SINGLE-SHOT LONGITUDINAL SHAPE MEASUREMENTS OF NANOSECOND PARTICLE BUNCHES

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1. Introduction

Since September 1986 the CERN Proton Synchrotron (PS) machine, as part of the LEP injector chain, is able to accelerate electrons besides the various usual hadron*) particles.

It should be noted that owing to their peculiar dynamics, electron bunches are generally much shorter than hadron bunches. Typical values for the total bunch length in the PS are:

- for Gaussian electron bunches: 0.7–5 ns,
- for parabolic hadron bunches: 3–100 ns.

Peak current intensities range from less than 1 mA (oxygen) to more than 50 A for high-intensity proton beams, whilst electron bunches have peak currents of about 1–3 A.

In order to match the RF system and to avoid instabilities at injection in the Super Proton Synchrotron (SPS), the longitudinal dimensions (energy spread and length) of the electron bunches have to be carefully adjusted in the PS**) to the following nominal values[1,2] before extraction:

$$\sigma_E/E = 10^{-3}, \qquad 4\sigma_t = 2.1 \text{ ns}.$$

An instrument providing a precise measurement of the bunch shape is thus of primary importance. The apparatus presented here consists of a wide-band pick-up, a transient digitizer, and a small computer for control and signal handling. It has to satisfy the following requirements:

i) have a bandwidth (3 dB) of 0.1–1000 MHz—in order to measure long (> 100 ns) and short (< 2 ns) bunches;
ii) have single-shot capability—because the bunch shape evolves too rapidly to use any 'repetitive sampling' technique;
iii) have complete remote control—in order to install the digitizer as close as possible to the pick-up;
iv) acquire and transfer data in less than 2.4 s—corresponding to the minimum time interval between $\bar{p}$ pulses;
v) be user friendly—to allow routine measurements by 'non-specialists'.

2. The Wide-Band Pick-Up (Fig. 1)

To cover the required bandwidth mentioned under (i) above, the decision was taken to build a wall-current monitor (or resistive pick-up) adapted, from other designs developed at CERN[3,4], to the following PS machine conditions:

i) an available straight section length of 105 cm enabling us to maximize the size of the absorbing 'sump';
ii) an elliptical shape for the vacuum chamber, implying a highly accurate phase matching of the eight outputs at the summing network.

To reach the desired low-frequency cut-off of 100 kHz, six ferrite rings have been added at the bottom of the 'sump'.

To attain the fast rise-time needed for the electron bunches and at the same time obtain a high sensitivity, the effective capacitance seen at the gap had to be minimized. For this reason the gap was not realized with a vacuum-tight ceramic seal, implying that all materials used inside the 'sump' had to be acceptable for the high vacuum of the PS. This is the case for the Eccosorb NZ31 absorbing tiles placed along the body of the pick up and for the Ferroxcube 8C11 ferrite toroids placed at the end of the 'sump'. See Fig. 1.

The summing of the eight gap signals over the whole bandwidth of the monitor and the power delivered by the high-intensity beam, precluded the use of a reactive power combiner. We used, instead, the design shown in Fig. 2, which worked correctly in so far as the lack of insulation between the different users can be accepted. The overall sensitivity is about 5.5 Ω.

The wall-current monitor was tested using a TEM high-speed step (t_r = 25 ps) injected into a coaxial set-up of two lengths of PS vacuum chamber, with conical transition sections on both sides of the monitor. We measured a rise-time, for the whole set-up, of about 100 ps (Fig. 3), which roughly corresponds to an equivalent cut-off frequency in excess of 3.5 GHz for the monitor alone[5].

The low-frequency cut-off was measured to be 105 kHz at the −3 dB point.

The structure of the 'sump' with the gap loaded by its eight outputs shows a heavily damped resonance around 40 MHz. This is due to the quality of the 8C11 material, which has still negligible loss at these frequencies, and to the characteristic of the NZ31 tiles whose absorption factor is not yet very effective there. The use of low-frequency toroids will hopefully remedy this defect.

No loss-versus-frequency compensation was provided for the transmission lines between the monitor and the different users. Flexwell 7/8-inch cables were used as a compromise between low-loss, low-velocity dispersion, and enough separation between the high-frequency monitor cut-off and the onset of waveguide modes in the cable, rising at ~ 6 GHz.

