СООБЩЕНИЯ
ОБЪЕДИНЕННОГО
ИНСТИТУТА
ЯДЕРНЫХ
ИССЛЕДОВАНИЙ

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BETATRON TUNE MEASUREMENT

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1. INTRODUCTION

One of the most important parameters of cyclic accelerators is the frequency of the betatron oscillations ω_β or in other word the number of betatron oscillations per revolution period, the well-known Q-value.

The betatron tune Q must be chosen and kept far from any linear and nonlinear resonances. With the betatron tune Q a lot of other dynamic parameters such as chromaticity and tune dependence on the amplitude are expressed.

This paper represents a review of the methods for measurement of the betatron tune. The methods have been classified according to the way of beam excitation, i. e. methods using measurement of the statistical fluctuations of the beam current (Schottky noise) and methods using coherent beam excitation, either pulse or sinusoidal.

Theoretical derivations of the formulae used in the paper will not be given. The emphases is on the final results, which are important for the betatron tune measurement.

Some review papers devoted to tune measurement and related topics are references [1-9].

2. BETATRON TUNE MEASUREMENT USING INCOHERENT EFFECTS (STATISTICAL FLUCTUATIONS)

2.1. SCHOTTKY NOISE

The Schottky noise is due to the fact that the beams in accelerators consist of finite, although very large, number of particles. This finite number of particles in the beam with randomly distributed phases causes deviations of the instantaneous beam characteristics from their mean values. Statistical fluctuations give rise to signals proportional to $N^{1/2}$, where N is the number of particles in the beam (the power of the signal is proportional to N). These signals are called Schottky signals in analogy with the well-known Schottky noise signals in a dc current in electronics- [1-8]. When N is large, as this is in accelerators, the Schottky signals are small compared to the coherent signals produced by the beam, which are proportional to N.

The frequency domain picture of the statistical fluctuations is of special interest.

Four cases can be distinguished - unbunched beams in either longitudinal or transverse directions and bunched beams in either of these directions.

2.2 UNBUNCHED BEAM. LONGITUDINAL DIRECTION

The mean beam current is:

$$\langle i(t) \rangle = Nef_0 \tag{2.1}$$

N being the number of particles and f_0 being the revolution frequency of the reference particle.

This is mealy the macroscopic dc current of the beam.

The initial phases ψ_k of the particles are distributed in a random manner. They are mutually independent and evenly distributed in the interval [0, 2π]. This gives rise to statistical fluctuations and noise current - the Schottky noise.

We are interested mainly in the frequency domain picture.

The longitudinal Fourier spectrum of the beam current consists of bands around frequencies n.f_0. f_0 being the revolution frequency of the reference particle - Fig.1.

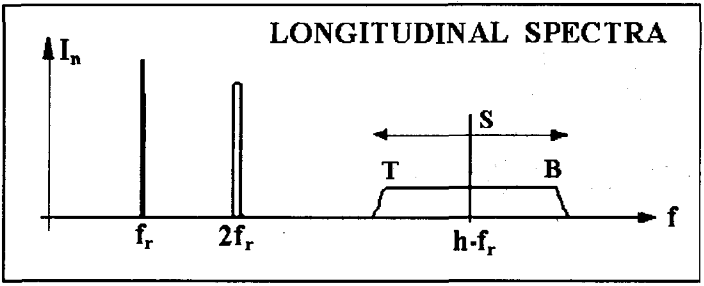

Figure 1. Longitudinal Schottky spectrum - [2].

The width of the n[th] band is given by:

$$\Delta f = n f_0 \eta \frac{\Delta p}{p} \tag{2.2}$$

where:

$$\eta = \frac{df/f}{dp/p} = \left(\frac{1}{\gamma_{tr}^2} - \frac{1}{\gamma^2}\right) \tag{2.3}$$

is the machine parameter.

In (2.3) γ is the relativistic energy parameter and γ_{tr} is its value at transition energy.

The power spectral density is:

$$\frac{di_{rms}^2}{df_0} = 2e^2 f_0^2 \frac{dN}{df_0} \approx \frac{\langle i^2 \rangle}{\Delta f} \tag{2.4}$$

and decreases with the harmonic number n until an overlap occurs when $\Delta f > f_0$.

The spectrum analyzer record the frequencies around the n[th] bend (around nf_0). The average power dissipated by the beam in 1 Ω resistor is:

$$\langle i^2(t) \rangle = (Nef_0)^2 + i_{rms}^2 \tag{2.5}$$

The Schottky current per n-th band is:

$$i_{rms} = 2ef_0 \sqrt{\frac{N}{2}} \tag{2.6}$$

It is independent of the harmonic number 'n' and is proportional to the square root of the number of particles N.

Fig. 2 shows the longitudinal Schottky noise line profile.

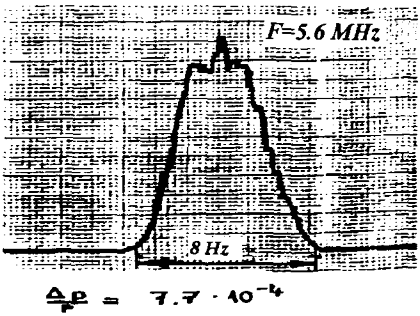

Figure 2. Longitudinal Schottky line - [2].

2.3. BUNCHED BEAM. LONGITUDINAL DIRECTION

The synchrotron oscillations of the particles in the bunch modulate the time of passing in front of the BPM with respect to the synchronous particle. This results in splitting of the n[th] band in the longitudinal Fourier spectrum to an infinite number of so-called synchrotron satellites. In practice only the first few are of importance.
The significant bandwidth of the n[th] spectral band is:

$$2\Delta f = 2\Omega_S \, n f_0 \tau_m \tag{2.7}$$

where Ω_s is the synchrotron frequency and τ_m is the maximum amplitude of the synchrotron oscillations (in time) or the time bunch length.

The width of the p[th] synchrotron satellite is given by:

$$\Delta f = p\left(\frac{\Delta\Omega_s}{2\pi}\right) \tag{2.8}$$

where $\Delta\Omega s$ is the synchrotron frequency spread.

The synchrotron satellites are separated by $\Omega_s/2\pi$ and their amplitude is proportional again to $N^{1/2}$ and to $J_p(nf_0\tau_m)$, J_p being the Bessel function of order p.

For the central line in the band (p=0) the contributions from all the particles in the bunch add coherently and therefore it intensity in proportional to N and its width is zero (in absence of any magnetic field and RF imperfections). This is the longitudinal macroscopic signal - Fig. 3.

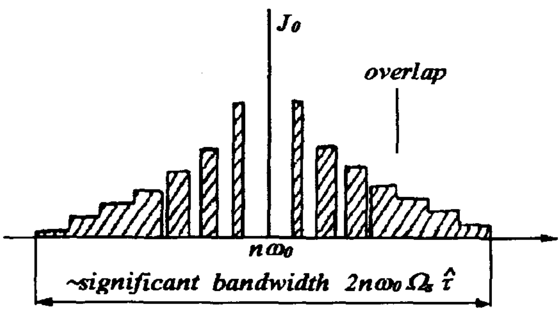

Figure 3. Longitudinal Schottky spectrum of a bunched beam- [7].

2.4. UNBUNCHED BEAM. TRANSVERSE DIRECTION

In transverse direction the BPMs measures the dipole momentum of the beam:

$$d(t) = a(t) \cdot i(t) \tag{2.9}$$

where a (t) is the centre of charge transverse displacement from the reference trajectory.

The betatron motion modulates the BPM signal through:

$$a(t) = a \cos(Q\omega_0 t + \phi) \tag{2.10}$$

Observed is only the non-integer part of the betatron tune $Q = k+q$ because we record only $d_n = d\,(nT_0)$ at BPM, T_0 being the revolution period of the reference particle.

The transverse Fourier spectrum consists of so-called betatron sidebands at frequencies $(n-q)\,f_0$ and $(n+q)\,f_0$ -Fig.4. The betatron sidebands appear at each multiple of the revolution frequency - nf_0. The positions of the betatron sidebands $(n \pm q)\,f_0$ for non-integer part of the betatron tune $q<0.5$ and for $q>0.5$ are shown in Fig.5.

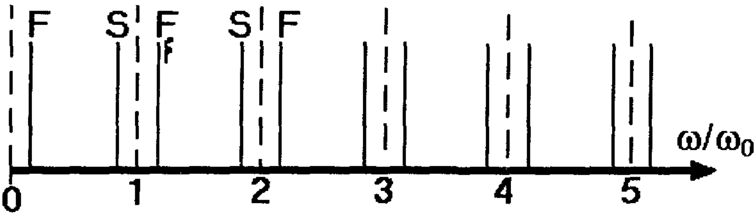

Figure 4. Fast and slow waves in the coasting beam transverse Schottky spectrum - [1].

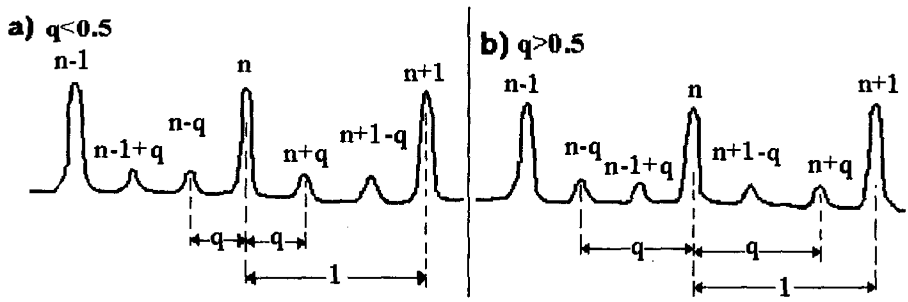

Figure 5. Position of betatron sidebands $(n \pm q)\,f_0$.: a.) For $q < 0.5$ the two bands right and left of a revolution harmonic $n.f_0$ are the bands $(n \pm q)\,f_0$. ; b.) For $q > 0.5$ the two bands closest to $n.f_0$ are the $(n + 1 - q)\,f_0$ and $(n - 1 + q)\,f_0$ bands - [3].

If the closed orbit has a non vanishing distortion at the Schottky pickup azimuth the coherent longitudinal signal (proportional to N^2) appear at the BPM Δ-signal. Careful beam centring in the pickup may reduce greatly the longitudinal contribution. However an strong coherent signal at the orbital harmonic frequencies is usually present in the transverse Schottky spectrum - Fig. 6. This signal may be suppressed by use of bandpass filters.

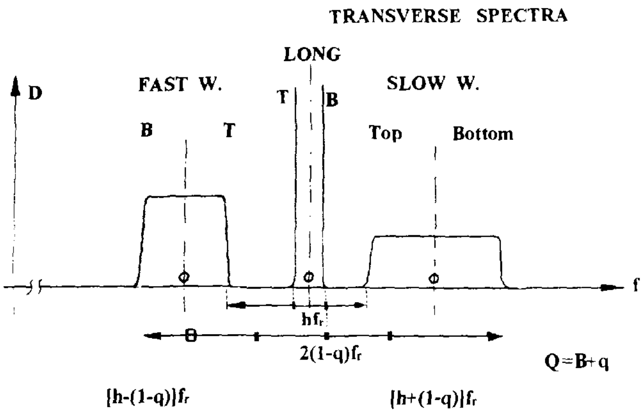

Figure 6. Transverse Schottky spectrum with the coherent longitudinal line at the centre - [10].

The band width is determined by:

$$\Delta f = f_0 \frac{\Delta p}{p}((n \pm q)\eta \pm Q\xi) \tag{2.11}$$

In (2.11) ζ denotes chromaticity which is defined trough:

$$\Delta q = \xi Q \frac{\Delta p}{p} \tag{2.12}$$

The total power per Schottky band is independent of the location in the frequency spectrum and is proportional to the number of particles in the beam and to the square of the rms betatron amplitude:

$$d_{rms} = e f_0 a_{rms} \sqrt{\frac{N}{2}} \tag{2.13}$$

An example of measured transverse Schottky spectrum is shown in Fig. 7.

