Wall Current Monitor

Results of the Beam Test in the PS on 25.6.75

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1. Beam Position Monitor and Electronic Equipment

A new wall current monitor has been developed for the SPS in order to measure the beam position in the enlarged straight sections at the injection and ejection points of the SPS where the split electrodes used in the short straight sections would become too large for the wavelength of the SPS beam. A prototype wall current monitor made of bronze (see fig. 1) was installed in the PS in SS 13 for testing with the PS beam bunched at 199.5 MHz by the new RF-cavity in SS 6.

The purpose of the test was to check the electrical and mechanical design of the wall current monitor for the first time with a particle beam. The principle of operation of this new beam position monitor has been described in ref. 1.

The position of the beam bunched at 199.5 MHz was measured by the wall current monitor both in the horizontal and vertical co-ordinates. Port 1 and port 3 of the monitor station were connected to a hybrid ring for the horizontal position measurement; port 2 and port 4 connected to a second hybrid ring were used for the vertical position measurement. The block diagram of the electronic equipment for the RF-signal processing and computer acquisition is given in fig. 2. The sum and difference RF-signals of both hybrid rings were filtered and mixed with a local oscillator running at 197.7 MHz to produce an intermediate frequency
of 1.781 MHz.

The IF-signals amplified by 30 dB in the receivers in SS 13 were transmitted to the MCR of the PS over about 150 m of POD cable. There, the IF-signals were demodulated by synchronous detection and observed on an oscilloscope at the input and output of the demodulator. (see photos 1 - 4.)

In order to keep the intermediate frequency constant, the frequency of the local oscillators in the tunnel must keep pace with the RF-frequency programme of the cavity. The local oscillators are steered by a signal generator linked to the RF-frequency by means of a phase locked loop. (see fig. 3.) The phase locked signal generator was installed in the central building of the PS and worked successfully with the beam control equipment of the RF-Group.

2. Computer Acquisition

A NORD computer installed in the MCR of the PS was used for digital acquisition of the sum and difference channels from the demodulators. In order to measure the position of the closed orbit of the beam unaffected by betatron oscillations, the demodulator signals must be integrated over several beam revolutions, normally during 1 ms in the SPS. As shown in fig. 2, this was done by a voltage-to-frequency converter and a CAMAC scaler summing up the pulses of the converter during the gate was opened for 1 ms. The gating and the subsequent computer acquisition of the scalers was synchronised with the M-train of the PS. The duration of the measurements was controlled by a triggerable CAMAC preset counter fed by a 1 MHz clock. Up to two computer acquisitions per PS cycle could be handled by a real-time programme with two direct memory accesses within 50 ms.

The computer has calculated the beam position in horizontal and vertical co-ordinates for two measurements per cycle and has displayed them cycle by cycle on a Vistar-terminal. The beam positions were
calculated by the computer according to:

\[ X = \frac{\Delta X_1 - \Delta X_3}{\Sigma X_1} \cdot K_X \cdot L \]

\[ Y = \frac{\Delta Y_1 - \Delta Y_3}{\Sigma Y_1} \cdot K_Y \cdot L \]

- \( X \): horizontal beam position
- \( Y \): vertical beam position
- \( \Delta X_1, \Delta Y_1 \): counts of difference channel during measurement of horizontal \((\Delta X_1)\) and vertical \((\Delta Y_1)\) positions
- \( \Delta X_3, \Delta Y_3 \): counts of difference channel during zero calibration of horizontal \((\Delta X_3)\) and vertical \((\Delta Y_3)\) positions
- \( \Sigma X_1, \Sigma Y_1 \): counts of sum channel during measurement of horizontal \((\Sigma X_1)\) and vertical \((\Sigma Y_1)\) positions
- \( K_X, K_Y \): gain calibration factor between sum and difference channel of horizontal \((K_X)\) and vertical \((K_Y)\) measurement.
- \( L \): scaling factor of wall current monitor \( L = 125 \text{ mm} \)

At the beginning of the tests, the gains of the sum and difference channels were adjusted so that the gain calibration factors became unit:

\[ K_X = K_Y = 1.00 \pm 0.01 \]

At the end of the test, 8 hours later, the calibration factors had drifted only by 1%.