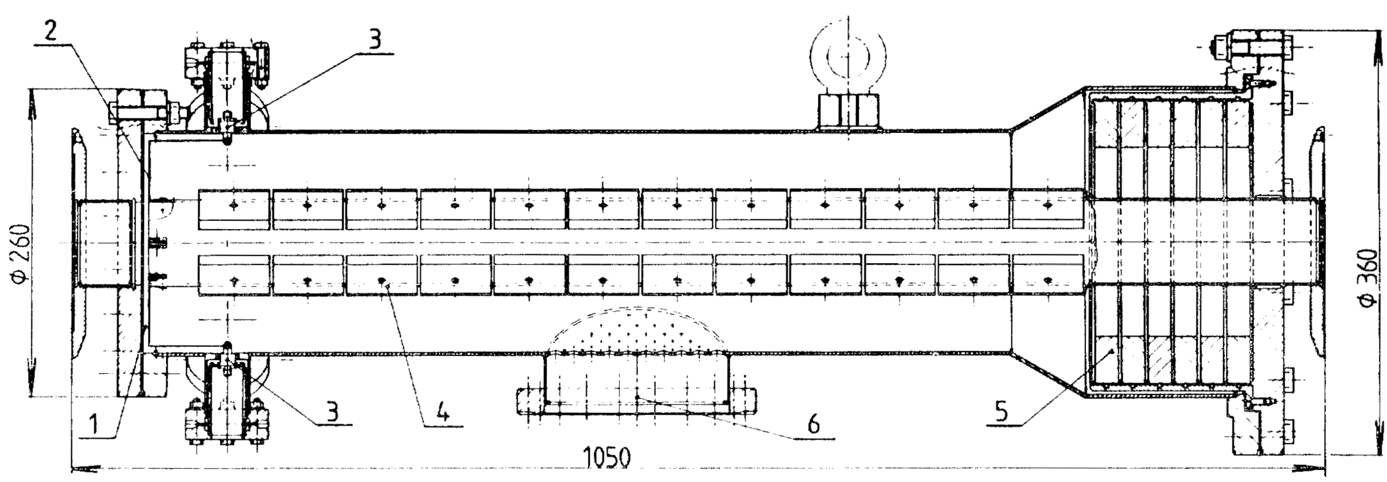

Fig. 1 The wall current monitor: 1, gap; 2, microstrip lines; 3, vacuum feedthroughs (eight) with SMA connectors; 4, absorbing ferrite tiles; 5, ferrite toroids; 6, vacuum-pump connection.

3. Data Handling

*) 'Hadron' stands for: protons, antiprotons, deuterons, alphas, and oxygen ions.

**) In short: the energy spread is adjusted by using wigglers to change the longitudinal partition number, and the bunch length is set by changing

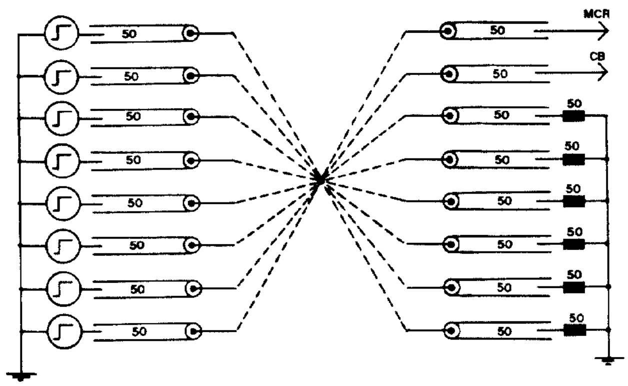

Fig. 2 The summing network scheme

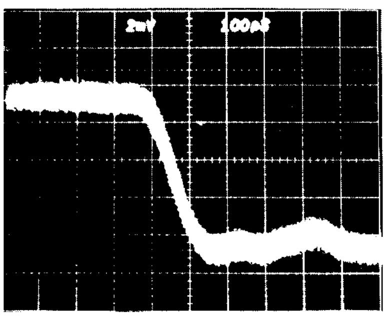

Fig. 3 The pick-up rise-time (inverted) 100 ps/div.