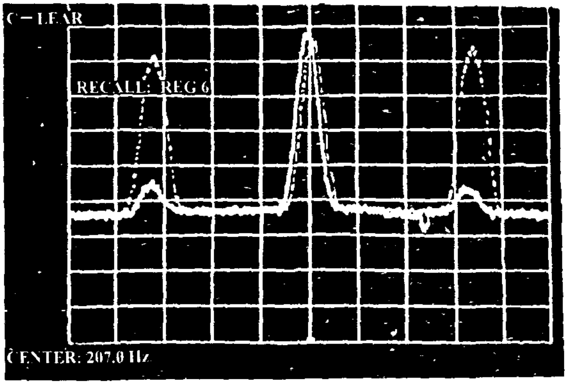

Figure 7. Horizontal Schottky spectrum at CERN- LEAR at 600 MeV/c. The central band with harmonic number n=100 of the revolution frequency is visible as the beam is not completely centred at the pickup. The right and left bands are the sidebands (98+Q) f_0 and (102-Q) f_0 with Q=2.3. During electron cooling the sidebands decrease. The difference between the base line of the track and the bottom line is given by the noise-[3].

2.5. BUNCHED BEAM. TRANSVERSE DIRECTION

In this case we have amplitude modulation of the BPM signal by the betatron oscillations and phase modulation by the synchrotron oscillations.

Now each betatron sidebands around (n-q) f_0 and (n+q) f_0 is splited to an infinite series of synchrotron satellites separated by $\Omega_s/2\pi$ - Fig. 8.

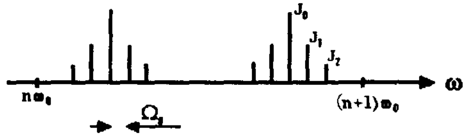

Figure 8. Decomposition of each betatron line into synchrotron satellites - [7].

The total power of the n^{th} band is:

$$<d_n^2> \ = \ e^2 f_0^2 <a^2> \frac{N}{2} F_{n,p} \tag{2.14}$$

where $F_{n,p}$ is a form factor.For the central line (p=0) and the synchrotron satellites (p≠ 0) the form factor $F_{n,p}$ is the integral along the bunch of $J^2_p(\ \Omega_p\ \tau_m\ )$ weighted by the normalized momentum distribution.

The amplitude of each synchrotron satellite is proportional to $J_p\,((n\pm Q)\omega_0 - \omega_\xi)$, where:

$$\omega_\xi \ = \ \frac{\xi}{\eta} Q\omega_0 \tag{2.15}$$

is the so-called chromatic frequency.

In transverse direction the bunched beam produces spectral bands all of them proportional to $N^{1/2}$ i.e. there is no transverse macroscopic signal proportional to N. The central line (p=0) here adds up rms wise. The width of this central line is determined by the RF and magnetic field fluctuations and also by transverse nonlinearities. The widths of the other lines are determined manly by the synchrotron frequency spread.

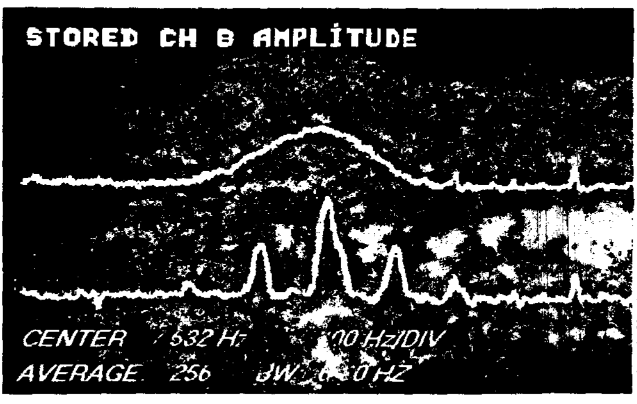

Figure 9. SPS Schottky signals. Top-debunched beam, bottom- bunched beam-[10]

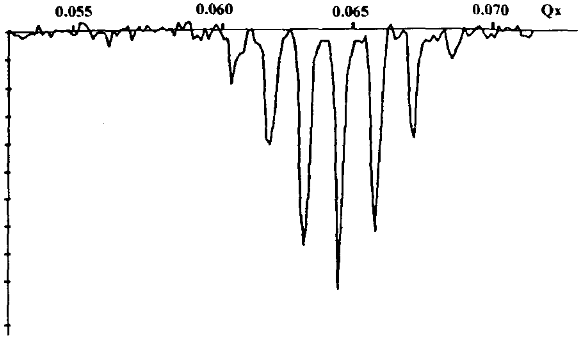

Figure 10. Schottky line with synchrotron satellites, measured in ADONE- [1].

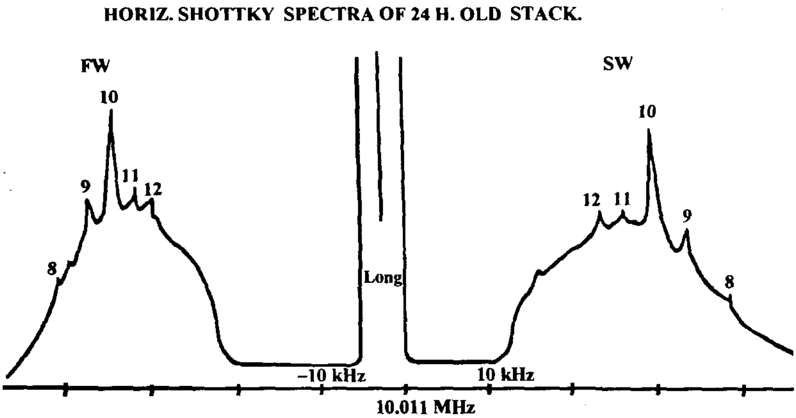

Figure 11. ISR horizontal Schottky spectrum - [38].

2.6. OBSERVATION OF THE SCHOTTKY SPECTRUM

It should be underlined, from instrumental point of view, that the incoherent Schottky signals are proportional to $N^{1/2}$ i.e. they are very small, in the μV range. The intensity of the transverse sidebands are about 1/100 times of these in the longitudinal direction (for ISR for instance)-[8].

The Schottky noise diagnostics have been extensively used since 1972 in CERN ISR to monitor the radial density distribution, to measure the Q values and to detect the growth of the transverse beam emittance.

For Schottky noise spectrum observation strip line pickups or wall-current monitors are used-Fig.12.

For low intensity beams the Schottky noise detector should possess high sensitivity and we should reduce the coherent signals.To avoid the coherent longitudinal bands, which are proportional to N the beam should be carefully centred at the position pickup and the output signal shoud be carefully filtered.

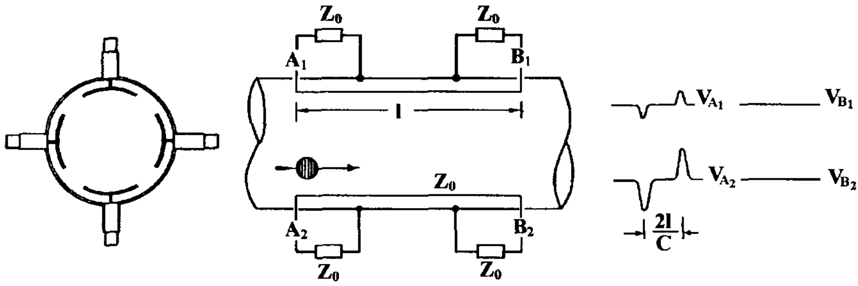

Figure 12. Schematic representation of a stripline monitor-[1].

The sensitivity of the Schottky pickup could be enhanced by means of resonant tuning of the electrodes.

As an example we will describe here the transverse Schottky noise detector of CERN SPS- [10-12]. This is a resonating pickup with a length 3 m. The two plates of the pickup are movable to match the gap between the electrodes to the beam width at high energy. The parasitic coherent signals are reduced by careful filtering. The resonance is achieved by means of an air or ferrite tuning core coil. The output signal is obtained by one turn loop inductive connection. The central frequency was chosen to be 10.7 Mhz and the band- width is 50 kHz. The block diagram of the Schottky receiver is shown in Fig. 13. The system uses sharp bandpass filters. Finally the signal is mixed down to between d. c. and 100 kHz and analysed by an averaging FFT spectrum analyser.

The SPS Schottky pickup works reliably with 0.3 mA continuous beam and 0.01 mA single bunch beam.

A very low noise broad band amplifiers with good linearity should be used.

The mechanical layout of the SPS Schottky pickup is shown in Fig. 14.

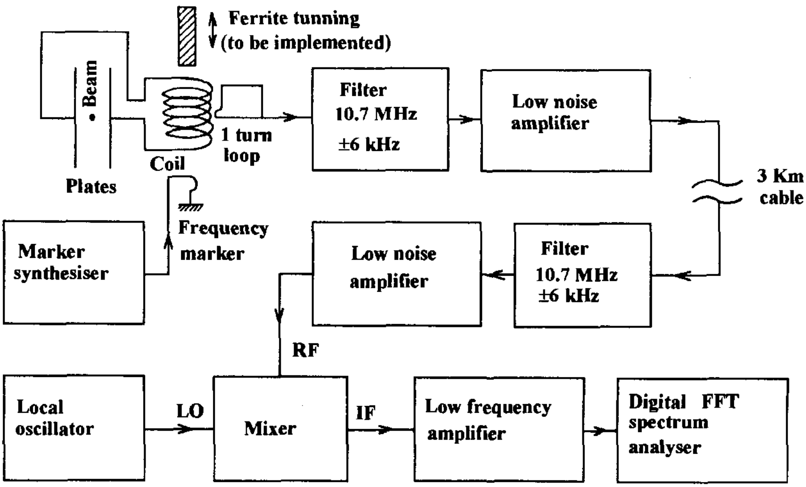

Figure 13. Block diagram of the electronic system of the CERN Schottky receiver - [10].

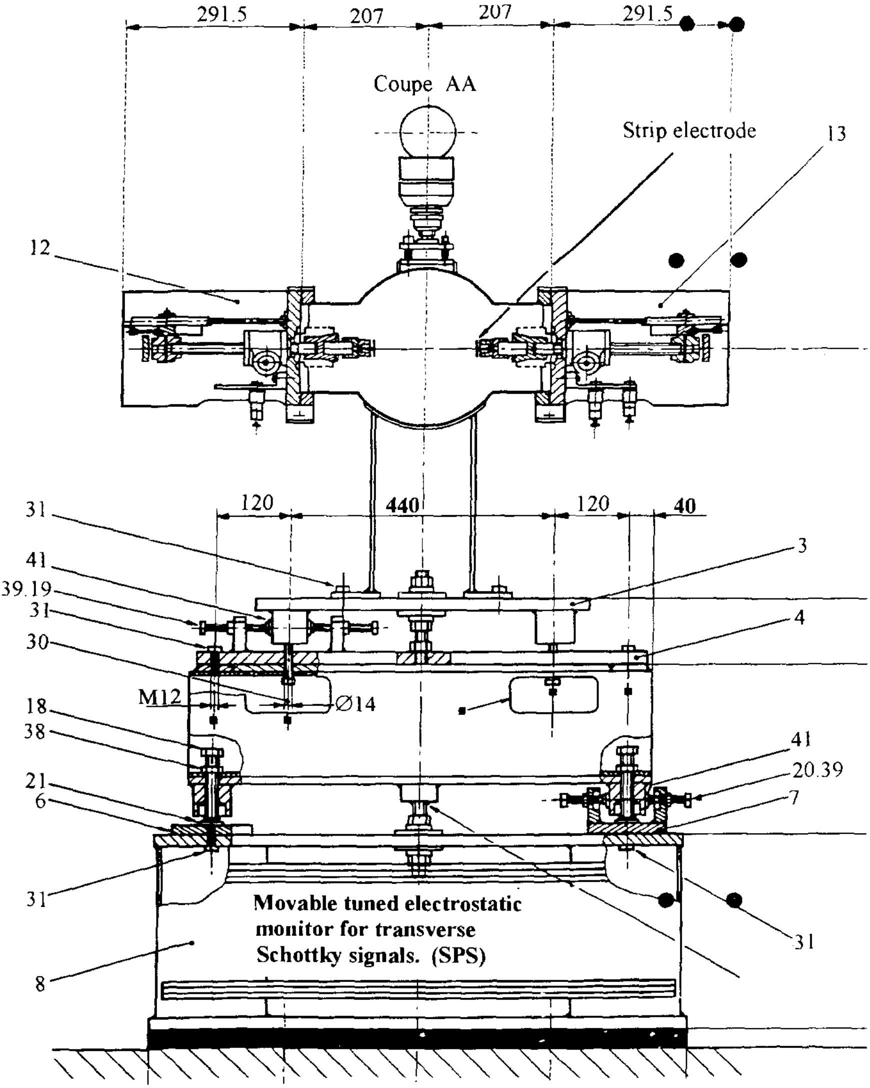

Figure 14. SPS Schottky pickup - [2].

