\overline{\tau}_a) \;, \quad \text{where}$$

N' is the number of protons in the band with $n\omega_0\overline{\tau}_a$ the average phase space oscillation amplitude and J_k is the Bessel function of the first kind. The detector signal power depends on the square of the pick-up sensitivity S; i.e. $P_s \sim (I_{RMS} \times S)^2$. Therefore high frequency cavity pick-ups are mostly chosen although the Spectral density of unbunched beams is proportional to $(n\omega_0)^{-1}$. In our case the large amplitude behavior of the bunched beam is of main interest so the pick-up should have not only a high sensitivity but also a linear response to the bunched beam. At a given sensitivity the choice for the measurement frequency $n\omega_0$ has to take the argument of the Bessel function $(n\omega_0\overline{\tau}_a)$ and the spectral density of the coasting beam into account.

60 MHz is a good choice for applying a narrow-band crystal filter and for avoiding strong harmonics from the 10.4 MHz bunch frequency. To prevent ringing of the filter due to the strong peak voltage from the beam, a voltage limiter is used at the input. The filter output is purely sine-wave at 60 MHz with a small phase modulation which contains the signal information. The amplitude is related to the coherent revolution harmonic and can be suppressed for dynamic reasons using a limiting amplifier with low phase distortion. A high resolution FFT can be applied to the signal after down converting to baseband.
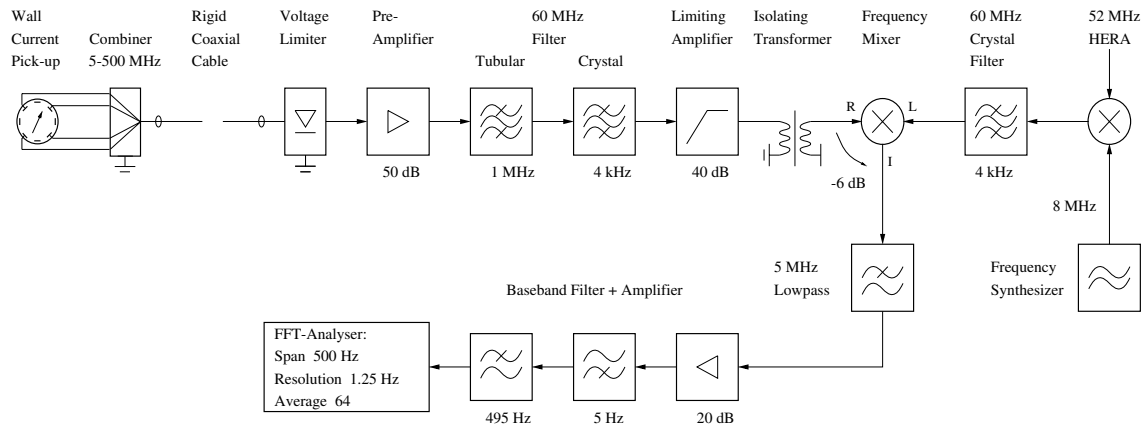
Fig. 1 shows a block diagram of the detector.

Figure 1: Block diagram of the Schottky Detector.

3 HARDWARE

3.1 Wall Current Monitor

Four dedicated orthogonal striplines from one HERA wide-band bunch monitor are combined for a maximum sensitivity of $S = 7\Omega$ around 60 MHz. The output peak voltage into $50\ \Omega$ at the end of 100 m of rigid coaxial cable from a bunch with a 1.6 ns bunch length (FWHM) containing 7×10^{10} protons is about 50 V. For comparison, the signal power from an unbunched beam containing for example 1×10^{10} protons is

$$P_s = \frac{(I_{RMS} \times S)^2}{50\ \Omega} \approx 1 \times 10^{-18}\ W, \quad I_{RMS} \approx 1\ nA.$$

A $50\ \Omega$ load produces at room temperature the same amount of thermal noise in a frequency band of 270 Hz. Nevertheless, at 60 MHz a particle momentum spread of 1×10^{-4} is concentrated in a band of only 8 Hz which is sufficiently small for good resolution.