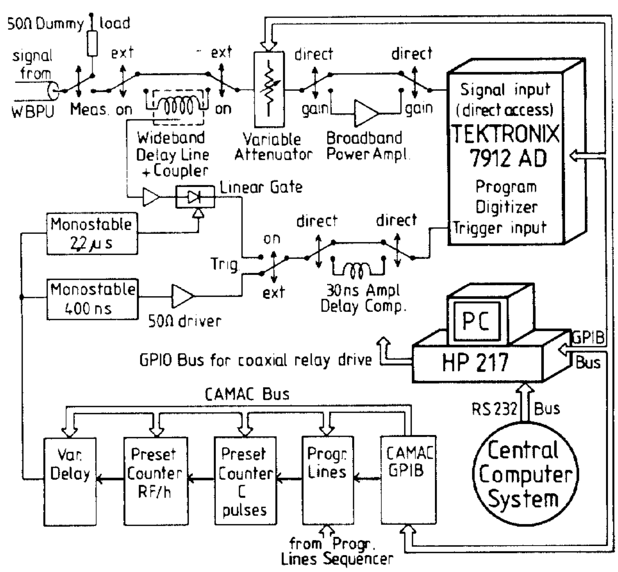

Fig. 4 The data acquisition block diagram

The bunch shape is acquired with a Tektronix-type 7912 AD transient digitizer. This instrument satisfies quite well the requirements (i), (ii), and (iii) listed in Section 1.

To achieve the 1 GHz bandwidth it has been necessary to work in 'Direct Access' mode, i.e. feeding the signal directly to the vertical plates. This degrades the sensitivity to $\approx$ 4 V/div., a drawback partially compensated by the relatively high sensitivity of the pick-up, which provides enough voltage swing, at least for the short electron bunches. For the very low intensity beams, a 1 GHz/5 W amplifier can be inserted.

To minimize the cable losses, the digitizer is located as close as possible to the pick-up, but outside the accelerator ring in order to avoid radiation damage. The connecting cable (50 Ω Flexwell $^7/_8$-inch) is 35 m long and provides about 2 dB of attenuation at 1 GHz.

The bunch shape, stored in the 1 kbyte local memory, is then transferred to an HP217 desk-top computer for signal processing. The computer, located in the PS Main Control Room a few hundred metres away, controls the digitizer and the variable attenuator via an extended GPIB bus and the coaxial relays via a GPIO bus.

The operator sitting at the computer desk has the usual controls—those for a traditional oscilloscope—of the amplitude (V/div.), the time-scale (ns/div.), and the trigger settings. For each setting of the time-scale, the correct values of the intensity and trace position are automatically set according to pre-established values.

The trigger command has some special features. In the 'external' mode, the trigger pulse is issued by a cascade of two preset counters, the first counting the time from the injection in millisecond steps, the second counting pulses at the revolution frequency to provide a synchronization on the beam. An adjustable fine delay in 1 ns steps (jitter < 500 ps) is used to place the bunch in the middle of the screen (this generally takes 5 to 10 machine cycles for adjustment).

Finding the right trigger settings for the rare $\bar{p}$ pulses, with repetition rates of one per hour (or less), can take quite a long time. In this case, the preset pulse is used to open, during one revolution period ($\approx$ 2 μs), a wide-band linear gate allowing a sample of the bunch signal, derived from a coupler, to trigger the digitizer. Wide-band delay lines are automatically inserted in order to synchronize the arrival of the signal at the digitizer input.

Also specific to the $\bar{p}$ mode is a special mode in which the complete system is put in a stand-by status, awaiting a Program Line Sequencer (PLS) logic line announcing a $\bar{p}$ acceleration on the next machine cycle. At this time the computer reads the foreseen $\bar{p}$ intensity (data available from the main computer system), adjusts the attenuator/amplifier accordingly, sets the right timing (usually just before the extraction), recognizes if it is a single or a multiple shot, and finally stores and displays the bunch shape.

The operation is entirely automatic, and all the $\bar{p}$ shots are thus stored in the computer memory for later analysis. To ensure that no $\bar{p}$ pulse is missed, the PLS 'NEXT PBAR' interrupt has first priority over whatever operation is actually being executed by the computer.

Once the data are in the computer memory they are displayed on the screen together with an estimate of the bunch length, whilst a bunch integration provides the intensity.

The approximate time taken for the various steps is

i)	digitizer setting:	90 ms
ii)	GPIB data transfer from the digitizer to the I/O computer port:	10 ms
iii)	internal data transfers and data formatting:	1.3 s
iv)	graphic display:	1.2 s

The present code is written in HP-BASIC 3.0. Such an interpreter does not provide the maximum speed, but nevertheless offers good flexibility for modifications and improvements 'on the spot'.

4. Results

Some typical examples of measurements are shown in Figs. 5 to 9.