3. **Beam Gymnastics**

The PS beam of about \(10^{12}\) ppp was accelerated up to 10 GeV/c at a frequency of 9.5 MHz and then the beam was adiabatically debunched. One single RF-cavity installed in SS6 rebunched part of the beam at a frequency of 199.5 MHz with an accelerating voltage of about 50 KV during 90 ms. After rebunching, the mean radial beam position of the RF-trapped beam could be shifted radially up to 20 mm outwards or inwards of
the initial trajectory. The beam was shifted by changing gradually the 
RF-frequency in the beam control equipment operated by the RF-Group in 
the central building.

The beam displacement was successfully detected by the wall current 
monitor. The beam positions measured at the beginning and on the top 
of the RF-displacement were compared with the mean radial beam positions 
calculated from the RF-frequency programme. This method provided 
fairly accurate results, which agree within a few percents.

A second check of the beam position measured at a fixed RF-
frequency of 199.530 MHz was to displace the wall current monitor by 
+ 10 mm from the centre position. The accuracy of this method depends 
only on the reproducibility of the PS magnet cycle and provided 
results which agree within 1 or 2 mm.

4. Beam Intensity Measurement

The sum signal of the wall current monitor is proportional to 
the intensity of the beam bunched at 199.5 MHz. The sum voltage \( \Sigma \) 
measured at two opposite ports of the wall current monitor is related 
to the fundamental frequency component of the beam intensity \( I_1 \) by 
the transfer impedance \( Z_t \) of the wall current monitor:

\[
\Sigma = 2 Z_t I_1 \\
Z_t = 6.5 \text{ ohms}
\]

For a PS beam of \( 10^{12} \) ppp, which is sine modulated at 199.5 MHz 
(weak bunching), the beam current \( I_1 \) and the sum signal \( \Sigma \) become:

\[
I_1 = 10^{12} \text{ ppp} \times 1.6 \cdot 10^{-19} \text{ As} \times 475 \text{ KHz} = 76 \text{ mA} \\
\Sigma = 2 \times 6.5 \Omega \times 76 \text{ mA} = 990 \text{ mVp}
\]
The beam current in the PS is 11 times higher than in the SPS for the same number of particles accelerated. Attenuators of 20 dB were put in series with the outputs of the hybrid rings in the PS. The overall gain of the receivers, demodulators and voltage-to-frequency converters was calibrated prior to the beam tests with a signal generator 199.5 MHz in the tunnel. For a gain of 30 dB in the IF-amplifiers in the tunnel, which was remotely controlled from the MCR, the following signals were obtained:

hybrid ring : $\sum_{\text{in}} = 376 \text{ mVp}$
V/F converter : $\sum_{\text{out}} = 800 \text{ counts/ms}$

Converting the counts in protons per pulse we obtain the proportionality factor $C$:

$$C = \frac{800 \text{ counts/ms}}{376 \text{ mV}} \cdot \frac{990 \text{ mV}}{10^{12} \text{ ppp}} = \frac{21 \text{ counts/ms}}{10^{10} \text{ ppp}}$$

The sum signals of both the horizontal and vertical ports were counted for 1 ms just after rebunching at cycle time M 168 and compared with the beam intensity measured by the PS beam current transformer before the debunching at cycle time M 100. The results in table 1 show that the horizontal and vertical sum signals agree within 1%.

The beam intensity measured by the wall current monitor is systematically lower than for the beam current transformer of the PS, since only a fraction of the beam has been bunched by the RF-cavity. Assuming weak bunching with pure sine modulation at the fundamental frequency of 199.5 MHz only, the trapping efficiency can be estimated from table 1:

$$\eta = (77 \pm 15) \%$$
If there was strong bunching, the capture efficiency should be divided by a factor 2.

