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THE HIGH FREQUENCY LONGITUDINAL AND TRANSVERSE PICK-UPS IN THE CERN SPS ACCELERATOR

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Summary

The different applications and consequent specifications for longitudinal and transverse high frequency pick-ups in the CERN SPS have led to the use of three separate types of pick-up; they are the electrostatic, the wall current and the directional coupler pick-up. The high frequency longitudinal pick-ups are protected from propagating waveguide modes by traps. Certain points in the design are described and a brief summary of their performance and use is given.

A. Specification and use of pick-ups

The machine parameters of interest in the design of the pick-ups are noted in Table I and the applications are as follows:-

a) The electrostatic pick-up. A bunch-into-bucket transfer from the CPS is used. Observation of the longitudinal structure for the first turn in the SPS allows an estimation (and hence optimization) of the capture efficiency in the CPS. This implies a low frequency cut-off $\sim f_{rev}/10$, and a high frequency cut-off $\sim 3 \times f_{acc}$ (full buckets). The continuous presentation of the SPS "turn" throughout the cycle is also a valuable diagnostic tool for quick observation of anomalies during normal operation.

b) Wall current pick-up. Clearly a basic requirement for a longitudinal pick-up is the measurement of bunch length and hence longitudinal emittance. For accurate measurements near transition and at high energy this implies an upper frequency cut-off > 3 GHz, the lower being at $\sim f_{acc}/10$ for minimum distortion of the bunches. Another major use is for the observation of instabilities, coherent bunch, microwave, etc., for which the frequency response should be as above or better and for which as high a sensitivity as possible is required. This pick-up is the major research tool.

c) The directional coupler pick-up. This pick-up can also be used for high frequency observation in the longitudinal domain. However, it is primarily used for instability observation in the transverse plane. Here the requirements are set at:- low frequency cut-off < f_{acc}, high frequency cut-off > 3 GHz with as high a sensitivity as possible. A difference signal offering discrimination against the sum signal and linearly proportional to the beam position is also needed.

Table I

Machine parameters

Accel. freq. (f_{acc})	200 MHz
Rev. freq. (f_{rev})	43.3 kHz
Bucket length (ℓ_0)	1m50 (5 nsecs)
Bunch length @ γ_{tr} (ℓ_{tr})	$\sim$ 0.18 m ($\sim$ 600 psecs)
Max. beam int. (I_0)	> 2×10^{13} ppp
Min. beam int.	$\sim 10^{10}$ ppp

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B. Design of the pick-up elements

The design of the electrostatic pick-up has been fully described in Refs. 1 and 2. Performance details are given in Table II.

The wall current pick-up

For a relativistic proton beam the charge image in the walls of the vacuum chamber is an accurate representation of the charge distribution in the beam. If the vacuum chamber is cut and a resistance inserted in the gap, then a voltage proportional to the beam current is developed and can be measured. Refer to Fig. 1.

The gap length should be much shorter than the minimum bunch length for good resolution, while the gap capacitance should be small to provide a good high frequency response. If ceramics are avoided, (i.e. a vacuum joint is made with an external chamber), then an acceptably low capacitance ($\sim$ 7 pf) can be obtained even with a 2 mm gap length. (This also alleviates the signal extraction problem, see later).

The chamber around the gap shields the gap from external fields, defines clearly a d.c. shunt path and, for this pick-up, provides the vacuum seal. Normally, the chamber is filled with ferrites to provide a good low frequency response, such ferrites also becoming lossy at high frequencies and damping unwanted resonances. The impedance of this chamber referred to the gap is however ill-defined and a smooth amplitude/phase versus frequency response is difficult to achieve. To overcome this problem the chamber has been designed as a coaxial line (Z_0 = 25 Ω), the inner conductor being the vacuum chamber, terminated by a matched load[3]. Techniques for producing matched loads in waveguides and coaxial lines are well known, the problem here being the wide frequency range. The final solution is in two parts:- a) lossy ferrite tiles arranged symmetrically in lines around the inner conductor to give a slow change in properties along the line and b) a ring of ferrite at the end. The reflection coefficient on the line is thus < 0.13 for 300 MHz to > 4 GHz. Below 300 MHz, the reflection coefficient slowly increases as the ferrites become less absorptive and more inductive. The tiles are screwed to the vacuum chamber, the heads of the screws being recessed below the surface of the tile. The ring at the end is made from tiles machined into segments and held by Be-Cu clips. The cutting and drilling was made with ultrasonic machining techniques. The vacuum properties of the ferrites are very good once they are cleaned and baked; this processing does not affect the RF properties.