Significative measurements have been performed on bunches not shorter than $\approx$ 1.3 ns (see Fig. 9).

Thanks to the good signal-to-noise ratio, 30 ns long bunches with less than 10^8 charges, have been easily resolved (see Fig. 7).

Overall reliability has proved to be quite good. No major faults were recorded during several months of continuous operation.

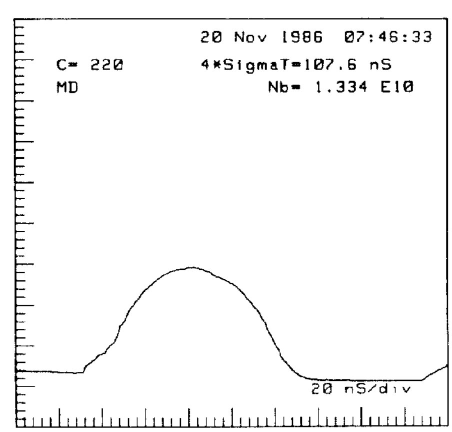

Fig. 5 Deuteron bunch — one of the longest

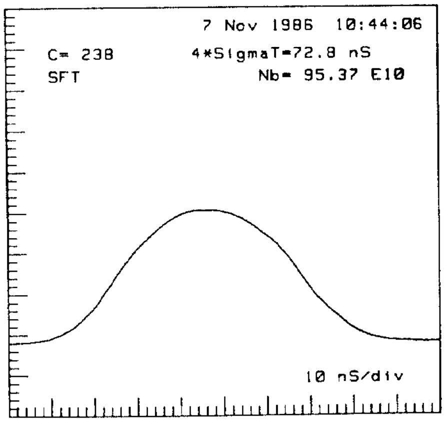

Fig. 6 Long and high-intensity proton bunch

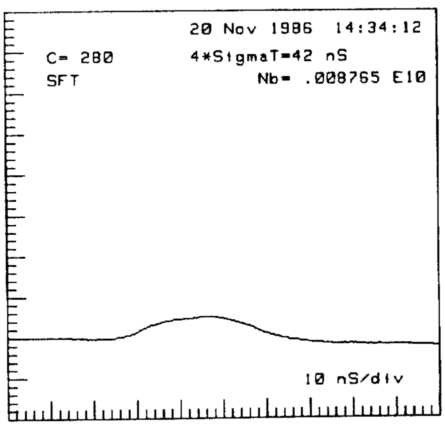

Fig. 7 Very low intensity oxygen bunch

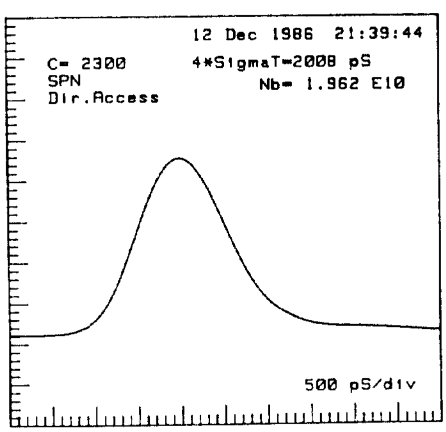

Fig. 8 'Nominal' length electron bunch before extraction

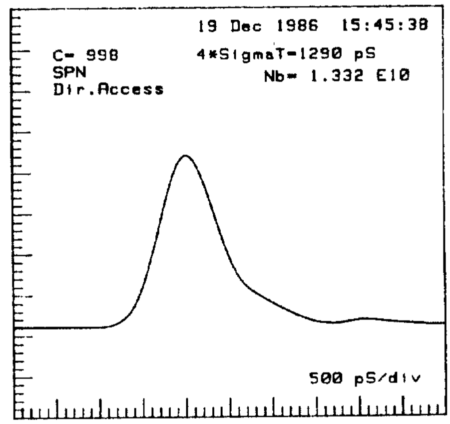

Fig. 9 Short electron bunch

5. Future improvements

An RS232 link with the central control system will give the possibility to start the measurement from the standard MCR consoles. We are investigating the possibility of improving the bandwidth by software signal processing. Since the transfer function of the Flexwell cable can be easily predicted, the cable losses could be compensated by computing the ratio between the Fourier transform (FFT) of the measured bunch shape and the cable transfer function, then 'antitransforming' (FFT^{-1}) back in the time domain. To speed up the computations we actually use a dedicated FFT processor (Ariel Co.) inserted into the HP217.

Acknowledgements

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