3.2 Peak Signal Limiter and Preamplifier

The pick-up signal is fed into a thin-film diode limiter with low phase distortion and fast recovery from saturation (Avantek, Inc.: UTL-1002). This reduces the contribution to the signal from the peak voltage to a level acceptable for input into the two stage low noise preamplifier.

3.3 Bandpass Filter

At this point the detection can concentrate on a single revolution harmonic using analog filtering in two steps. First a tubular bandpass filter is used to reduce unwanted signal power and second a crystal filter with a few kHz bandwidth around $1268 \times f_0$ is used to extract the signal information.

3.4 RF Signal Limiter

This signal information of interest is purely phase modulation of the 60 MHz filter output. Therefore a limiting amplifier can be applied to reduce unwanted contribution from the rotation harmonic. A bipolar three-stage rf limiter

with low phase distortion and 40 dB of input power range is used for this task (Avantek, Inc.: UDL-503).

3.5 Down Conversion

To avoid ground loop distortion the detector is isolated up to this stage. The signal level now is high enough to connect to the local ground using an rf transformer. Down conversion to baseband for high resolution FFT is mandatory. A 60 MHz reference derived from the 52 MHz acceleration frequency and 8 MHz from a synthesizer achieve about 0.1 Hz in long term stability. The baseband signal from 5 Hz to 495 Hz centered at 250 Hz is now amplified up to a level convenient for standard signal processing.

3.6 FFT-Analyser

The total detector amplification for the signal power P_s is about 97 dB. A standard FFT-Analyser with 1.25 Hz of resolution detects a noise level of -85 dBV which is equivalent to an input noise figure of 3 dB. Hence the detector resolution is about

$$\frac{P_{s,min}}{\Delta f} \approx 1 \times 10^{-20}\ \frac{W}{Hz}.$$

For data display VEE [1] visual engineering software is used connecting to the FFT-Analyser via an HP-IB [1] interface.

4 MEASUREMENTS

4.1 Coasting Beam Signal

Fig. 2 shows a Schottky signal from a coasting beam just after debunching at 920 GeV/c. The number of protons is about 6×10^{12} and the momentum spread $\Delta p/p$ is 5×10^{-4} within a frequency spread of 40 Hz.

4.2 Bunched Beam Spectra

The spectrum measured just after ramping the beam energy to 920 GeV/c shows many coherent longitudinal modes of
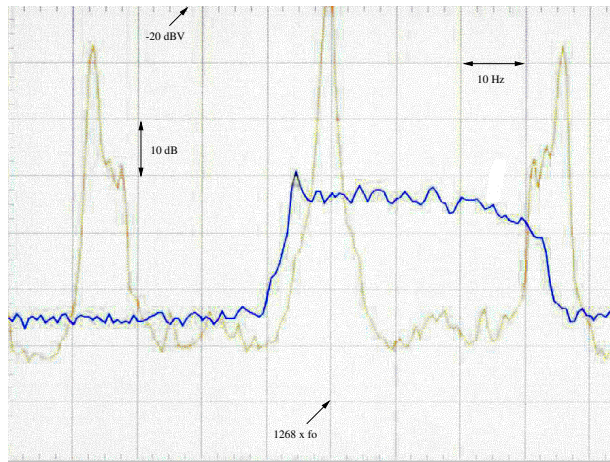
[1] trademark

Figure 2: Bunch spectrum with some coherent oscillation in HERA and the coasting beam spectrum at the same output just after switching off both rf systems.