In the cooler synchrotron and storage ring COSY-Julich - [13,14] the resonant tuning is made at each electrode with cables of $\lambda/4$-length and tuning capacitors - [15,16]. The length of the Schottky pickups is 4 meters-Fig.15. Low noise preamplifier with 50 Ω input impedance are coupled to the point of 50 Ω for power matching. The sum and difference signals are produced by 180^0 hybrid.The spectrum is measured either by spectrum analyzer or by FFT analyzer. For the latter case the signals are mixed down into the 0 - 100kHz frequency range of the FFT analyzer. The longitudinal Schottky spectrum is measured near 50 Mhz and the transverse Schottky spectrum is measured near 10 MHz.

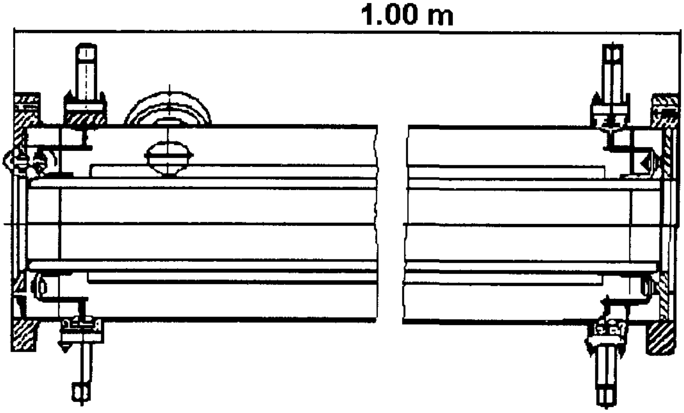

Figure 15. Mechanical layout of theCOSY stripline monitor.

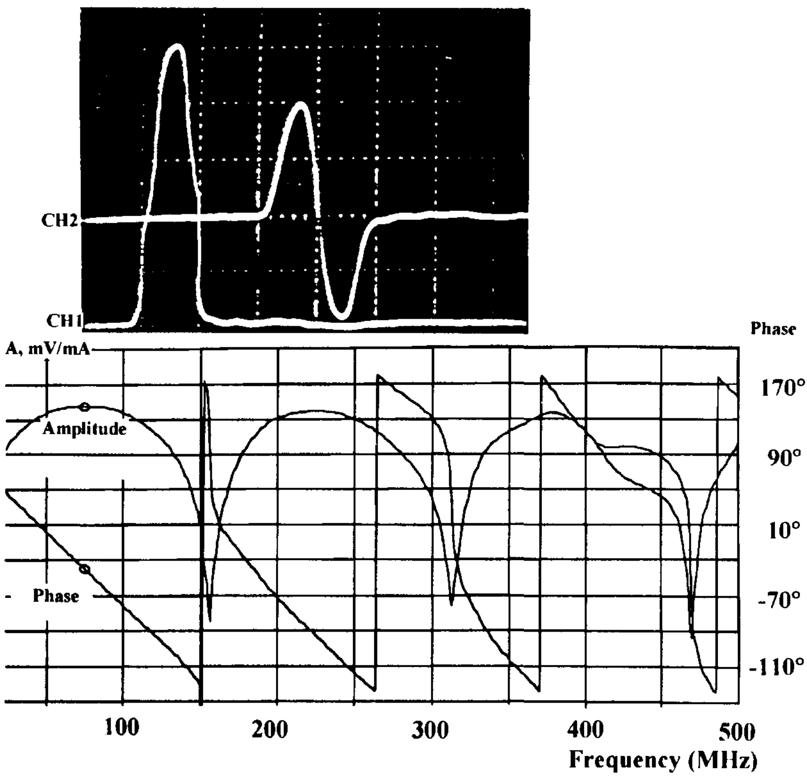

Figure 16. Response of the COSY Schottky pickup in time (a) and frequency (b) domain - [16].

The spectrum is recorded either by a spectrum analyzer or with an FFT-analyzer, which is much more fast and sensitive. The FFT-analyzer require frequency shifting down to 0 - 100 KHz by the usual heterodyning and mixing technique.

It is natural to sample and hold the Schottky signal at every bunch period. for the successive FFT. In this way one directly obtains the Schottky spectrum in the frequency range 0 to $f_0/2$.

The thermal noise of the amp [lifier:

$$V_{th,\,rms} = \sqrt{4kTBR} \tag{2.16}$$

where B is the filter bandwidth in Hz and R is the load (50 Ω). The thermal noise appears as a white noise in the output whereas the Schottky signal has a bandwidth determined by the machine conditions.

Repeated spectrum scan with signal averager will enhance the sensitivity of the measurement.

2.7. BEAM DIAGNOSTICS BY SCHOTTKY NOISE

When N is large the Schottky signal, proportional to $N^{1/2}$, is small compared to any coherent signal, which is proportional to N. However it is possible to observe the Schottky noise both on coasting and on bunched beams by menace of low-noise longitudinal and transverse pickups. A spectral scan of Schottky noise serves to monitor a lot of important beam parameters.

As we have seen in the transverse Schottky noise spectrum betatron sidebands for all harmonics of the revolution frequency nf_0 appear as result of modulation of the revolution frequency by the betatron oscillations.

From the distance of these betatron sidebands to the harmonic lines the non-integer part q of the Q-value can be determined and from their shape the emittance of the beam can be revealed.

If the machine parameter η is known the measurement of the power spectral density of the longitudinal signal in one particular Schottky band gives $\Delta p/p$ of the beam directly.

Comparing two betatron sidebands (n+q) and (n-q) in the transverse spectrum of a coasting beam Δq of the beam could be measured.

It follows from (2.6) and (2.13) that:

$$\frac{d_{rms}}{i_{rms}} = \frac{a_{rms}}{2} \tag{2.17}$$

which can be used to measure the transverse beam emittance.

3. BETATRON TUNE MEASUREMENT USING COHERENT EFFECTS

The Schottky signals are an incoherent sum of the individual particle signals and therefore are very small. The signal levels could be strongly enchanted if we force the beam with an external shock or sinusoidal excitation.

i.) A steady-state coherent beam motion can be excite by applying a sine-wave external force. The amplitude and phase response of the beam is measured by a downstream pickup and is called " beam transfer function " (BTF). This resonant excitation is made by a stripline unit. It is time consuming and is used for tune measuring under constant conditions- at the flat- top.

ii.) On the contrary a fast kicker magnet can produce a shock beam excitation. The resulting free oscillations of the beam could be measured by means of a BPM and the fractional tune q as well as other paramcters could be extracted. Such a δ-pulse beam excitation needs much less time and could be applied for tune measuring during the acceleration cycle.

3.1. BETATRON TUNE MEASUREMENT USING SHOCK BEAM EXCITATION

3.1.1. SHOCK BEAM EXCITATION

The principle of the shock beam excitation consists in exciting the beam particles to collective transverse oscillations by means of a fast kicker magnet. The resulting free oscillations -[17-19] are measured by a downstream BPM.

Let's first look at a monochromatic beam and therefore at a beam with a single betatron frequency ω_β (Q) The excited coherent betatron oscillations are:

$$y_n = A\cos(n2\pi Q + \phi) \tag{3.1}$$

where the amplitude of the oscillations is:

$$A = \sqrt{\beta(s)\varepsilon} \tag{3.2}$$

ε being the emittance of the kicked beam.

In fact the particles in the beam have different energies (momenta) and therefore different betatron tunes.

We will consider here an ensemble of particles with Gaussian tune distribution:

$$f(Q) = \frac{1}{\sqrt{2\pi}\sigma_Q} e^{-\frac{(Q-Q_0)^2}{2\sigma_Q^2}} \tag{3.3}$$

After averaging of the beam oscillations on Q one obtains that:

$$<y_n> = Ae^{-\frac{(n2\pi\sigma_Q)^2}{2}} \cos(n2\pi Q+\phi)+y_{CO} \tag{3.4}$$

where y_{co} is the closed orbit at the BPM azimuth.

In (3.4) $<y_n>$ is the displacement of the beam centre of mass, which is the only measured value.

Fig. 17 shows the response of a beam with Gaussian distribution of the betatron tunes to pulse excitation.

Fig. 18 shows the coherent beam oscillations of a beam with Gaussian distribution of the betatron tunes.

The phenomenon that a collection of lossless oscillators responds like a damped oscillator is well-known in the plasma physics and is called " Landau damping - [17-19].

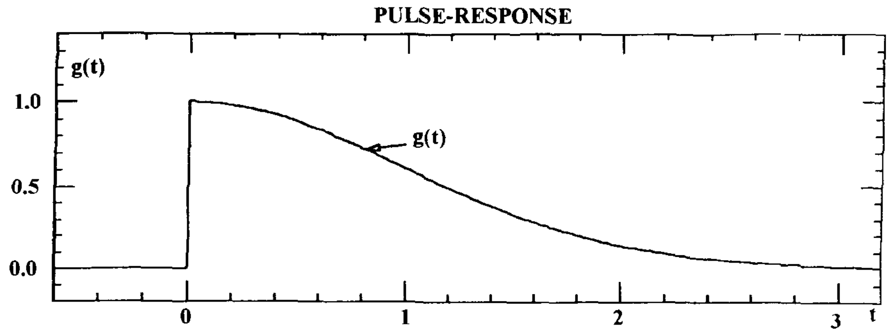

Figure 17. Response of a beam with Gausian tune distribution to pulse excitation - [17].

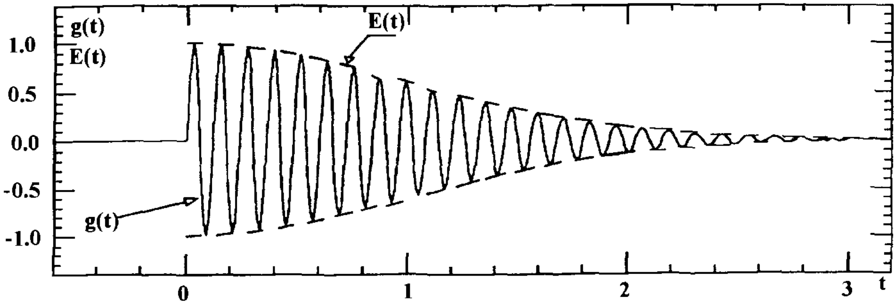

Figure 18. Coherent beam oscillations of a beam with Gaussian tune distribution - [17].

3.1.2. FOURIER SPECTRUM OF THE SHOCK EXCITED BEAM

It could be shown that the Fourier spectrum of the signal after a δ-pulse beam excitation (3.4) represents a series of amplitude modulated oscillations at frequencies $(n - q)\, f_0$ and $(n + q)\, f_0$:

$$y=\sum_{n}[A\frac{\Delta t}{T_0}\int_0^{\infty} c(\omega)\cos\omega t\, d\omega]\cdot[\cos((n+q)+\phi)+$$
$$+\cos((n-q)+\phi)] \tag{3.5}$$

where Δt is the time of passing in front of the BPM.

$$c(\omega) = \frac{1}{\sqrt{2\pi}\,\sigma_{\omega_\beta}} e^{-\frac{\omega^2}{2\sigma_{\omega\beta}}} \tag{3.6}$$

$\omega_\beta = Q\, \omega_0$ being the betatron frequency.

The fast Fourier transformation (FFT) of the signal (3.5) is of special importance.

