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RECENT DEVELOPMENTS ON SCHOTTKY BEAM DIAGNOSTICS AT THE CERN SPS COLLIDER

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Abstract

Optimisation of pick up and detection techniques for observation of " Schottky " signals in bunched beams is discussed. Methods for distinguishing coherent and incoherent motion are described.

Bunched Beam Schottky Signals

Consider a tranverse resonant, high frequency pick-up excited by an off center particle (charge e, displacement x_t) and assume that the output waveform is an RF burst of amplitude v and duration τ in a load R_o = 50 ohms (Fig. 1).

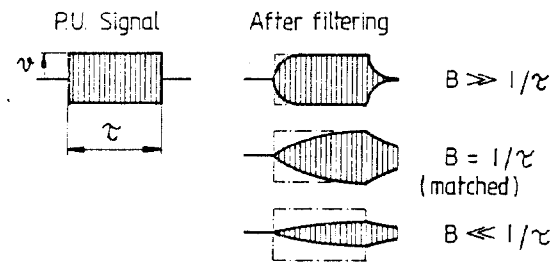

Fig. 1 Filtering the rectangular RF burst.

(It is shown later that this model approximates to a travelling wave pick-up). The RF power $v^2/2R_o$ is available for time τ. If the transfer impedance of a transverse pick-up is Z, Volts in load / (beam current x displacement), then v is given by:

$$v = 2e \frac{Z}{\tau} x_t = 2e \frac{Z}{\tau} (x_o + x) \qquad (1)$$

where x_o is the steady closed orbit offset at the pick-up and x is the betatron oscillation. For N particles in a bunch of length $2\Delta t$ ($\Delta t \ll \tau$), the total voltage is the sum of the steady term $v_o = 2NeZx_o/\tau$ and a fluctuating, or Schottky, term of rms value :

$$v_{s_{rms}} = \sqrt{\frac{N}{2}} \cdot 2e \frac{Z}{\tau} \sqrt{\langle x^2 \rangle} \qquad (2)$$

At the output of the first RF amplifier, noise figure 3dB, where the bandwidth is limited with a filter to B Hz we also find a fluctuating component due to the thermal noise of the amplifier. Referred to the input, the rms thermal noise voltage is given by:

$$v_{th_{rms}} = \sqrt{4k\ T\ B\ R_o} \qquad (3)$$

If we measure the amplitude of the burst after the filter and disregard the steady term coming from v_o, we find that the ratio of Schottky to thermal power, 1/U, observed on the detected signal is:

$$\frac{1}{U} = \frac{\langle v_s^{\ 2} \rangle}{\langle v_{th}^{\ 2} \rangle} = \frac{N\ e^2\ Z^2\ \langle x^2 \rangle}{2\tau^2\ k\ T\ B\ R_o} \qquad (4)$$

As the burst repeats at the revolution frequency f_o, it is natural to sample and hold the amplitude at every bunch passage (Fig. 2). In this way, one directly obtains the Schottky signal in the frequency band 0 to $f_o/2$. Sampling, a linear process, does not change the factor 1/U ; it provides, in addition, a convenient way of rejecting all steady components at multiples of f_o.

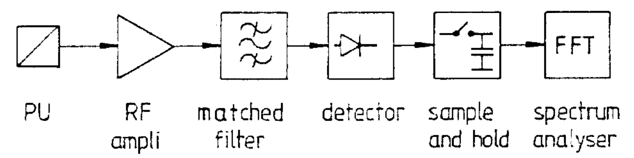

Fig. 2 Schematics of bunched beam Schottky detector.

To optimize, we must carefully select the filter bandwidth B as the thermal noise power increases linearly with B whereas the burst amplitude (and the fluctuating part) is a non-linear function of B which approaches a maximum. This is a well known problem in radar signal detection, the solution being the "matched filter" where impulse response is the time reversed image of the pulse to be detected[1]. For our idealized rectangular burst, the matched filter bandwidth B is simply the inverse of the pulse length: B = $1/\tau$. In other words B becomes the minimum bandwidth for which the RF burst amplitude is negligibly attenuated after time τ (Fig. 1). For a non rectangular burst, (simple resonant circuit with exponential decay for instance), the matched filter is less simple, but the following result remains qualitatively valid:

$$\frac{1}{U} = \left(N \frac{T_o}{\tau} \right) \frac{e^2\ f_o\ Z^2\ \langle x^2 \rangle}{2k\ T\ R_o}\ ; \qquad (T_o = 1/f_o) \qquad (5)$$

