EVALUATION OF STRIP-LINE PICK-UP SYSTEM FOR THE SPS WIDEBAND TRANSVERSE FEEDBACK SYSTEM

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Abstract

The proposed SPS Wideband Transverse Feedback system requires a wide-band pick-up system to be able to detect intra-bunch motion within the SPS proton bunches, captured and accelerated in a 200 MHz bucket. We present the electro-magnetic design of transverse beam position pick-up options optimised for installation in the SPS and evaluate their performance reach with respect to direct time domain sampling of the intra-bunch motion. The analysis also discusses the achieved subsystem responses of the associated cabling with new low dispersion smooth wall coaxial cables, wide-band generation of intensity and position signals by means of 180 degree RF hybrids as well as passive techniques to electronically suppress the beam offset signal, needed to optimise the dynamic range and position resolution of the planned digital intra-bunch feedback system.

INTRODUCTION

Transverse motion is caused by impedance and electron cloud driven instabilities, in particular in the vertical plane in the SPS and represents a limitation to the bunch intensity and therefore the performance of the SPS as injector for the High Luminosity Upgrade of LHC [1].

The proposed High Bandwidth SPS Transverse Feedback System requires that the internal bunch transverse motion of a proton bunch is sampled at several GS/s. The task of the feedback is to damp this internal motion within an analog bandwidth in excess of 1 GHz [2]. In the framework of the SPS for the LHC Injectors Upgrade Project (LIU) development of a prototype system has started using an existing exponentially tapered stripline as pick-up and an identical stripline as kicker.

In the following we will first look at the existing pick-up system and analyse limitations relevant to the transverse feedback system followed by design guidelines for a new pick-up.

OPTIONS FOR PICK-UP

Stripline pick-ups are widely used in accelerators today and represent the most simple approach to resolving in time domain the internal bunch motion [3]. As the requirement is to cover a bandwidth from the very low frequency end up to beyond 1 GHz, button pick-ups and slotted pick-ups, the latter frequently used for stochastic cooling systems, have either a strong dependence of the amplitude on frequency or phase on frequency over the desired range of frequencies. A slotted coaxial structure has been proposed as kicker for this system as an option in the future [4].

In a matched homogenous stripline with constant impedance and coupling to the beam, the signal extracted at the upstream port is composed of two pulses, separated in time corresponding twice the length of the stripline. The first pulse is generated directly at the upstream port where time domain direct sampling yields the bunch internal motion. Untreated, the second inverted pulse generated at the downstream port creates notches in the frequency response. In time-domain this is typically suppressed through gating on and measuring only the first pulse, which produces a flat frequency response within the bandwidth of the strip-line.

The wide-band feedback tests used an exponentially tapered strip-line in the SPS [3, 5, 6]. The strips are exponentially tapered both in width and distance to the vacuum chamber in order to maintain a 50 Ω characteristic impedance. This tapering suppresses the secondary pulse. This stripline has a length of one quarter of an RF bucket (200 MHz) so that for a bunch length of 2.5 ns signals from two adjacent bunches remain completely separated. However, a drawback of the tapering is that both the amplitude and phase response are non-linear. The varying delay with frequency can be compensated electronically [7].

Optimisations of the tapered pick-up consist of changing the width (i.e. beam coupling) in a different way so as to reduce the amplitude ripple. As an example, pick-ups with linear coupling have successfully been built and were recently tested at CERN [8]. With their simple triangular shape they are easier in the manufacturing, and with a steeper low-frequency roll-off w.r.t. exponentially tapered striplines their improved low frequency reach is an attractive variant of tapered pick-ups.

Another alternative is a resistive wall pick-up as described in [9].

Alternatively, wide-band electro-optic and synchrotron-light-based beam position monitors are being studied, that aim at providing bandwidth in excess of 12 GHz [10].

SIGNAL FROM PICK-UP PLATES

A transverse beam position monitor system determines the beam position from a difference of two signals in a usually perfectly symmetric structure in which the beam induces a voltage depending on the dipole moment of the beam, i.e. $charge \times displacement$ or $current \times displacement$. The difference is usually generated with

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a hybrid which we will assume for the moment to be perfectly generating the sum (Σ) and the difference (Δ) signals.

The time varying voltages $V_\mathrm{a}(t)$ and $V_\mathrm{b}(t)$ before the hybrid induced by a beam offset by x_0 in the pick-up and oscillating in time $x(t)$ can be expressed by

$$V_\mathrm{a,b}(t) = Z_\mathrm{T} \int_{-\infty}^{t} \left(1 \pm \tfrac{x_0}{2d} \pm \tfrac{x(\tau)}{2d}\right) \times q\lambda(\tau) c_\mathrm{a,b} h_\mathrm{a,b}(t-\tau)\,\mathrm{d}\tau \qquad (1)$$

where the factor d accounts for the position sensitivity of the PU, and h_a and h_b are the impulse responses of the system before the hybrid, including cabling and PU transfer characteristics differences between the two sides. Index a refers to one side of the pick-up using the upper sign and b to the other side. Z_T denotes the nominal transfer impedance of the pick-up (single sided) and $\lambda(t)$ a normalised bunch shape distribution.