According to the Nyquist's sampling theorem the maximum frequency in the spectrum of a continuous function discretely sampled at intervals Δt is:

$$f_C = \frac{1}{2\Delta t} \tag{3.7}$$

If we have N samples at $t_k = k.\Delta t$, k=0,1, . . . (N-1) then FFT gives N Fourier amplitudes at frequencies:

$$f_n = \frac{n}{N\Delta t}, \qquad n = 0,1,\ldots(N-1) \tag{3.8}$$

The first N/2 of amplitudes are independent whereas the last N/2 are related to them trough $H_{N-n} = H^*_n$.

$$H_n = \sum_{k=0}^{N-1} h_k e^{\frac{2\pi kn}{N}} \tag{3.9}$$

The successive frequencies in the FFT spectrum are spaced by:

$$\Delta f = \frac{1}{N\Delta t} \tag{3.10}$$

In other words (3.10) is the accuracy of the FFT analysis.

If we take the sampling time Δt equal to the revolution period of the reference particle - T_0, we obtain that:

$$f_C = \frac{1}{2} f_0 \qquad\qquad \Delta f - \frac{1}{N} f_0 \tag{3.11}$$

With such a bunch synchronous sampling the FFT reveals only the first line in the Fourier spectrum, namely that at $q.f_0 < 0.5.F_0$.

3.1.3. LONGITUDINAL SHOCK BEAM EXCITATION

In the longitudinal direction the beam is excited by means of a cavity, which produces shock energy modulation – [18]. .

The beam is excited through a cavity which is fed by a voltage pulse

$$U = U_0 e^{-i\omega t} \tag{3.12}$$

producing a sudden energy modulation. The frequency of the excitation is $\omega \approx n.\omega_0$. We assume that a harmonic voltage is applied to a single cavity during one turn of the machine.

We observe the free oscillations of the particles thereafter.

The beam response represents beam current oscillations with frequency $n.\omega_0$ and slow varying amplitude which is determined by the so-called Green function G(t) .

$$I_1(t) = -\frac{e\omega_0^2 \eta \Delta E_0}{\beta^2 E_0} sin(n\omega_0 t)\cdot G(t) \tag{3.13}$$

where ΔE_0 is the amplitude of the energy change during the beam excitation.

For Gaussian particle distribution in energy/revolution frequency:

$$F_0(\Delta\omega_r) = \frac{N}{2\pi\sqrt{2\pi}\,\sigma_\omega} \cdot e^{-\frac{\Delta\omega_r^2}{2\sigma_\omega^2}} \qquad (3.14)$$

where σ_ω is the rms width of the distribution the response to a pulse excitation is:

$$G(t) = -\frac{N}{2\pi\sqrt{2\pi}\,\sigma_\omega}\sigma_\omega t e^{-\frac{\sigma_\omega^2 t^2}{2}} \qquad (3.15)$$

3.1.4. TUNE MEASUREMENT BY SHOCK BEAM EXCITATION

The beam is short time deflected by means of a kicker magnet.

In the CERN PS booster - [20], the kicker is pulsed from a delay line to give rectangular pulses with a duration of 0.7 revolution period. The maximum kick amplitude produces 1mm betatron amplitude at 800 MeV. The kick can be repeated every 3 ms. The pulse length can be chosen from 0 to 1 of the revolution time in steps of 0.1.

In the cooler synchrotron and storage ring COSY in the Research centre Julich-[21], the kicker magnet is a window frame magnet with single turn bakable to 300^0 C and situated in UHV coils. It is loaded from 12.5 Ω (4x50Ω in parallel) pulse forming cables, resonantly charged to 33kV and discharged via thyratron switchers.

After the shock excitation the resulting free oscillations of the beam are observed.

The BPM sygnal can be treated either in time or in frequency domain.

A. In time domain.

The measured successive beam centroid positions at a single machine azimuth are LSQ fitted by the theoretical function (3.4). Accurate estimates of Q value and of many other key machine parameters can be obtained through this fitting. This method has been applied in many accelerators - [22-29].

In 800 MeV high intensity proton synchrotron ISIS which works as a neutron spallation source by means of chopper a very short injected pulses are produced - [22.23]. They have pulse lengths less than 100 ns, while the revolution period is $T_0 = 1.48$ μs.

Transverse positions of the beam centroid over 40 successive turns are measured. If the magnetic field is changed the argument of the cosine in (3.4) should read:

$cos(2\pi n(Q_0 + \frac{n\Delta Q}{2}))$, Q_0 being the initial Q value and ΔQ is the change of Q per turn. In this case we should add $n.\Delta y_{CO}$ to the closed orbit, Δy_{CO} being the closed orbit change per turn (if any).

In ISIS the Q value is measured by an accuracy of ± 0.002.

In the cooler synchrotron and storage ring COSY in the Research centre Julich -[24-29] the beam is short-time deflected for 0.75-2 μs. The kicker excitation is synchronized with the COSY rf signal and can be adjusted in time by a programmable delay. The BPMs Σ and Δ signals are digitazed by means of flash 20 MHz ADCs and stored in 64K FIFO memory. Up to 3200 successive turns can be measured. Fig 19 shows the kick-excited damped beam centroid oscillations around the closed orbit. Dots are the measured values from turn to turn whereas the solid line represents a fit for the damped oscillations assuming a gaussian tune distribution.

Fig.19 shows the damped coherent beam oscillations around a 9 mm closed orbit at COSY-Julich.

Fig.20. represents a comparison between the coherent oscillations amplitude at BPMs and the square root of the β-function values taken from a lattice code calculations (MAD).

Fig. 21 shows the emittance of the kicked beam deduced from the coherent oscillations amplitude with β-function values taken from a lattice code calculations (MAD).

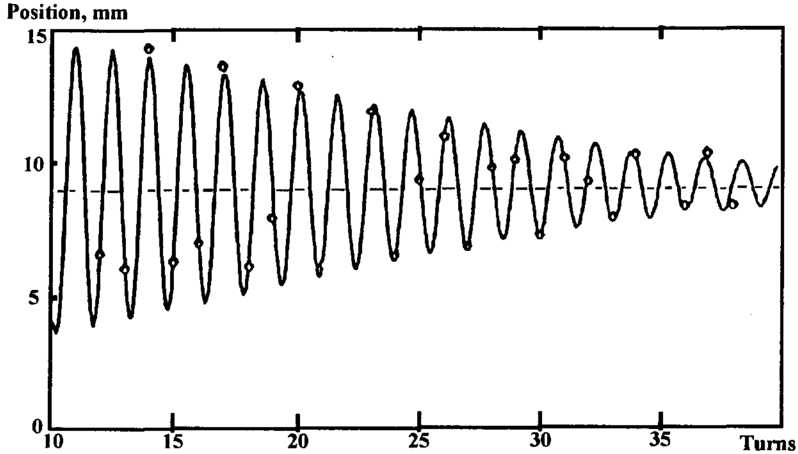

Figure 19. Damped coherent beam oscillations around a 9 mm closed orbit at COSY-Julich - [21].

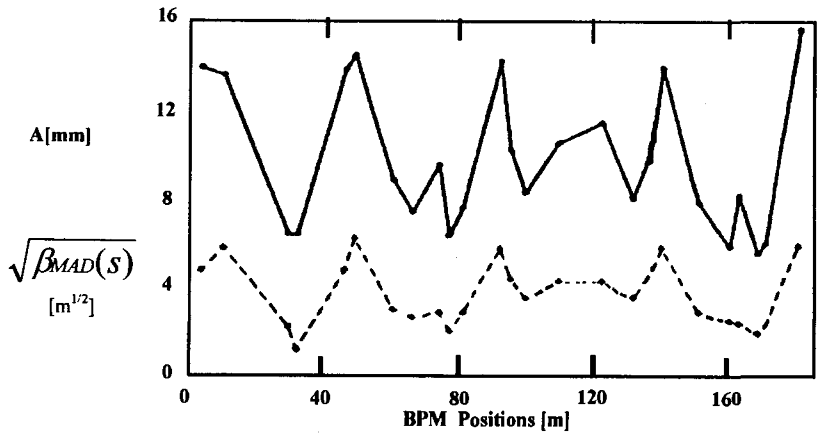

Figure 20. Cooler synchrotron COSY-Julich: comparison between the coherent oscillations amplitude at BPMs and the square root of the β-function values taken from a lattice code calculations (MAD) - [25].

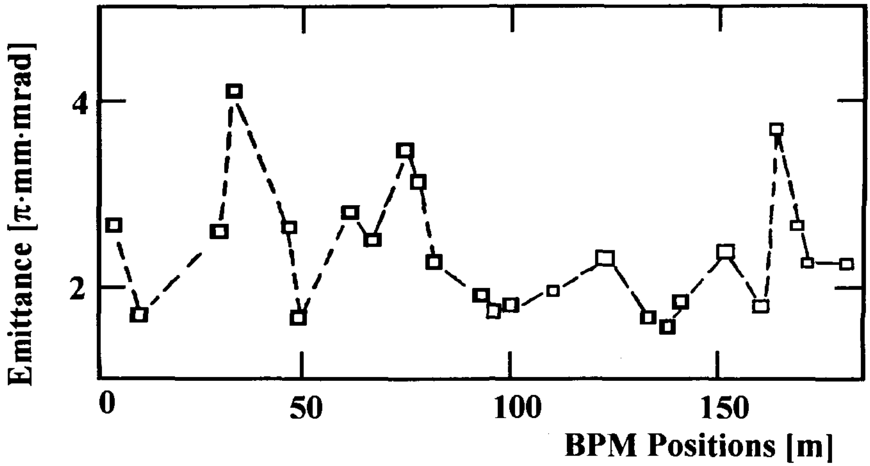

Figure 21. Cooler synchrotron COSY-Julich: emittance of the kicked beam deduced from the coherent oscillations amplitude with β-function values taken from a lattice code calculations (MAD) - [25].

B. In frequency domain.

On line tune measurement could be realized if we perform fast Fourier transformation of the turn-by-turn BPM signal.

An early realization of on-line tunemeter based on beam deflection by a kicker magnet is described in [30]. The principle of the measurements consists in performing FFT of the measured centre of charge positions with a beam itself as a clock. The electronic system consists of integrator, timing circuit, transient recorder which digitizes the signals and store them in 8 bits x 2048 words memory. In the cases when the timing pulse from the beam signal is very noisy the timing signal is taken from the RF system. Not only betatron frequencies but also coupling and damping have been measured.

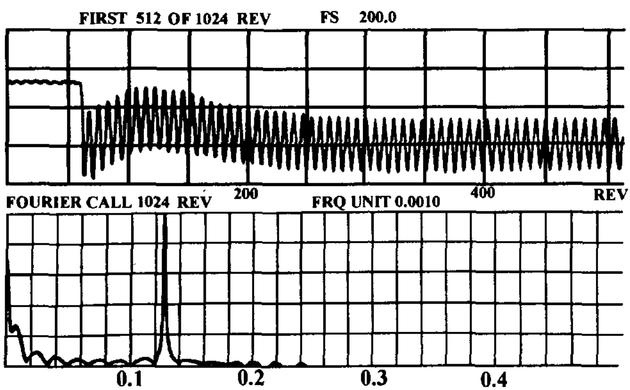

Figure 22. Upper- KEK booster free betatron oscillations for 512 turns, Lower- FFT of 1024 data points; q= 0.1270 - [30].

In CERN 28 GeV proton synchrotron CPS an automatic Q measurement system has been developed-[31] using δ-pulse beam stimulation and spectrum measurement by means of a swept filter. The system is shown in Fig. 23.