This result, already obtained by a different approach [2] shows that, for a bunched beam, it is the effective number of particles $N_{eff} = NT_o/\tau$, which can be much larger than N, which determines the Schottky to thermal noise ratio. As τ -> To, equation (5) reduces to the continuous beam case. This shows the interest in making use of the pulsed nature of the signal compared to the conventional continuous beam solution using narrow band filtering (10.7 MHz SPS System [3]).

After sampling, the thermal noise appears as white noise in the band 0 to $f_o/2$, whereas the Schottky signal has a bandwidth determined by the machine conditions and pick-up frequency f_{pu}. For a bunched beam, each betatron band splits into a central line and an infinity of synchrotron satellites, spaced by f_s (synchrotron frequency). However, the significant synchrotron satellites are contained in a bandwidth of the order of $\pm\ 2\pi f_{pu}.\Delta t.f_s$. The central line width, in an ideal machine without ripple or non linear fields is infinitely narrow; in reality its width reflects the incoherent tune spread in the bunch, (octupole and beam-beam fields), as well as fluctuations of the tune.

It can be shown that amplitude detection of the RF burst only shows even synchrotron satellites. After half a synchrotron period,all the elementary RF bursts (from each particle) are triggered at instants symmetrical with respect to the synchronous particle. The total resulting RF burst amplitude is the same, after half a synchrotron period, as if there were no

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synchrotron motion: the periodicity of the betatron oscillation is therefore 2 f_s and no odd multiples of f_s will appear in the spectrum. One obtains the same result with in phase synchronous detection, using an RF reference linked to the synchronous particle, for example an appropriate multiple (at f_{pu}) of f_o or a signal derived from the bunch itself. The odd satellites would be displayed with a quadrature synchronous detector.

At high frequencies, the Schottky band may contain several overlapping synchrotron satellites making interpretation of the spectrum difficult. In particular to observe the central line, which gives information on the incoherent tune and tune spread, the rejection of the first synchrotron satellites by amplitude detection is a very useful feature (Fig. 3).

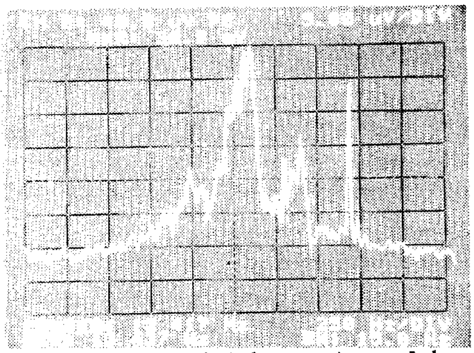

Fig. 3 Observed Schottky spectrum, 1 bunch $2f_s$ satellites observed (f_s=160 Hz).

High frequency tranverse pick-ups

Rewrite equation 5 to make the pick-up dependent parameters appear together:

$$\frac{1}{U} = \frac{Ne^2 \langle x^2 \rangle}{2kT} \cdot \alpha \quad ; \quad \alpha = \frac{Z^2}{\tau R_o} \qquad (6)$$

α is the pick-up factor of merit. Using (1) one obtains:

$$\frac{v^2 \tau}{2R_o} = \alpha q^2 x^2 \qquad (7)$$

The term $v^2/2R_o$ is the power in the load when excited by charge q displaced by x, and therefore the quantity $v^2\tau/2R_o$ is the total energy W delivered to the load. Assuming negligible power loss in the pick-up, W is also the energy deposited in the structure by the charge q. For a longitudinal mode, the energy lost by a charged particle passing through the structure is characterized by the loss factor k. Similarly, for a transverse mode, we write:

$$W = k\, q^2\, x^2 \qquad (8)$$

and find that the pick up factor of merit is nothing but the loss factor for the corresponding transverse mode of the pick up structure.

For a given periodic structure, α is proportional to the pick up length as the total energy deposited by the charge in the structure is proportional to the number of cells.