Because of the uncertainty of the bunching factor and the trapping efficiency, the transfer impedance of the wall current monitor could not be measured with the beam. However, the theoretical value $Z_t = 6.5$ ohms, calculated from the geometry of the coaxial cavity and its load, is not contradicted by the trapping efficiency $\gamma < 100\%$. Probably, the theoretical transfer impedance is somewhat altered by the strong discontinuity of the vacuum chamber at both sides of the wall current monitor, where the electromagnetic field of the beam is distorted and reflections arise.

Higher resonances of the wall current monitor due to cavity modes of the enlarged vacuum chamber were attenuated by damping resistors mounted at both ends inside the monitor. No beam instability caused by the wall current monitor was observed in the PS since it was installed a month ago.

The sum and difference signals observed at the input and output of the demodulator (see photos 1 - 4) were amplitude modulated by a ripple of 100 Hz, which is due to the beam. The ripple was introduced probably by the high voltage power supply of the RF-amplifier.

5. **Beam Position Measurement**

The position of a beam is not so easy to measure as a wire, since the beam has neither a constant shape nor a constant position with time. The nominal beam diameter of the PS for $10^{12}$ ppp at 10 GeV/c amounts to 12 mm for 90% of the particles inside this diameter in SS 13. It is therefore difficult to define the position of a beam with an accuracy less than 1 mm. The resolution of the wall current monitor BPA and the electronic equipment however is a factor 10 better, as has been shown by laboratory tests (ref. 1).
5.1 Comparison of Beam Position with RF-Frequency Programme

The radial beam position \( R \), the RF-frequency \( f \) and the bending magnet field \( B \) are related by the differential equation:

\[
\frac{dR}{B} = \gamma^2 \frac{df}{f} + (\gamma^2 - \gamma_{tr}^2) \sqrt{\frac{\beta}{\beta_{13}}} \frac{dR}{R}
\]

where:

- \( \gamma \): ratio of total energy of particle to its rest energy
- \( \gamma_{tr} \): ratio of total energy to rest energy at transition
- \( \beta_{13} \): betatron function in SS 13
- \( \overline{\beta} \): mean betatron amplitude

If the magnet field is constant and \( dB = 0 \) during the flat top, the beam displacement \( \Delta R \) and the RF-shift \( \Delta f \) are related by:

\[
\frac{\Delta R}{R} = -\sqrt{\frac{\beta_{13}}{\beta}} \cdot \frac{\gamma^2}{\gamma^2 - \gamma_{tr}^2} \cdot \frac{\Delta f}{f}
\]

\[\triangle R/mm = -0.866 \Delta f/KHz\]

During the machine development the RF-frequency for trapping the debunched beam was kept constant at 199.5300 MHz by a stable frequency synthesizer. After the beam had been trapped by the RF, the beam control shifted the RF-frequency gradually back and forth. In the first programme the beam was displaced radially outwards by decreasing the RF-frequency. (see photos 1 and 3.)

The direction of the frequency shift could be inverted, and in a second programme, the RF-frequency was increased from 199.5300 MHz up to a top, displacing the beam inwards. (see photo 2.)
The horizontal positions calculated by the computer were counted positive inwards, i.e. towards the centre of the PS. The vertical position is positive downwards, i.e. towards the earth centre.

In table 2, a set of 10 measurements has been recorded for the first RF-programme displacing the beam outwards. The vertical position is remarkably stable within a few tenths of a millimeter, except for the last two measurements, which are disregarded because of beam instability. The horizontal beam displacement between the first and second acquisition within 50 ms was measured $\Delta X = (19.6 \pm 0.8) \text{ mm}$. The measurements agree well with the theoretical value of $\Delta R = 20.3 \text{ mm}$ calculated from the RF-frequency shift of 23.5 KHz.