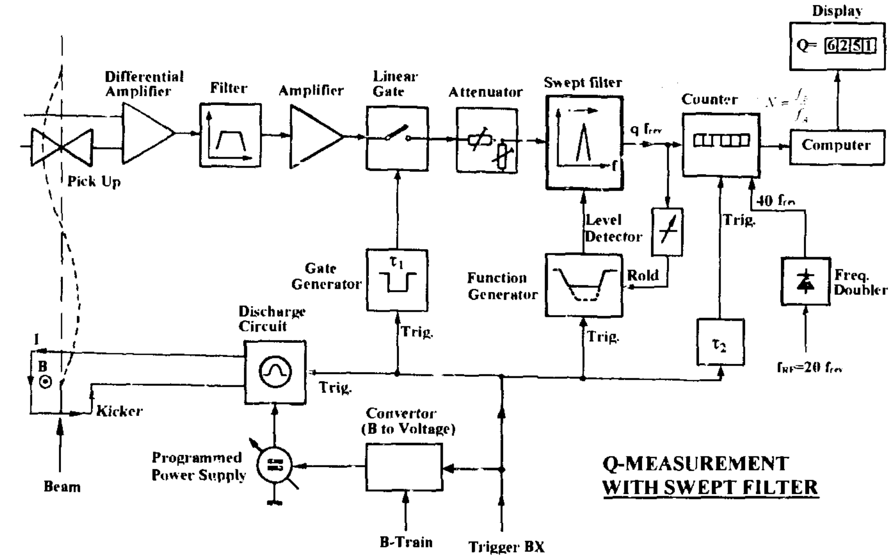

Figure 23. Block diagram of the CERN-CPS Q-meter system with swept filter - [31].

At the desired moment the beam is excited to 1mm betatron oscillations by kicker magnet. The kicker is fed by a half sine wave current produced by a discharge circuit. The position signal is measured by PUE. After amplification the PUE signal passes through a bandpass filter, which cuts low frequencies noise and frequencies higher or equal to the revolution frequency f0. The linear gate is open only during the measurement time, which is 0.8 ms. The heart of the electronic system is an active RC filter in which the resonance frequency is controlled by an external voltage that modulates the drain-source resistances of a FET pair. The filter frequency is moved with a ramp voltage produced by a function generator from 10 kHz to fmax = 250 kHz. The signal spectrum contains the frequencies $f= (n\pm q)f_0$, $n=0,1,2,...$ When the increasing filter frequency equals the lowest frequency of the pickup spectrum $f= q.\ f_0$, $n=0$ the level detector switches the filter and a signal appear at the output which contains the desired betatron frequency. A counter is triggered to measure the ratio of the betatron frequency $q.f_0$ and $f_{rf} = h.f_0$ (in CPS h=20).

In CESR, Cornel BTF is measured by means of a dual channel FFT spectrum analyzer - [32]. Since the revolution frequency in CESR is 390 kHz a heterodyne must be used to transfer the frequency of interest to the 0-100kHz input range of the analyzer.

In CERN SPS the beam is kicked every 60 ms - [33]. The beam response is measured and subsequently the data are Fourier analyzed to find the tune value. The beam is kicked by an electrostatic deflector of about 0.001 mrad at 315 Gev. The resulting beam response is measured by a Schottky detector for 256 turns and digdtised on each turn and stored in a memory. Then the beam position signals are read out and stored in the memory of a microprocessor, The data (about 200K) are process by a computer which performs a FFT to produce a frequency power spectrum. The computer search the spectrum for main and subsidiary peaks as the coupling between the horizontal and vertical oscillations often produces extra peaks in the spectrum.

The results of the measurement is displayed as a gràph of the tune versus time in the cycle.

The block diagram of the tune measurement system, called MULTIQ is shown in Fig.24.

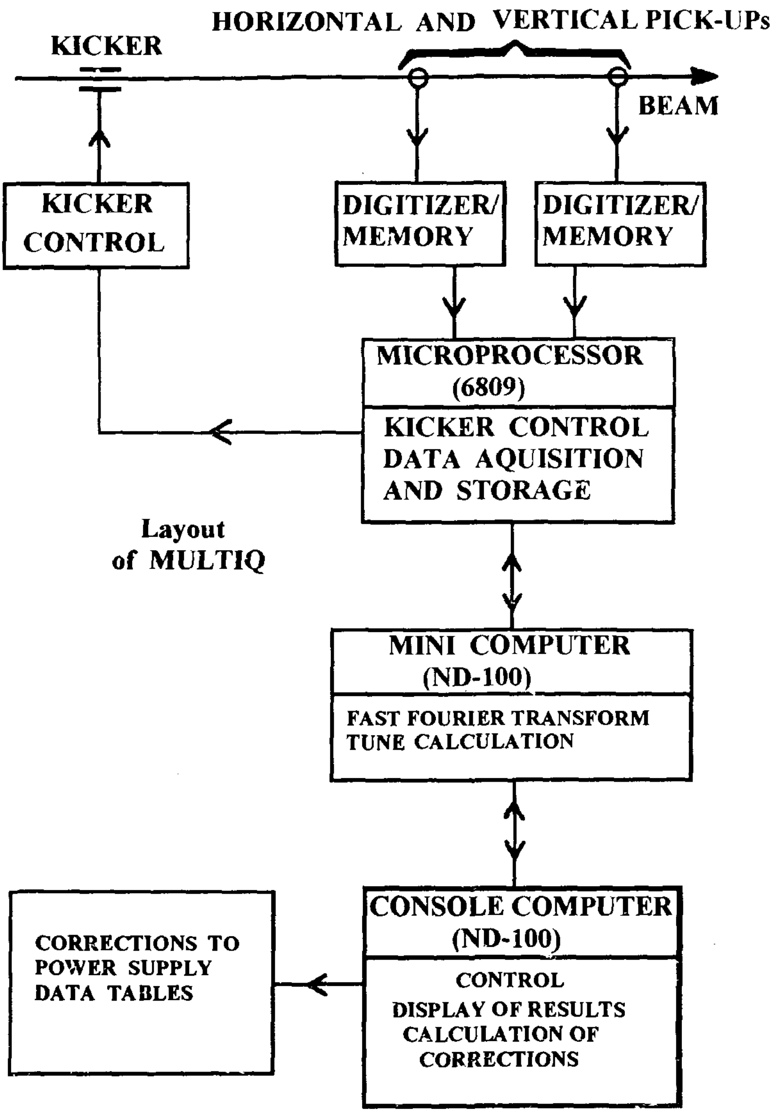

Figure 24. CERN-SPS MULTIQ tune measurement system - [33].

In synchrotron TRISTAN in KEK -[34] the on-line betatron tune measurement system is part of the automatic control system of the accelerator and it is based on both CAMAC and VME hardware and HP 9000 workstation. The software is based on Xwindows. The turn-by-turn beam oscillations in either horizontal or vertical phase space are measured by means of a phase-space monitor -[35], which provides information about the beam position and angle at one point in the ring..

The analog signals from the phase-space monitor are digitized by 12 bits buffered ADC and stored in memory. VME/OS-9 system realizes the connection between CAMAC and Ethernet parts of the hardware. VME system reads data every 40 ms from CAMAC and sends them to the Workstation. The results are shown in multiple windows. In one window the time domain picture of the damped beam oscillations is shown; the other window shows the phase portrait at a given azimuth; third window shows FFT spectrum of the monitors data; the fourth window shows the tunes over period of time.

Tune measurement with kick deflection of the beam has some disadvantages. The kicker magnet operates usually only in the horizontal plane. The electronics is rather complicated and needs a long recovery time. For that reason only one measurement can be performed within the machine cycle.

3.2. BETATRON TUNE MEASUREMENT USING SINUSOIDAL BEAM EXCITATION

3.2.1. BEAM TRANSFER FUNCTION

An generally more fruitful approach is to produce some external coherent stimulation of the beam and thus to enhance the signal intensity.

This approach leads to the definition of the so-called beam transfer function (BTF), which is one of the major characteristic of an accelerator-[2, 4-8,37,38].

Beam transfer function (BTF) is by definition the response (amplitude and phase) of the beam to an external sinusoidal excitation. The frequency dependence of the BTF is of interest.

The transverse excitation is done by a TEM travelling-wave kicker-Fig. 25, while the longitudinal excitation of the beam is done by a cavity-[8,9].

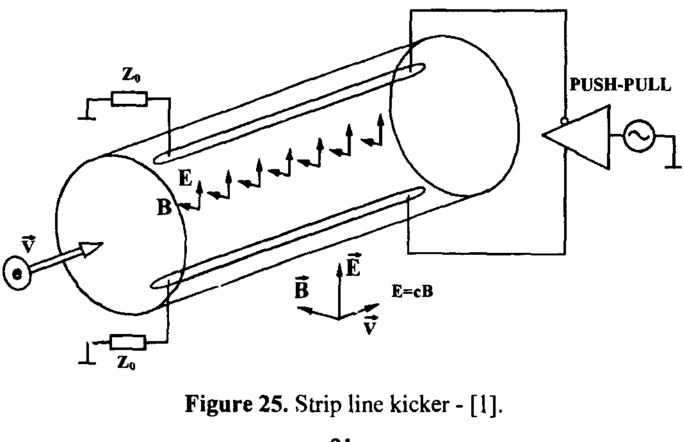

Figure 25. Strip line kicker - [1].

The driving signal is usually taken from the RF output of a tracking spectral analyzer - Fig.26. The frequency of this internal sinusoidal tracking generator is the same as the frequency displayed by the analyzer.

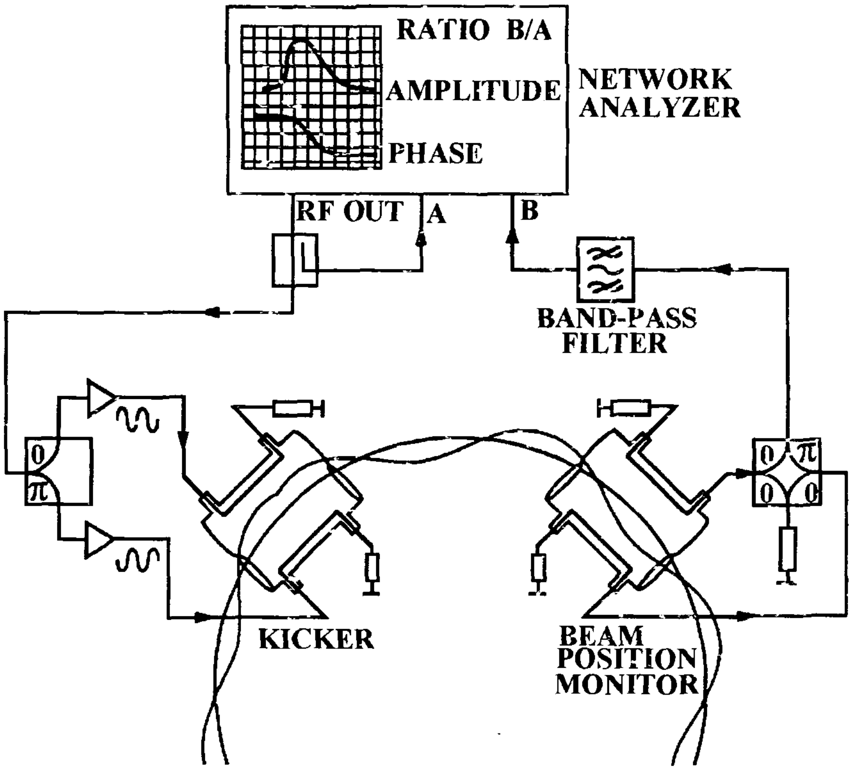

Figure 26. Principle of beam transfer function - [37] measurement by means of a tracking generator and network analyzer.

An alternative approach is to excite the beam with a white noise - Fig. 27. The noise applied to the kicker excites all betatron modes simultaneously. The beam response , which is also a noise, is then analyzed by a FFT analyzer and the N samples of the time signal are transformed into N/2 Fourier coefficients. FFT approach is much faster.

BTF gives important information about the beam behaviour (Q-value, betatron distribution) and its electromagnetic environment (the impedance of the complete vacuum chamber). The traditional BTF application is to monitor the stability margins.

From the instrumentational point of view, it should be underlined that the beam response and hence the monitor signals are proportional to N. This is a coherent response of the centre of mass of the beam. Thus we are dealing with signals much higher than the Schottky noise signals. In the same time the disturbance of the individual particle is proportional to 1/N i.e. it is very small. Hence the method is undistructive- [8].

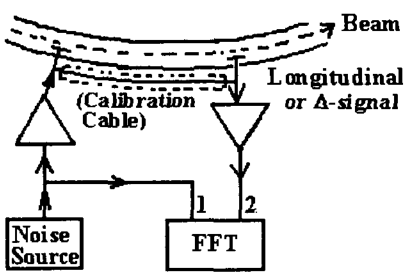

Figure 27. Principle of beam transfer measurement - [38] with noise excitation of the beam and FFT analyzer.