Consider, as a simple example, the E_{011} mode of a cylindrical cavity of length L where the field is purely longitudinal and changes sign across the axis.

$$E_x = E_\phi = 0 \quad ; \quad E_z = E_o J_1\left(\frac{2\pi x}{\lambda}\right)\cos\phi \qquad (9)$$

The loss factor for this mode can be calculated assuming an infinitely small beam hole. When a charge q crosses the cavity, the induced field E_z decelerates the particle by an amount W. W is also the energy deposited by the charge and so we have the two relations:

$$W = \frac{1}{2} q \int_0^L E_z \exp\left(j\frac{\omega z}{c}\right) dz \quad ; \quad W = \frac{1}{2}\int_v \varepsilon_o E_z^2\, dv \qquad (10)$$

The factor 1/2 in the first results from the "fundamental theorem of beam loading"[4].

Eliminating E_o from (9) and (10) we obtain

$$W = \left(\frac{\mu_o}{4\pi}\right)\frac{L\,\omega_{pu}^2}{2.38}\left(\frac{\sin\pi\frac{L}{\lambda}}{\pi\frac{L}{\lambda}}\right)^2\left(\frac{2\pi}{\lambda}\right)^2 q^2x^2 \qquad (11)$$

For a reentrant cavity, with gap g, the transit time factor is replaced by $(\sin \pi g/\lambda)/(\pi g/\lambda)$. Equation (11) shows the interest of high frequency pick-ups (terms ω_{pu} and $1/\lambda^2$) although the presence of a beam hole, with a diameter not small compared with λ will reduce the loss factor. Finally the chosen operating frequency comes from a compromise between pick up sensitivity and the significant synchrotron satellites displayed.

A complete tranverse pick-up could be built from a string of cavities coupled together. Two well known examples are the classical disk loaded structure with coupling through the beam hole, and the Alvarez linac structure with coupling outside the beam hole. The type of coupling determines how the energy given to one cell flows through the other cells towards the structure end, (group velocity v_g), but as a first approximation, the factor of merit does not depend on the coupling which changes little the energy deposited by the charge transit. For a long pick-up and a value of v_g not too large ($v_g \ll c, \tau \gg \Delta t$) the RF burst from a travelling wave structure has approximately constant amplitude and lasts $\tau = \ell/v_g$, ℓ being the total length of the pick-up.

It is interesting to compute in a similar way the energy deposited in a resonant electrostatic pick up, as used in the SPS 10.7 MHz Schottky system [3]. Neglecting circuit losses an equation of the same form as (11) is obtained:

$$W = \frac{1}{2C}\,\frac{\omega_{pu}^2}{c^2}\,\frac{\ell}{a^2}\, q^2x^2 \qquad (12)$$

C = capacity/unit length; 2a = distance between plates.

More detailed analysis of particular structures can be made using standard computer programs (R/Q calculation) or perturbation measurements, but it is remarkable that the analytic expression (11) already gives results close to exact values. For instance the exact k factor (in V/pc x cm^2) for the SPS 460 MHz pick up is 4.48 10^{-2} whereas equation (11) gives 3.37 10^{-2}. For the same total length, the electrostatic 10.7 MHz resonant pick-up only provides k= 1.3 10^{-2} for a more restricted aperture (a = 1cm).

The SPS 460 MHz Schottky apparatus

The SPS accelerator has four accelerating cavities working at 200 MHz [5]. Each cavity is similar to a proton linac Alvarez structure, with drift-tubes supported by symmetrical bars. The structure is periodic, with a phase shift per cell of $\pi/2$ at mid-band. Travelling wave operation, necessary to cope with the frequency swing during proton acceleration, is achieved with matched couplers at the cavity ends.

The first deflecting mode in the cavity at 460 MHz does not couple to the 200 MHz couplers and the resulting high Q, high transverse impedance resonator caused horizontal instabilities on the high intensity beam. To lower the impedance two symmetric antennas coupled to a termination via a vacuum feedthrough have been installed on each cavity end plate to match the structure at 460 MHz.

With this arrangement, each cavity is also a long (20m) horizontal travelling wave pick up (f_{pu} = 460 MHz). Although the antenna matching is not perfect, it is sufficient to provide 10 ~ 20 dB directivity and allow separation between proton and antiproton signals. However, time separation is more efficient in obtaining clean signals from one type of particle. This is possible because cavities are installed on either side of the intersection point: depending on the cavity, the proton or the antiproton signal arrives first, uncontaminated by the other signal.