The signal is taken from the gap using eight symmetrically placed 50 Ω striplines which use the end plate of the P.U. as the earth plane. The stripline is held at the gap by a spring finger clip and at the feedthrough by a screw. These lines are matched carefully through to the 50 Ω feedthroughs. The impedance at the gap is therefore given at high frequencies by the 8 × 50 Ω striplines in parallel with the 25 Ω coaxial line. This 5 Ω with the capacitance of 7 pf gives a cut-off frequency of $\sim$ 4.6 GHz. The feedthroughs are

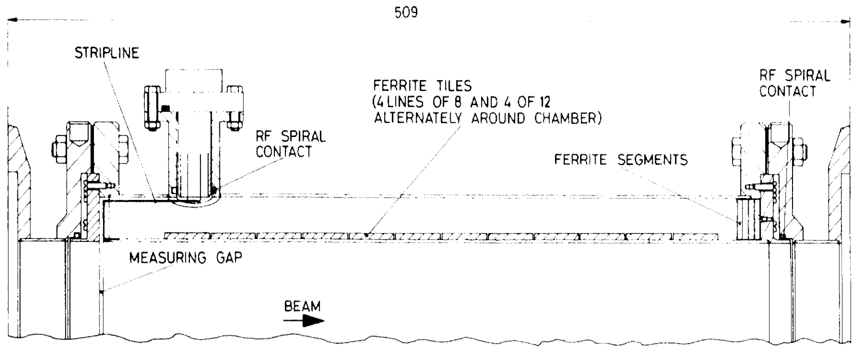


Fig. 1 - Wall current pick-up

limited to ∿ 5.6 GHz. The eight outputs are summed in a hybrid in order to give insensitivity to beam movement and increased transfer impedance. See Table II for the final results.

The directional coupler pick-up

This pick-up consists of an electrode, placed the length of the vacuum chamber, which couples to both the electric and magnetic fields. For relativistic beams the electromagnetic fields are equivalent to those produced by a coaxial line and the theory for the design of directional couplers, as developed by Oliver[4], can be used. The most important general result is $s(t) = \frac{1}{2}k(\frac{vt}{2})$, where s(t) is the response of the coupler to a step function, k(z) is the coupling to the fields at a point z on the electrode, t is the time and v is the velocity. The frequency response is then given by

$$F(\omega) = i\omega \int_0^{2\ell/v} \tfrac{1}{2}\, k(\tfrac{vt}{2})\, e^{-i\omega t}\, dt\ .$$

Such pick-ups have previously been constructed with electrodes having constant cross-section (k = constant[5].) In this case the frequency response is a repeated half sine-wave. The zeros present in such a response can be removed by using an electrode with varying, in particular exponentially varying, coupling. In this case $k(z) = k \exp(-za/\ell)$ where ℓ is the length of the electrode and 'a' is a constant (see Fig. 2). From the above, the step response is an exponentially decaying pulse (or increasing, if the beam direction reverses). The frequency response is given by

$$|F(\omega)| = \frac{\frac{k\omega\ell}{v}\left(1 + \frac{1}{e^{2a}} - \frac{2}{e^{a}}\cos\frac{2\omega\ell}{v}\right)^{\frac{1}{2}}}{\left[a + \frac{4\omega^2\ell^2}{v^2}\right]^{\frac{1}{2}}}$$

For 'a' large this becomes the response of a 1-pole, high-pass filter with 3 dB point at $va/4\pi\ell$. As 'a' decreases, the 3 dB point is pushed lower in frequency, a ripple is produced in the passband and for 'a' very small the constant coupling case is found again.

Each electrode, of which there are four per pick-up, is machined to the required exponential shape, correction having been made for the apparent increase in width due to the finite thickness, on a numerically controlled mill. Mechanical constraints, longitudinal space, rigidity, fixing capability of the thin end etc., determine to a large extent the value of 'a' (= 2.485). The distance of the coupler from the wall must be adjusted (using TDR techniques) to maintain the 50 Ω characteristic impedance. Similarly careful matching at the feedthroughs is required to minimize reflections.

The pick-up is used longitudinally with resistive summing networks (max. freq. response) or transversely with hybrids to give the sum and difference signals. In either case each electrode has a 50 Ω matched load at the downstream end. The primary frequency limitation in the transverse pick-up is given by resonances which couple the electrodes together (∿ 1.7 GHz limit). Laboratory measurements have shown that significant improvements can be obtained by simply placing a line of lossy ferrite beads against the chamber wall between each pair of electrodes. See Table II for final results.