3.2.2. COASTING BEAM TRANSFER FUNCTION

The transverse beam transfer function (BTF) is defined as the ratio of the amplitude of the centre of mass velocity to the excitation.

$$r(\omega) = \frac{\dot{y}}{G\frac{\Delta\theta}{2\pi}} = r_r(\omega) + i \cdot r_i(\omega) \tag{3.16}$$

where Δθ is the azimuthal length of the shaker and G is the applied excitation. It is accepted to work with the applied acceleration (force acting on the unit mass) in the BTF definition ($G = \hat{G}\cos\omega_e t$). In (3.16) I denotes the imaginary unit.

The so-called dispersion integral ID is the inverse of the BTF.

Either slow waves with frequency:

$$\omega_{\beta S} = (k - Q) \tag{3.17}$$

or fast wave with frequency:

$$\omega_{\beta f} = (k + Q) \tag{3.18}$$

are excited by the sine - shaker, k being an integer.

We are interested not in the individual oscillations of the beam particles, but in the centre of mass motion. This is the only measured by BPMs value. For that reason we have averaged the individual responses in (3.16) over the distribution the betatron frequencies ω_β. This averaging is denoted by ugly brackets ' < > ' .

It can be shown that:

$$<\dot{y}>_{fast} = \frac{G\Delta\theta}{2\pi}(r_r\cos(\omega_e t) + r_i\sin(\omega_e t)) \tag{3.19}$$

where ω_e is the excitation frequency.

The resistive part of the beam response for the fast waves is:

$$r_r = -\frac{1}{2}\pi f(\omega_e) \tag{3.20}$$

where f(ω) is betatron frequency distribution function.

The reactive part of the beam response for the fast waves is:

$$r_i = -\frac{1}{2} \mathrm{P.V.} \int \frac{f(\omega_{\beta f}) d\omega_{\beta f}}{\omega_{\beta f} - \omega_e} \tag{3.21}$$

P.V. denotes Cauchy principal value of the integral.

The corresponding expressions for the slow waves is obtained by changing the sign and replacing $\omega_{\beta f}$ by $\omega_{\beta s}$

Thus BTF has a real part for which the velocity is in phase with the applied acceleration and the beam absorbs energy. The real part of the BTF is proportional to the betatron frequency distribution at the excitation frequency ω_e. The BTF also has an imaginary part for which the velocity and the applied acceleration are out of phase which means that there is no energy exchange.

Fig. 28 shows the beam transfer function for a beam with Gaussian frequency distribution.

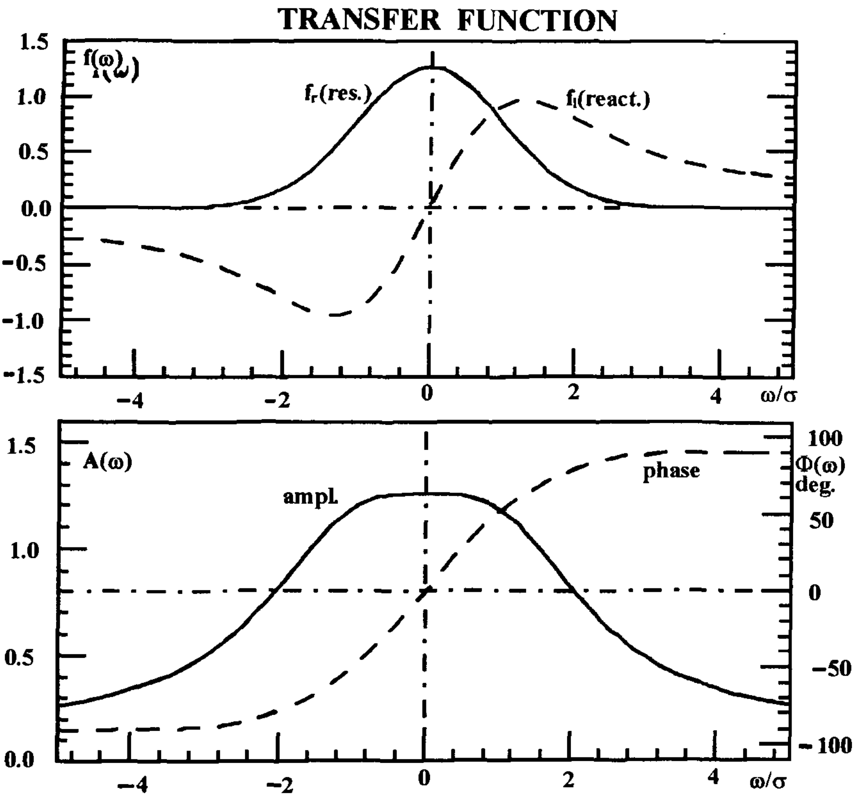

Figure 28. Beam transfer function for a beam with Gaussian frequency distribution-[17].

3.2.3. BUNCHED BEAM TRANSFER FUNCTION

The main difference with the coasting beam case is that an excitation of the beam at a frequency ω excites all frequencies $k\omega_0 \pm \omega$ because the bunched beam samples the frequency ω wave at the revolution frequency.The process is fundamentally nonlinear. The BTF is not defined in the general case.In some special conditions one can however define unambiguously BTF. For instance in the case of very small bunch to bunch coupling one can define a single bunch BTF for a given mode of oscillations - dipole, quadrupole etc- [7].

3.2.4. LONGITUDINAL COASTING BEAM TRANSFER FUNCTION

By definition the longitudinal coasting beam BTF is the response of the beam to a harmonic longitudinal (energy) excitation- [18].

The beam is excited through a cavity which is fed by a voltage pulse

$$U=U_0 e^{-i\omega t} \tag{3.22}$$

producing a sudden energy modulation. The frequency of the excitation is $\omega \approx n.\omega_0$.

The revolution frequency ω_r of the individual particles is related to their energy deviations ΔE through:

$$\Delta\omega_r=-\omega_0\eta\frac{\Delta E}{E} \tag{3.23}$$

With the help of the Vlasov equation one can obtain for the perturbed beam current: :

$$\hat{I}_1(\omega)=\frac{e^2\omega_0^3\eta U_0}{2\pi\beta^2 E_0 n}\left(\pm\pi\frac{dF_0}{d\omega_r}(\Delta\omega)+iPV\int\frac{dF_0(\Delta\omega_r)}{\frac{\omega}{n}-\omega_r}d\omega_r\right) \tag{3.24}$$

where:

$$\Delta\omega=\frac{\omega}{n}-\omega_0 \tag{3.25}$$

In (3.23) $F_0(\Delta\omega_r)$ is the frequency/energy distribution of the particles, ω_r is the revolution frequency of the individual particles and ω_0 is the revolution frequency of the reference particle.

The current:

$$I_1(t)=\hat{I}_1\cdot e^{-i\omega t} \tag{3.26}$$

induced by the excitation has a real and an imaginary parts. The real component of the current is in phase with the excitation voltage and absorbs power. This leads to damping of the oscillations, the so-called Landaw damping.

The imaginary part of the induced current is 90^0 out of phase to the excitation and does not lead to energy absorbtion and damping.

For Gaussian distribution in energy and revolution frequency:

$$F_0(\Delta\omega_r)=\frac{N}{\sqrt{2\pi}\sigma_\omega}e^{-\frac{\Delta\omega_r^2}{2\sigma_\omega}} \tag{3.27}$$

one can receive that:

$$\hat{I}_1(\omega)=\frac{e^2\omega_0^3\eta U_0}{(2\pi)^2\beta^2 E_0 n}\frac{N}{\sqrt{2\pi\sigma_\omega^2}}\left(-\pi\frac{\Delta\omega}{\sigma_\omega}e^{-\frac{\Delta\omega^2}{2\sigma_\omega^2}}-i\cdot P.V.\int\frac{\Delta\omega_r e^{-\Delta\omega_r^2}}{\sigma_\omega(\frac{\omega}{n}-\omega_r)}d\omega_r\right) \quad (3.28)$$

The principle value integral cannot be expressed in elementary functions.

Fig. 29 shows the response of a Gaussian beam to a harmonic excitation.

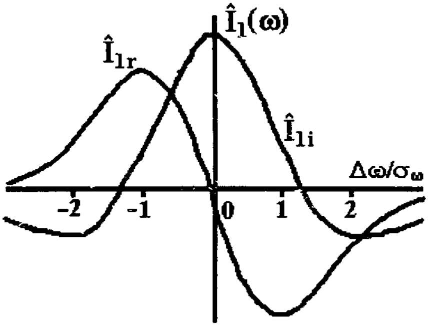

Figure 29. Longitudinal BTF of a Gaussian beam- [18]

3.2.5. TUNE MEASUREMENT USING BTF

Coherent betatron oscillations in horizontal or vertical directions can be exited by means of a stripline unit.

In CERN SPS a directional coupler is used. It allows preferential excitation of either proton or antiproton beams. With exciting power of 50 W kicks of 5.10^{-8} rad at 26 GeV/c are obtained- [12].

In the cooler synchrotron and storage ring COSY-Julich for 30 W output power the 50Ω stripline unit produces 10^{-7} rad beam deflection at 2.5 GeV-[40].

The betatron tune can be measured by resonant excitation of betatron oscillations.

The idea is to monitor the frequency of one of the betatron lines f_β together with the revolution frequency f_0. Then the tune q is calculated through:

$$f_\beta = (n \pm q)f_0 \quad (3.29)$$

As excitation signal the tracking signal of the spectrum analyzer can be utilized. An alternative approach is to excite the beam by white noise of an analogue noise source. The center frequency of the noise band should be shifted by mixer-electronics in order to reach the desired frequency range of the subsequent FFT-analyzer. Either selected sideband of the frequency spectrum during short time or the total frequency range during the accelerator ramp can be excited.

Performing iterative measurements by means of a 2-channel spectrum analyzer is time consuming. Much faster is the resonant excitation of the betatron oscillations by noise which is followed by FFT of the sampled beam centroid positions.

Fig. 30 shows the measured BTF and Fig. 31 shows measured vertical BTF in CERN - ISR. - [38].

Tunemeters for dynamical frequency measurement have been built on the base of the resonance beam excitation, digitizing the BPM signals by flash ADC and performing FFT of the data.

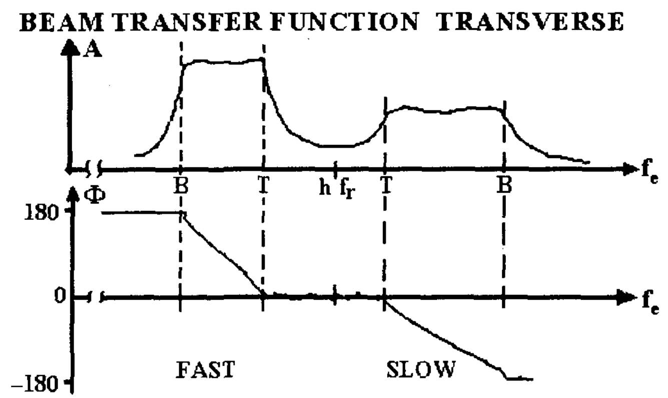

Figure 30. Transverse beam transfer function - [2].

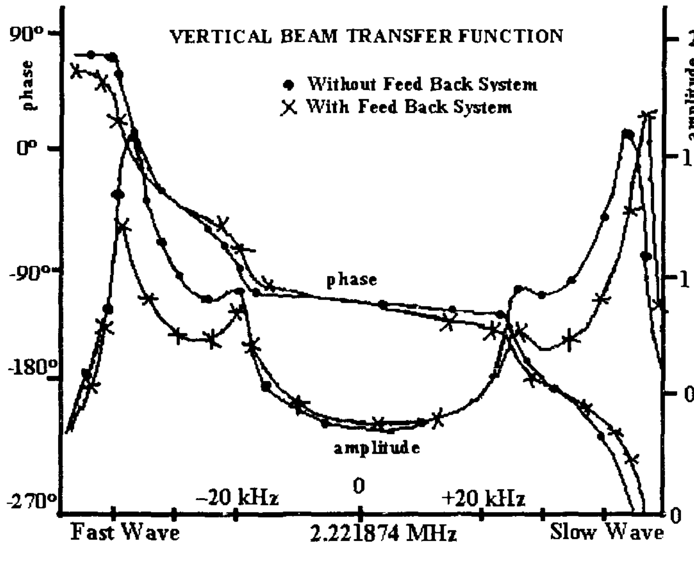

Figure 31. Vertical BTF at CERN ISR of 20 A stack at 26 GeV/c [38].