The difference voltage after an ideal hybrid follows from

$$V_\Delta = (V_\mathrm{a} - V_\mathrm{b})/\sqrt{2} \qquad (2)$$

Assuming the two sides of the pick-up are identical and the transfer functions match

$$h_\mathrm{PU}(t) \equiv h_\mathrm{a}(t) = h_\mathrm{b}(t) \qquad (3)$$

the coefficients c_a and c_b can be chosen to cancel the term related to the offset of the beam

$$c_\mathrm{a,b} = \frac{1}{1 \pm \frac{x_0}{2d}}\ . \qquad (4)$$

For the difference voltage one obtains

$$V_\Delta(t) = \frac{1}{1-\frac{x_0^2}{4d^2}} \frac{Z_\mathrm{T} q}{\sqrt{2}} \int_{-\infty}^{t} \lambda(\tau) \frac{x(\tau)}{d} h_\mathrm{PU}(t-\tau)\mathrm{d}\tau \quad (5)$$

which only has a small dependance on the absolute position x_0 of the beam and in a feedback system would only influence the gain, by a small amount.

SPS EXPONENTIALLY TAPERED PICK-UP

For transverse beam observations the SPS is equipped with four exponentially tapered striplines. These have a length of 375 mm corresponding to a quarter of a period of the 200 MHz SPS main RF system such that the signals from adjacent bunches do not overlap in time domain (for bunch lengths shorter than 2.5 ns).

There are four electrodes at $\pm 45°$ to the horizontal plane, the signals of which can be combined to have either a horizontal pick-up or a vertical pick-up. A single strip has a transfer impedance of $Z_\mathrm{T,s} = 4.39\ \Omega$ and when combined using an ideal hybrid each pair has $Z_\mathrm{T} = \sqrt{2} Z_\mathrm{T,s} = 6.21\ \Omega$.

In practice we use a resistive combiner so that the combined transfer impedance of a pair of strips is reduced to the single strip transfer impedance of $4.39\ \Omega$. The peak voltage without further attenuation for a bunch of charge 10^{11} and a 4σ bunch length of 2.5 ns is 44.8 V. The signal amplitude is reduced by a fixed value of 9 dB of attenuation, 6 dB at the level of the pick-up to improve matching and 3 dB on the surface installed as a protection. The resulting voltage peak amplitude of 15.9 V is then still further reduced by cable losses and dispersion by a factor 0.595 to 9.5 V. The voltage from each pair of strips passes through a variable delay to the hybrid that calculates the sum and difference signal (+3 dB). Taking into account the insertion losses of 1.4 dB results in a voltage peak amplitude of 11.9 V.

With the installation of a new pick-up in the SPS also new low dispersion smooth wall coaxial cables are installed. The new pick-up location allows for shorter cables of only 182 m (the current cable measures 291.7 m). With a length difference of 110 m and thus considerable lower losses these cables have a transmission factor of 0.714 which is a gain of 20% with respect to the existing cables. As outlined in the transfer function plot in Fig. 1 one identifies a phase retarding effect $\propto f^3$ [11]. This is probably attributed to losses in the dielectric material.

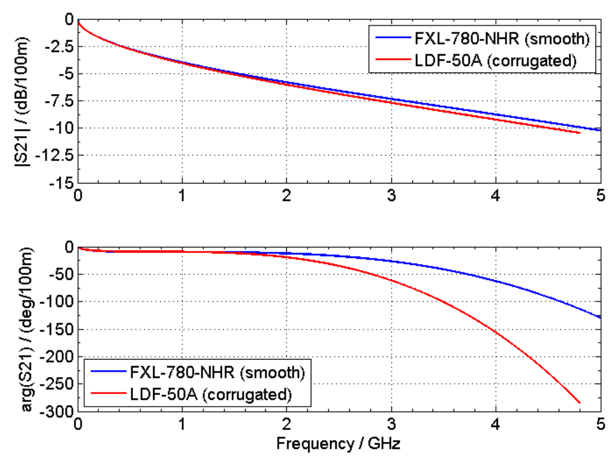

Figure 1: Comparison of new 7/8-inch smooth wall transmission line vs. typical coaxial cable with corrugated outer conductor.

Each electrode at $\pm 45°$ senses both the horizontal and vertical position reduced by a factor $1/\sqrt{2}$, however, when combined to a pair of strips the odd components cancel. Taking this geometrical factor into account one obtains for $d = 19.5$ mm and a peak difference signal of 0.3V for a 1 mm deviation.