Waveguide mode traps

Above the waveguide cut-off frequency of the vacuum chamber the pick-ups may be sensitive to waves that are excited by discontinuities etc. elsewhere in the machine. For the longitudinal pick-ups (placed in the machine where the beam size is minimum), the cut-off frequency is 2.12 GHz (TE_{11} mode). The first mode with longitudinal E field is the TM_{01} for frequencies greater than 2.7 GHz. To protect the pick-ups up to their upper

Table II

Results of pick-up measurements

*) 1st circumferential mode at 920 MHz

	Electrostatic		Wall current		Directional coupler		
	without amplifier	with amplifier	1 port (others 50 Ω)	hybrid Σ	resistive Σ	hybrid Σ: Σ	hybrid Σ: Δ
High frequency cut-off MHz	*	∿ 2000	4400	3100	5000	4000	
Low frequency cut-off MHz	80	0.005-0.006	4.2	4.4	187	133	
Transfer impedance Ω	11.6	1.81		15.5	3.5	5.73	0.11/mm
Linearity (½ chamber)							±5%
Directivity					16.5 dB		
Amplitude ripple (a = 2.485)					3 dB pk/pk		

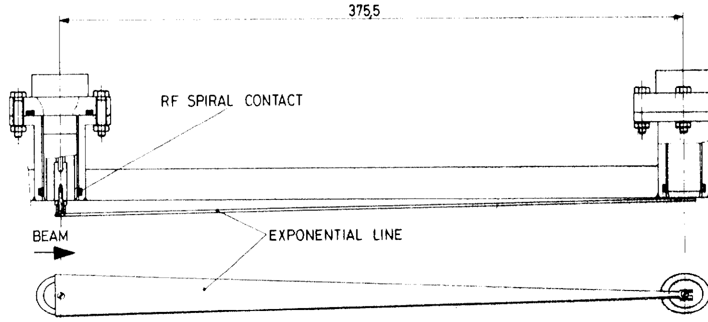


Fig. 2 - Directional coupler pick-up

cut-off frequency, ∿ 5 GHz, traps are installed on either side of each pick-up. These traps are designed to absorb microwave energy flowing in the waveguide without absorbing significant power from the fundamental beam fields. Not only must the trap absorb microwave energy, it must not reflect it, otherwise a resonator is created with the pick-up. A suitable material was found to be U60 ferrite. The attenuation of this ferrite remains low up to > 600 MHz and then increases rapidly. 600 MHz is the 3rd harmonic of the RF and calculations and subsequent experimental results show that the beam heating effect is insignificant. The final arrangement can be seen in Fig. 3. The ferrite beads are held in beryllium copper clips which are spot-welded to a support subsequently fixed in the vacuum chamber. The four lines of ferrites point towards the pick-up and present some matching. The absorption is mainly in the rings. The transmission loss measured is ⩾ 12 dB for the TE_{11} mode, ⩾ 14 dB for the TM_{01} mode while the reflection loss is > 16 dB, ⩾ 10 dB for the two modes respectively.

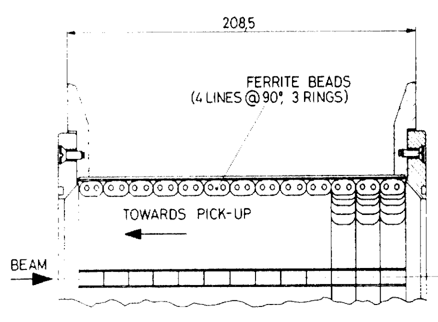
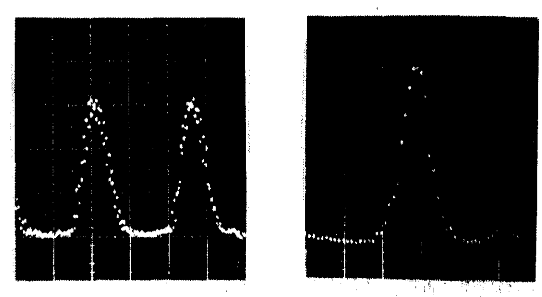


Fig. 3 - Waveguide mode trap

C. Observation systems

One wall-current pick-up is dedicated to the main control room (1⅝" coax. cable). The signal from a second of these pick-ups is divided between a cable and a sampling system, the latter located in a pit in the tunnel to make use of the maximum bandwidth. The samling system is a modified commercial instrument which can be triggered at the revolution frequency. The trigger signal is derived from the RF 200 MHz by division (< 20 psecs jitter), and is transmitted via a high quality cable to the tunnel. All the equivalent oscilloscope controls are made available at the surface and are manually or computer accessed. The low-frequency video signals (horizontal, vertical and blanking) are transmitted to the surface and then distributed. Typical displays of the sampled bunch are shown in Fig. 4. The bunch number can be chosen (0 → 4620 in steps of 10) and the trigger gated so that a particular bunch can be viewed at a particular time. Normally the trigger is not gated so that a continuous display of the bunch is provided throughout the cycle. (This facility is also very useful during single-bunch storage experiments.) If instabilities are present it is immediately obvious though the stroboscopic effect makes exact interpretation more difficult. The signals from the cables are used in the normal way; transient digitizer, peak detection, spectrum analyzer, filters and diodes, etc.



γ = 15 2 ns/div γ = 200 0.5 ns/div

Fig. 4 - Sampled bunch

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