One example is the COSY - Julich dynamical tunemeter- [36]. After the beam excitation the maxima of the BPMs Δ- signals are digitized by flash ADC, as mentioned already above. Then Fast fourier Transformation of the signals is performed. The sampling is at frequency f_0 (revolution frequency). The synchronous with the bunch signal is taken from the Σ data of the same BPM. The data for N successive turns are then stored in a 512K FIFO memory. This data are later transformed by a FFT processor to FFT spectrum . The FFT spectrum contains only the first betatron sidebands with $f_\beta = q.f_0 < 0.5\ f_0$ .The value N determins the resolution of the FFT spectra, which is 1/(NT), where $1/T = f_{sampling} = f_0$.

Fig. 32 represents the block diagram of the COSY-Julich FFT tunemeter.

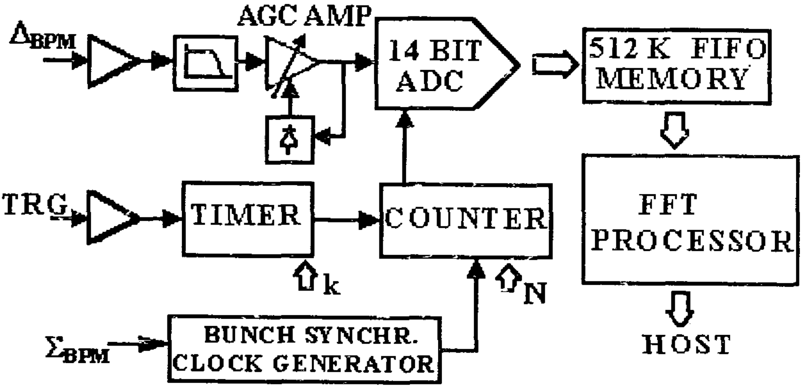

Figure 32. Block diagram of the COSY-Julich FFT tunemeter- [36].

Fig.33 depicts COSY-Julich FFT spectra with equidistant time steps. The sideband line is clearly seen. Dashed curve at the bottom represents the frequency ramp.

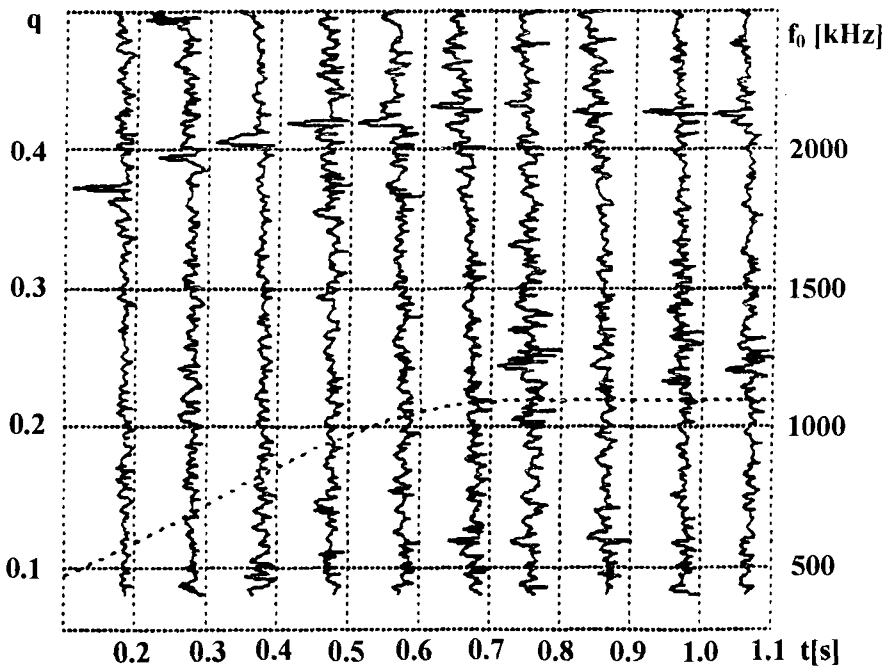

Figure 33. COSY-Julich FFT spectra with equidistant time steps. The sideband line is clearly seen. Dashed curve at the bottom represents the frequency ramp- [36].

By means of BTF measurement the horizontal-vertical betatron coupling can be measured - [41]. For this purpose the beam is excited in one plane while the BTF is measured in the complimentary transverse plain. BTF has been found to be a very efficient means of measuring the coupling and to minimize it- Fig. 34,35.

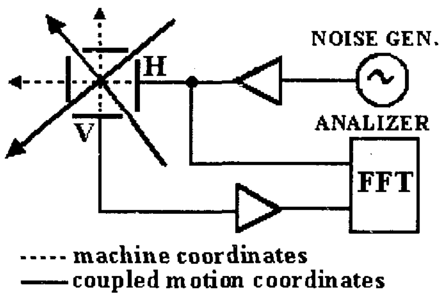

Figure 34. Schematic layout of a coupling BTF measurement - [41].

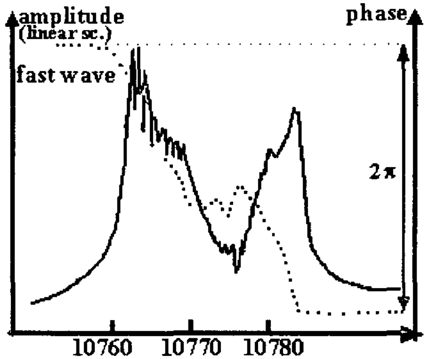

Figure 35. Coupling beam transfer function - [41].

3.4. CONTINUOS TUNE MEASUREMENT WITH PHASE - LOCKED LOOPS

The continuous tune measurement is an important feature of many accelerators. It is necessary when we change the machine energy or the lattice mode. Also it allows to measure the tune dependence on the time.

The tune measurement techniques with kick-deflection of the beam by means of a kickermagnet or with resonant excitation of the beam by means of a stripline unit and subsequent observing the BPM signal by 2-channel spectrum analyzer are both time consuming methods. Only one measurement per acceleration cycle can be carried out. Thus these kind of tune measurement require many machine cycles for revealing of the tune dependence on the time.

For continuous tune measurements the so-called phase-locked-loop (PLL) circuit is widely used - [8,42,43]

The principle of the tune measurement utilizing a phase-lock loop circuit consist in the following - Fig. 36.

The beam is resonantly excited by means of a stripline unit. The excitation signal is taken from a voltage-controlled oscillator (VCO). The frequency of the excitation is adjustable. The role of selective element is played by the beam .

The coherent beam response (BTF) is observed then by meanse of a pickup monitor. The phase of the coherent beam response (BTF) is measured by a phase detector and the frequency of the excitation is varied via the VCO until this phase reaches a preset value (usually $90^{0)}$.

At that point the VCO is locked through a feedback signal.After the phase lock the VCO frequency corresponds to the selected betatron sideband. Usually the PLL loop is locked to the first betatron sideband with frequency $f_\beta = q.f_0$ (n=0).

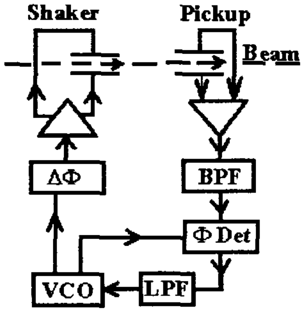

Figure 36. Principle of tune measurement withphase lock loop - [8].

As examples we will describe here two practical realizations of tune measurement PLL systems.

In the CERN SPS- [32], the chosen betatron line $f_\beta = (n+q).f_0$ is strongly enhanced by exciting the beam with a directional coupler. The PLL loop consists of an voltage-controlled oscillator (VCO) which excites the beam; a resonant Schottky pickup which detects the coherent beam response (BTF) and a feedback from this pickup to the VCO, which includes a phase detector. The excitation is 50 W at 10.7 MHz. The block diagram of the system is shown in Fig. 37 The tune measuring system has been used operationally with one bunch of protons in SPS.

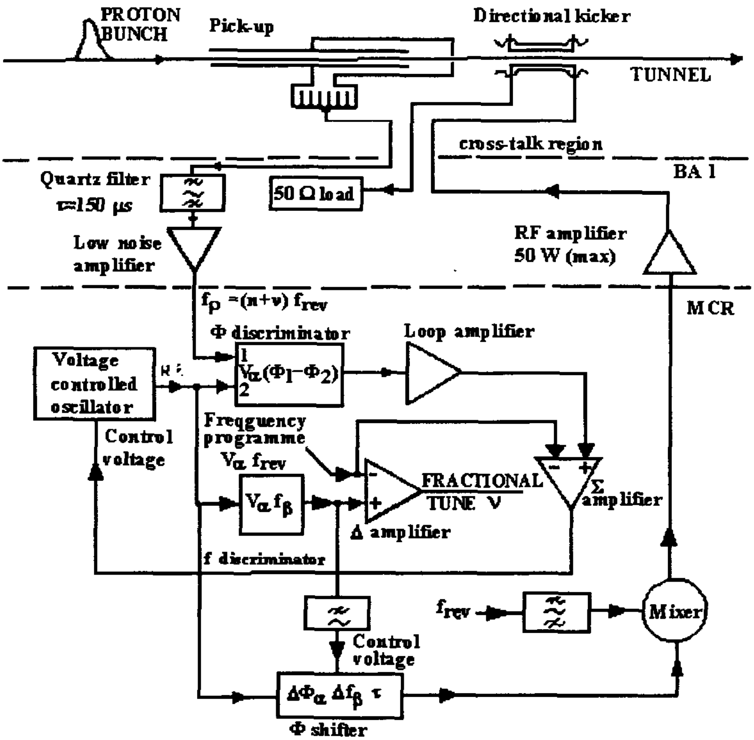

Figure 37. Block diagram of CERN-SPS continuous tune scan system - [32].

The signal from the Schottky detector (whit resonant frequency 10.7 MHz) is filtered by a quartz filter of bandwidth ± 4.2 kHz which rejects the coherent longitudinal (Σ) lines at $m.f_0$ adjacent to the selected sideband ($246.f_0$ and $247.f_0$).

The signal after amplification is sent to the main control room (MCR) where it is used as the phase-lock-loop reference signal.

The VCO provides a signal at 10.7 MHz which is compared in phase with the reference signal The phase error is amplified and used in the correction loop to control the VCO frequency.

In the cooler synchrotron and storage ring COSY - Julich a continuous tunemeter using a PLL technique is used -[36]. It block diagram is shown in Fig.38.

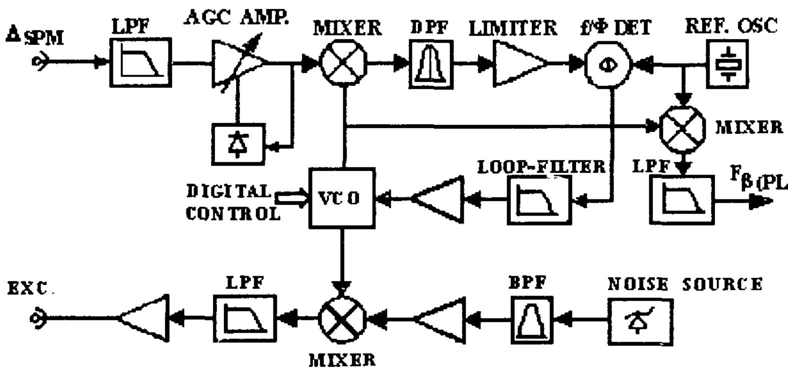

Figure 38. COSY - Julich tracking tunemeter - [36].