Preliminary, wide band filtering rejects the strong residual 200 MHz component. The burst length is ~400ns, in good agreement with the calculated $v_g = -0.13$ c. The closed orbit component is reduced by centering the beam in the cavity with two correction dipoles. This reduces the dynamic range requirements for the RF preamplifier (gain 16 dB, output ± 5Vpk), located in the ring close to the cavity. For practical reasons, our measurements used a less than optimum, wide bandwidth multipole filter (B = 20 MHz).

Amplitude detection is simply done with a biased diode followed by a low noise preamplifier, the output sampled and held at f_o. The sample and hold circuit has three separate outputs corresponding to the three proton or antiproton bunches in the machine. We have checked, measuring and calculating the rms noise levels at various points of the chain that the dominant source of noise is indeed the RF preamplifier (noise figure 4 dB).

Natural and excited Schottky signals

Unlike a continuous beam, any tranverse excitation, frequency f_e, of a bunched beam appears everywhere in the bunch spectrum, since the bunch, in sampling f_e, generates all frequencies $f_e + nf_o$ (n integer). Consequently, a low frequency excitation, near the first betatron line (f_β = 13 kHz in the SPS) will be found at 10.7 MHz or 460 MHz, by the ultra sensitive Schottky systems. For a large machine, like the SPS, f_o is so low that excitation around f_β by magnet field noise and ripple at high multiples of the 50 Hz mains is not suppressed by the metallic vacuum chamber. As a result one observes not only the true Schottky signal but also the excited signal due to machine imperfections.

To distinguish between "natural" and excited signals, consider first the case of a single frequency f_e in the vicinity of f_β. The three SPS bunches are excited in phase, and provided they are identical in shape, number of particles and emittance, the three signals given by the 460 MHz system are the same. Substracting the signals of two bunches cancels the coherent (excited) part and adds quadratically the incoherent (Schottky) components. The result is spectacular (Fig. 4) showing not only the large reduction of most of the 50 Hz lines, but even more interesting the difference between the incoherent tune (Schottky signal) and the coherent tune (excited signal). The signal given by the 10.7 MHz narrow band system is essentially the excited signal (coherent tune), whereas, with the new 460 MHz bunched beam Schottky system, the coherent and incoherent tunes can be measured directly.

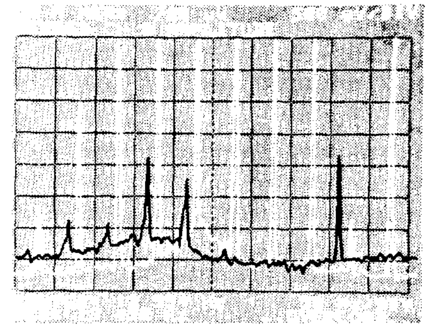

Fig.4 Coherent (white) and incoherent (black) tune measurement.

Another rejection technique has been successfully tried on the SPS. The signal from one bunch or from the sum of all bunches is used to suppress the coherent excitation by a feedback loop acting on the beam at 13 kHz via a directional kicker [6]. The coherent signals are cancelled whereas the Schottky components add quadratically.

We have checked that the "natural" Schottky signals are independent of bunch shape. By shaking one of the three bunches with the RF system one can reduce its 460 MHz longitudinal component by a substantial factor (> 3) at constant intensity. The line related and coherent components are reduced by the same amount, but the incoherent part changes very little, as expected.

There is experimental evidence that higher exciting frequencies are present (for instance a phase shift of $2\pi/3$ between bunches has been observed). For those frequencies, and also in the case of unequal bunches, the simple method of substracting the signals from two bunches fails. However, more refined signal processing techniques can be considered to extract the correlated and uncorrelated components of the signals of all bunches.

Conclusions

The new 460 MHz System is a powerful tool for observation of coherent and incoherent motion in a particle bunch. Measurement of tune shifts and spreads hopefully leads to better understanding of transverse impedance, beam-beam interaction etc.. Transfer function measurements using this system plus a kicker are a natural extension to improve measurements of coherent response.

Acknowledgements

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