IMPACT OF IMPERFECTIONS

Having a good isolation between the strong sum signal and the difference (11.9 V on the sum signal vs. 0.3 V on the delta signal) is of great interest for the performance of the receiver circuit. Amplitude and phase bal-

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ance, crosstalk of the sum signal to the difference signal port, and imperfect matching can be limiting factors for the performance of a beam position monitor system.

Imperfect Attenuation

For the case of non matching attenuation where one branch deviates from the otherwise identical transfer function by a factor $h_{\mathrm{PU}} \times (1-k)$ one obtains for the difference voltage (here $c_{\mathrm{a}} = c_{\mathrm{b}} = 1$)

$$\begin{aligned} V_\Delta(t) &= \frac{Z_{\mathrm{T}} q}{\sqrt{2}} \times \int_{-\infty}^{t} \lambda(\tau) h_{\mathrm{PU}}(t-\tau) \\ &\times \left[k + \frac{x_0 + x(\tau)}{d} \left(1 + \frac{k}{2}\right) \right] \mathrm{d}\tau \,. \qquad (6) \end{aligned}$$

The non matching attenuation between the two branches introduces a fake position signal that is proportional to the amount of mismatch k. For example a difference of 0.1 dB in attenuation causes a faked position reading of ≈ 1 %.

The additional factor $k/2$ scales the position reading and consequently affects also the gain in the feedback system.

Delay Mismatch before Hybrid

Consider the voltages (phasors) to have slightly different delay and attenuation

$$V_{\mathrm{a,b}} = (1 \pm a) V_0 \times e^{\pm j \Delta\phi/2} \,. \qquad (7)$$

The difference signal will become

$$V_\Delta \equiv \frac{V_a - V_b}{\sqrt{2}} = \frac{V_0}{\sqrt{2}} \left[2a\cos(\Delta\phi/2) + j2\sin(\Delta\phi/2) \right] \qquad (8)$$

A delay mismatch in the two branches generates a fake position reading. A phase difference of 1° gives an error $|V_\Delta / V_0|$ of about 1%. This number roughly doubles for 0.1 dB attenuation added per branch.

Imperfect Pick-Up Response

Assuming a perfectly centred beam in the pick-up it follows from (2) and with $x_0 = x(t) = 0$ that any discrepancies in the impulse responses h_{a} and h_{b} result in an error signal $e_\Delta(t) = h_{\mathrm{a}}(t) - h_{\mathrm{b}}(t)$. This spurious signal is most disturbing when it appears within the wanted bunch signal (5 ns RF bucket). In particular imperfections of the pick-up electrodes fold directly into the bunch signal.

The main sources for spurious signals are local deviations in the stripline height provoking signal reflections that cause an additional beam signal to be induced. Both effects are less critical in case the height transitions are smooth and are not very localised.

The matching of each of the four electrodes of the wideband exponential pick-up BPWA 321.01 in the SPS was measured (S11) in time domain. The responses were found to be approximately similar and in the same order of magnitude, with reflection coefficients less than 8%.

At this point it is worth noting that for a known electrode width one can determine the pick-up impulse response also from a measurement of the stripline matching. It can be shown that by computing the local line height from S11 the coupling function can be extracted, and the impulse response following as the time derivate of half the coupling function.

Imperfect Hybrid

The RF 180° hybrid junction has four ports and generates the analog equivalent of a sum (Σ) and difference (Δ) signal of the two input electrodes.

The H-9 is a commonly used wide band hybrid and is specified for operation between 2 MHz and 2 GHz and can support up to 5 W input power [12]. The hybrid ferrites may saturate for high peak power, which in turn may add as spurious ringing to the delta output. For a typical application with bunch length 2.5 ns and a charge of 10^{11} protons one would expect a peak power of 2.88 W, however, for shorter bunch lengths more attenuation on the input is recommended.

Figure 2 shows the nominal transmission and common mode rejection of a tested batch of H-9 hybrids. The transmission of the common signal from the hybrid inputs (A) and (B) to the sum output indicates an insertion loss of better than 0.5 dB below 200 MHz. This factor is largely independent of the bunch length since most of the beam spectral power of a typical SPS bunch with $4\sigma = 2.5$ ns is below 500 MHz where the attenuation is reasonably flat.

As indicated in the bottom plot of Fig. 2 the expected crosstalk between Σ and Δ has considerable scatter among different hybrids of the same type, the values varying in the order of 10 dB.