A second set of measurements for a beam displacement inwards is given in table 3. For all measurements, the beam stands perfectly stable within a few tenths of a millimeter. The horizontal beam displacements between the two acquisitions within 50 ms of a cycle amount to $\Delta X = -(12.8 \pm 0.2) \text{ mm}$. The measured displacements are about 1 mm smaller than the theoretical value $\Delta R = -(13.9 \pm 0.9) \text{ mm}$ derived from the RF-frequency programme.

5.2 Comparison of Beam Position with Displacement of Monitor

Many experiments in the past have shown that comparing the measurements of the beam position monitor with other equipment does not always offer the accuracy desired. We wanted therefore to keep the beam position constant and to displace the wall current monitor horizontally by $\pm 10.0 \text{ mm}$ from the axis of the PS. The wall current monitor was mounted on a mobile platform with flexible bellows at both ends of the monitor. The stability of the beam position during successive accelerator cycles was checked by means of the PS closed orbit detection system. It was observed at pick-up station 13 of the PS
at the beginning of the flat top at M 145, that the beam remained constant from cycle to cycle within 1 mm at a position of 2 mm inside the PS axis. During debunching and rebunching at a constant RF-frequency of 199.5300 MHz, the beam could shift radially and the position of the captured beam was only dependent on the flux density B of the bending magnets during the flat top. For a constant capture frequency, i.e. \( \Delta f = 0 \), the differential equation between the variation \( \Delta R/R \) of the radial beam position and the variation \( \Delta B/B \) of the flux density of the PS magnet cycle is given by:

\[
\frac{\Delta R}{R} = \sqrt{\frac{3}{2}} \cdot \frac{1}{\gamma} \cdot \frac{1}{\sqrt{\gamma^2 - \gamma^2}} \cdot \frac{\Delta B}{B}
\]

\[\Delta R/mm = 0.32 \Delta B/\text{Gauss}\]

Unfortunately the stability of the PS magnet cycle was not measured over the duration of the tests. A long term drift of 3 Gauss was sufficient to shift the beam position by 1 mm.

The horizontal beam position after capture is shown in photos 1, 2 and 3 for three different positions of the wall current monitor BPA. The results of all measurements (1st acquisitions) recorded at the capture frequency 199.530 MHz can be summarized by:

- BPA 10 mm outside of PS axis \( X_1 = +(12.7 \pm 0.7) \text{mm} \)
- BPA centred on PS axis \( X_1 = +(3.8 \pm 0.4) \text{mm} \)
- BPA 10 mm inside the PS axis \( X_1 = -(5.6 \pm 0.4) \text{mm} \)

The offset of the measurements corresponds to the displacements of the monitor within 1 or 2 mm.

6. **Conclusions**

The accuracy of these results confirm the validity of this type of wall current monitor for the SPS enlarged beam position monitors and
of its associated electronics and acquisition systems.

The only modifications for the series production to be installed in the SPS will consist in some mechanical modifications using stainless steel instead of bronze to avoid problems with soldering and outgassing of the bronze cavity.

Acknowledgements

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Reference

### TABLE 1

Horizontal and vertical sum signals $\Sigma_H, \Sigma_V$ versus number $N$ of protons accelerated by the PS:

<table>
<thead>
<tr>
<th>$N$ [10$^{10}$ ppp]</th>
<th>$\Sigma_H$ [counts/ms]</th>
<th>$\Sigma_V$ [counts/ms]</th>
<th>$\Sigma_H/C$ [10$^{10}$ ppp]</th>
<th>$\Sigma_H/NC$ [%]</th>
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<tr>
<td>91</td>
<td>1680</td>
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<td>1460</td>
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<td>70</td>
<td>81</td>
</tr>
</tbody>
</table>

Trapping efficiency: $\eta = \frac{\Sigma}{NC} = (77 \pm 15)\%$
Beam positions measured for 10 successive PS-cycles.
RF-frequency programme I, BPA 10 mm outside of PS-axis.