Figure 3: Coherent oscillation modes at the beginning of the high energy run. The 50 Hz lines are artificial due to line disturbance.

oscillation (see Fig. 3). These modes are continuously decaying during the first hour. After several hours the spectrum is more or less relaxed and reveals some structure inside the synchrotron band (see Fig. 4). The sidebands at about 9 Hz are most likely related to some protons inside the outer composite 52 MHz bucket. Probably it is a coherent dipole mode oscillation because of the missing second Bessel component. The oscillation frequency of 9 Hz corresponds to 100 kV from the 52 MHz system in conjunction with 580 kV from 208 MHz. Other conspicuous peaks in the spectrum may result from unknown beam excitation. The synchrotron frequency band of the main 208 MHz bunch at 37 Hz is not particularly pronounced due presumably to the peak signal limiter and the absence of coherent oscillation. Another example For a bunched beam spectrum is shown in Fig. 5. Here the 52 MHz voltage was 140 kV resulting in a slightly higher sideband frequency.

Figure 4: HERA proton spectrum after several hours at 920 GeV. The 52 MHz voltage level is 100 kV composing an island with synchrotron frequencies at about 9 Hz.

ACKNOWLEDGMENT

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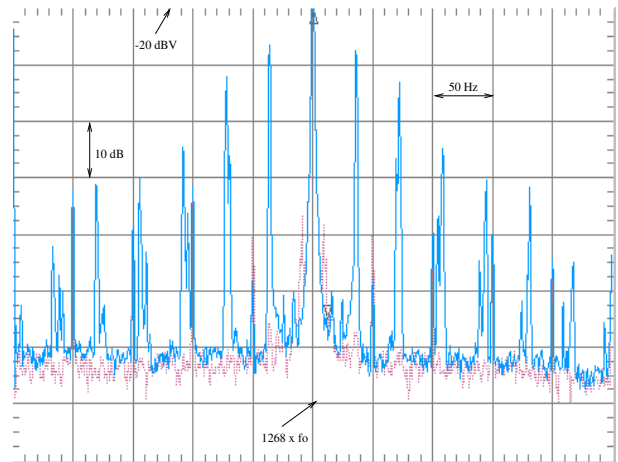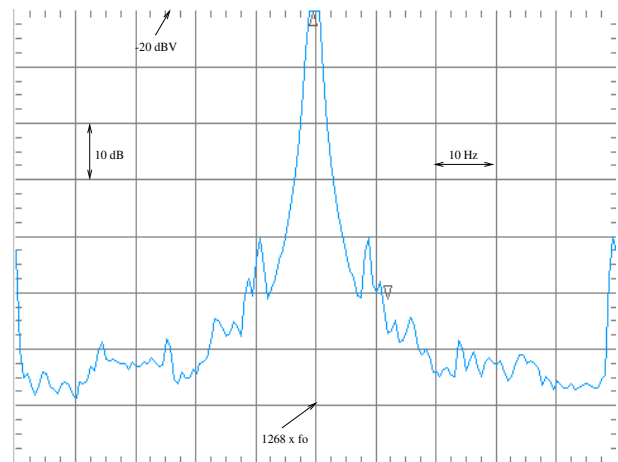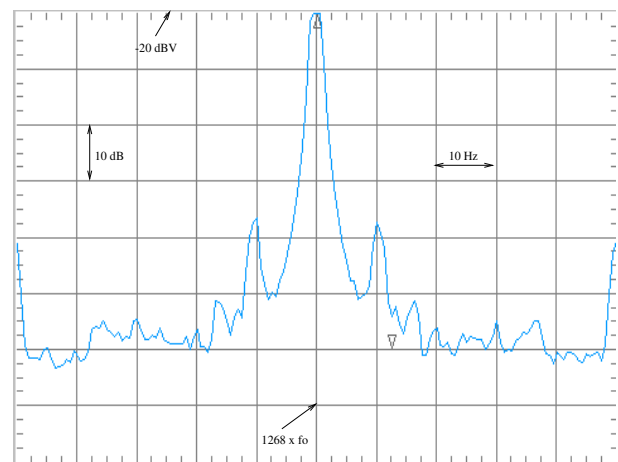

Figure 5: The same condition as in Fig. 4 but the 52 MHz voltage level is 140 kV.