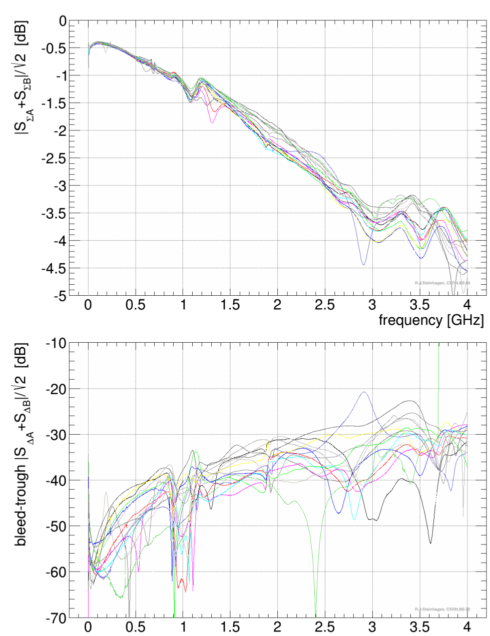

Figure 2: Measured attenuation (top) and crosstalk (bottom) of a set of H-9 Hybrids showing significant spread.

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From measured S-Parameters the normalised mode conversion calculates to $\kappa = (S_{41}+S_{42})/(S_{41}-S_{42})$ which is a measure for the cross talk – or, how much of the common signal relative to the differential signal is visible at the difference output. The normalised cross talk appears slightly higher due to the losses in the hybrid. The underlying high-pass characteristic in the response to mode conversion suppresses to a great amount the dominant beam spectral power at lower frequencies (assuming Gaussian distribution) leaving the mode conversion for a typical hybrid from Σ to Δ to below 0.7% for a bunch lengths of 4σ=1.0 ns. More generally, all evaluated hybrids were found to be below 1.5 % for the same bunch length.

Other hybrid options are for example the H-183-4 [13], with a slightly higher operation range from 30 MHz to 3 GHz and comparable characteristics with the H-9, or a custom built multi-octave RF hybrid design with lower frequency range (4 kHz to 400 MHz) [14]. According to [14], the upper frequency could be further pushed by an octave when using dedicated ferrite materials.

OPTIMUM SUPPRESSION OF COMMON MODE SIGNAL

The dynamic range of the planned intra-bunch feedback system is reduced when the sampling ADC has to cope with additional bias voltages originating from closed orbit offsets in the pick-up. As shown in (6) this biasing term can be suppressed by selectively attenuating the signals before the hybrid. Evaluating the values for $c_{\mathrm{a,b}}$ suggests an attenuation range of -2.0 dB to +2.6 dB for ± 10 mm displacement, or equivalently 0.2 - 0.26 dB/mm depending on side. As suggested above using a step size of 0.1 dB requests for 46 steps to cover the entire range of 4.6 dB and would allow to compensate down to 0.45 mm/step.

Specifications for Pick-up

If the pick-up length is shorter than half the bunch length the two pulses form the upstream and downstream end overlap. Therefore an optimum pick-up for a bunch length of max. 5 ns given by the SPS 200 MHz system and a bunch spacing for the LHC type beams in the SPS of 25 ns would be $L > 0.75$ m so that the two pulses are separated.

The pick-up shall be manufactured such that the expected crosstalk of 1.5% in the combining element, i.e. the hybrid, is not exceeded. This asks for a reflection coefficient ρ better than 0.015. With a required VSWR of 1.03 it is the same quality standards as one finds for instance for high performance RF connectors. For an exemplary line width of 30 mm, a beam tube diameter of 107 mm, and with constant coupling, a VSWR = 1.03 means that the electrode height shall be adjusted to be better than $\Delta \mathrm{h} < 0.4$ mm. Further studies are required to detail the impact of height variations on beam coupling.

Special care must be taken also in the design of the pick-up environment, with focus on wake-fields that have their origin in vacuum pipe discontinuities prior to the pick-up. These wake-fields manifest as ringing after the bunch at frequencies which may fall well into the operational bandwidth.

REALISATION OF DYNAMIC PASSIVE CLOSED ORBIT SUPPRESSING

A simple and robust way to passively compensate for beam orbit offsets is to selectively insert discrete attenuation elements into the signal path using RF switches. Resistive attenuators usually are intrinsically linear from DC up to several GHz and have high power handling capabilities.

Another technique uses PIN diodes as current controlled resistors. Here, PIN diodes are placed in a bridged T-attenuator. State of the art PIN diodes have excellent power handling capabilities and range over several octaves in bandwidth.

CONCLUSION

Bunch intensities in the SPS are limited by electron cloud, in particular by instabilities in the vertical plane. It is panned to mitigate this effect by a wide-band transverse feedback system with an analog bandwidth in excess of 1 GHz. The resolution of the system is limited by the systematic offset due to orbit and electronics (noise). Using the presented suppression scheme the off-centered beam can be compensated down to the level of imperfections of hybrid, cabling, pick-up, and attenuator granularity. For bunch lengths of 1.0 ns we expect residual off-set errors of 1.0% w.r.t. the quarter aperture of the pick-up.

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