The system uses a narrow pasband filter with frequency 10.7 MHz which suppressed the noise to large extent. Therefore the first betatron sideband frequency $f_\beta = q.f_0$ must be converted to the constant 10.7 MHz frequency by means of a mixer.Hence the output frequency of the VCO is (f_β + 10.7 MHz).

Another mixer converted the frequency band of the noise source which is generally about 10.7 MHz down to the sideband frequency.

A third mixer surves to reveal the required sideband frequency by down conversion with 10.7 MHz of the VCO output.

The Q value is measured by means of a counter. The measuring time of the counter is preset to k. T_0=k. ($1/f_0$). It is determined by another counter, which counts k periods of the machine rf. The number k determines the accuracy of the tune measurement through $Z_{counter} = f_\beta .k/f_0 = k.q$.

4. NOTES ABOUT SIGNAL PROCESSING

Swept spectrum analyzers.

The swept spectrum analyzer represent a tuneable bandpass filter, whose central frequency is swept over the frequency range of interest. The bandwidth of the filter is adjustable - Fig. 39a.

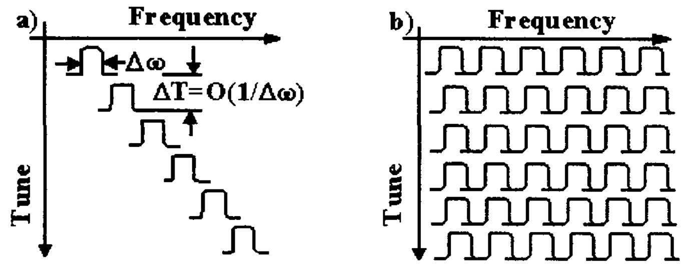

Fig. 39 Swept (a) and filter bank (b) spectrum analyzer operation - [48].

The output can be linear, square-law or logarithmic. It detects the rms amplitude of the input spectrum within the spectrum analyzer bandpass. Usually the swept spectrum analyzer has inbuilt tracking generator, which generates sinusoidal signal of the same frequency as the central frequency of the analyzer filter. This feature is useful for beam transfer function measurement.

If the swept spectrum analyzer displays both amplitude ratio and relative phase of the measured and reference signals it is called a network analyzer.

Let $\delta\omega$ be the resolution of the analyzer. The time for which the central frequency ω_0 passes through frequency interval $\delta\omega$ is called dwell time δt.

The analyzer averages the signal over the dwell time. As a consequence of this the longer the dwell time δt (i.e. the slower the swept), the more suppressed will be the noise.

From the uncertainty principle:

$$\delta\omega\delta t \sim 1 \tag{5.1}$$

Therefore the swept speed must be:

$$\frac{d\omega_0}{dt} \leq \delta\omega^2 \tag{5.2}$$

Let $\Delta\omega$ be the whole spectrum interval of interest. Let:

$$r = \frac{\delta\omega}{\Delta\omega} \tag{5.3}$$

be the spectrum resolution.

It follows that the time necessary to measure the frequency interval of interest is:

$$\Delta t \geq \frac{1}{r^2\Delta\omega} \tag{5.4}$$

For example if $\Delta f=\Delta\omega/2\pi=2$ MHz and $r=1/800$ we receive at least 50 ms measurement time. To this time we should add the other dead-times of the electronic system.

Often this time is too long for detecting the tune changes in time, especially in rapid cycling synchrotrons.

In order to enhance the signal-to-noise ratio many swept spectrum analyzers can average the results of several repeated sweeps.

The useful feature of a swept analyzer is that it can be stopped at a precise frequency. The analyzer then can display the time dependence of the signal within the selected band.

Between the latest swept spectrum analyzers is Rhode & Schwarz FESB30/FSEM30 spectrum analyzer.

Filter bank spectrum analyzer.

Tektronix 3052 Digital Signal Processing System uses 1024 bandpass filters operating in parallel - Fig. 39b.

The filters simultaneously measure the signal within their passbands to produce the entire spectrum at once.

The time required for spectrum observation is now:

$$\Delta t = \frac{1}{r \Delta \omega} \tag{5.5}$$

Tektronix 3052 takes 200 μs to measure 2 MHz spectral range with a resolution r=1/800.

Fig.40 shows the block diagram of the NSLS tune measurement system.

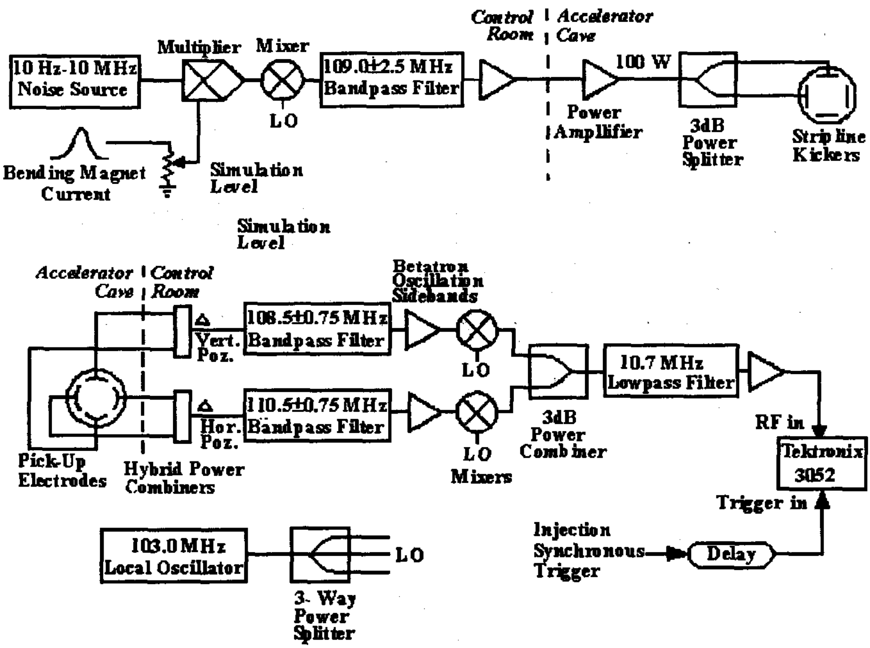

Fig. 40 NSLS tune measurement system.

FFT spectrum analyzer.

N signal samples during a time T are digitized and store in a memory. The data are process by fast Fourier transformation and the resulting spectrum is displayed. The sampling frequency is f_S = N/T.N/2 complex Fourier coefficients are calculated within a frequency range from DC to $f_C = N/2T = f_S/2$ (at least two samples per cycle are needed). The frequency resolution is $\Delta f = 1/T$.

As the whole spectrum is available at once the FFT spectrum analyzer is at least N/2 times faster than the swept spectrum analyzer.

The working range is usually 0 - 100 kHz, so additional frequency translation will be necessary. This is due to the limit set by the maximum digitizing rate.

FFT spectrum analyzer usually have two channels and a noise generator.

The frequencies outside the maximum Nyquist's frequency $f_C = f_S/2$ fall back to the frequency interval 0 - f_C, the so-called aliasing, which distort the spectrum. Aliasing effect could be reduced by appropriate filtering.

Single board digital signal processors (DSP) are available.

One example is Spectrum TMS320C30 Real-Time System DSP board. It performs 1024 point FFT, followed by a peak search. A voltage proportional to the found tunes is the output of the DSP board. The DSP board is used with a PC. The software is written in C, with SPOX application programming interface and can be modify. The DSP board is a user-friendly system.

Spectrum TMS 320C30 DSP has been used in the JUCF tune measurement system - Fig. 41.

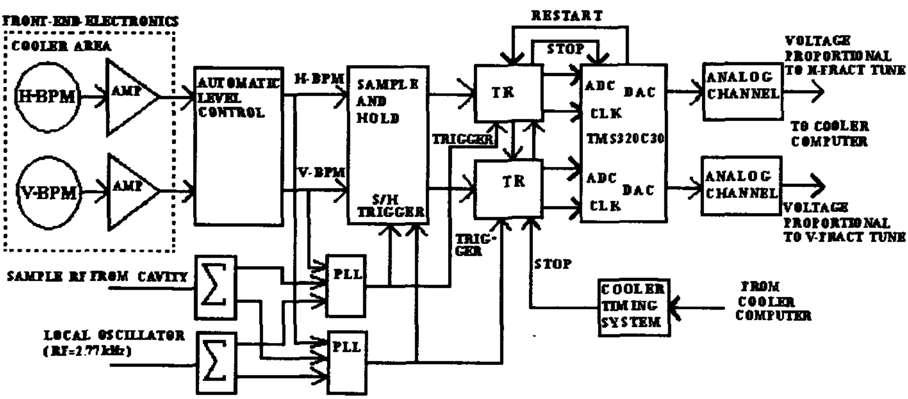

Fig.41. JUCF tune measurement system - [47]

Vector Signal Analyzer.

Hewlett Packard 89400 Series Vector Signal Analyzers is another powerful tool for spectrum measurement. It performs powerful and flexible digital signal processing. The family comprise three models: HP 89441A, which operates from dc to 2.65 GHz with enhanced sensitivity and dynamic range, HP 89440A, with coverage to 1.8 GHz; HP 89410 is for those concerned only with signals below 10 MHz and performs high-speed analysis of recorded or externally downconverted signals.

Features:

- dc to 2.65 GHz frequency range.
- Scalar and vector analysis modes.
- Full frequency coverage in spans to 2648 MHz.

- Exceptional speed and additional signal processing in RF mode for enhanced time-domain characteristics and demodulation.
- Vector RF mode capture phase and amplitude characteristics in time-series data.
- Optional digital radio and digital video demodulation.
- Frequency span in vector mode 1.0 Hz to 7 MHz.
- Frequency resolution 0.001 Hz.

HP 89441A covers baseband through RF frequencies of dc to 2.65 GHz in scalar and vector analysis modes. The scalar RF instrument mode allows full-frequency coverage in spans to 2648 MHz. Vector RF mode offers exceptional speed and additional signal processing for enhanced time-domain characterization. Vector spans as wide as 7 MHz can be selected anywhere in the 2.65 GHz range. In vector mode both phase and amplitude characteristics are captured in the time-series data.

5. CONCLUTIONS

The only completely non-destructive method for betatron tune measurement is the observation of the natural Schottky noise. If this weak signals are averaged over a long enough time the tune can be revealed from the positions of the betatron sidebands in the transverse Schottky spectrum.

The signals can be enhanced by coherent excitation of the beam, either shock or sinusoidal, but this makes the method more or less destructive.

Thus kicking of the beam is accompanying by unvanted effects such as emittance grouth, particle loss and increase of the background in the experimental area. In this circumstances the tune measurement may only be done during the machine setting-up time.

The more sensitive the BPMs the less kick strength is required.

For that reason in many machines pickups used for Schottky noise observation are used also for tune measurement by means of external beam excitation. As a rule these are resonant units with long (4 m) electrodes. In CERN SPS where highly sensitive Schottky pickups are used for measuring the centre of mass positions kicks smaler than 10^{-8} rad are sufficient for the tune measurement. With this small amplitude of the kick the intensity loss during the cycle is less than 0.5 % and emittance grouth is less than 2.5 %.

The shock beam excitation can be realized in either time or frequency domain.

Fitting of the time signal by the theoretical curve could deduce a great deal of information about the beam dynamics.

In the frequency domain the turn-by-turn beam centroid positions are processed by fast Fourier transformation with the beam itself as a clock.

Tune measurement with kick deflection has some disadvantageous. Usually the kicker magnet can deflect the beam only in the horizontal plane. The kicker electronics is rather complicated and neads a long recharge time. Only one measurement can be performed within the machine cycle. The dependence of Q on time must be revealed for a number of cycles.

The sinusoidal beam excitation can be done either by the signal of a tracking generator or by white noise sourse. In the latter case all the frequencies in the spectrum range of interest are excited simultaneously. For data processing FFT spectrum analyzer which measure the spectrum much faster than the 2-channel swept spectrum analyzers is used. Furtheremore the FFT technique allows the measurement by low level noise excitation of the beam.

FFT analyzer approach is almost real-time.

Coherent beam excitation with a sinusoidal signal with varying frequency and utilyzing a phase-lock loop circuit is a wide-spread method for betatron tune measurement. It allows dinamical tune measurement to be carried out.

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