<table>
<thead>
<tr>
<th>horizontal position (positive inwards)</th>
<th>vertical position (negative upwards)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( t_1 = M 168 )</td>
<td>( t_2 = M 183 )</td>
</tr>
<tr>
<td>( f_1 = 1999.530 \text{ MHz} )</td>
<td>( f_2 = 1999.5065 \text{ MHz} )</td>
</tr>
<tr>
<td>12.0</td>
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</tr>
<tr>
<td>12.4</td>
<td>-2.4</td>
</tr>
</tbody>
</table>

BPA \( X_1 = (12.5 \pm 0.6) \text{ mm} \)
\( \Delta X = X_1 - X_2 = (19.6 \pm 0.8) \text{ mm} \)
(last 2 measurements are disregarded because
of beam instability, see also \( Y_2 \))

RF \( \Delta R = 0.866 (f_1 - f_2) = 20.3 \text{ mm} \)
Beam positions measured for 7 successive PS-cycles.
RF-frequency programme II, BPA 10 mm inside of PS-axis

<table>
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<th>horizontal position (positive inwards)</th>
<th>vertical position (negative upwards)</th>
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<td></td>
<td>( t_1 = M 162 )</td>
<td>( t_2 = M 175 )</td>
</tr>
<tr>
<td></td>
<td>( f_1 = 199.530 \text{ MHz} )</td>
<td>( f_2 = 199.546 \text{ MHz} )</td>
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<tr>
<td>( X_1 ) [mm]</td>
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<td>+7.1</td>
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<tr>
<td>( X_2 ) [mm]</td>
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<td>+7.3</td>
</tr>
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<td>-5.4</td>
<td>+7.2</td>
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<tr>
<td></td>
<td>-5.5</td>
<td>+7.3</td>
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<td>+7.2</td>
</tr>
<tr>
<td></td>
<td>-5.7</td>
<td>+7.3</td>
</tr>
<tr>
<td></td>
<td>( \Delta X = X_1 - X_2 = -(12.8 \pm 0.2) \text{ mm} )</td>
<td></td>
</tr>
</tbody>
</table>

\( \text{BPA:} \)

\( X_1 = (-5.6 \pm 0.2) \text{ mm} \)
\( X_2 = (+7.2 \pm 0.1) \text{ mm} \)
\( Y_1 = (-1.5 \pm 0.1) \text{ mm} \)
\( Y_2 = (-1.6 \pm 0.1) \text{ mm} \)

\( \Delta X = X_1 - X_2 = -(12.8 \pm 0.2) \text{ mm} \)

\( \text{RF:} \)

\( \Delta R = 0.866 \ (f_1 - f_2) = -(13.9 \pm 0.9) \text{ mm} \)
Photo 1  BPA 10 mm outside of PS-axis
IF-signals at demodulator inputs
1st acq. X = +12.9 mm  M162
2nd acq. X = -2.8 mm  M175
beam intensity 95.10^10 ppp

Photo 2  BPA centered on PS-axis
IF-signal at demodulator inputs
1st acq. X = +3.8 mm  M168
2nd acq. X = +18.8 mm  M177
10 ms/div

Photo 3  BPA 10 mm inside of PS-axis
IF-signals at demodulator inputs
1st acq. X = -5.5 mm  M162
2nd acq. X = -21.0 mm  M175
beam intensity 102.10^10 ppp
Photo 4  BPA 10 mm inside of PS-axis
demodulator input and output signals
top: hor. IF difference \( \Delta \),
100 mV/div bottom: demodulated hor.
diff. \( \Delta \), 200 mV/div, \( \ell \) - IF gain
increased by 10 dB
1st acq. +1.2 mm
2nd acq. -0.2 mm

Photo 5  spectrum analysis of vertical
sum IF-signal 0.5 MHz/div, 10 dB/div
log. ref. level +10 dBm
trigger M 163
beam intensity 77.1010 ppp