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Resonant Beam Position Monitor

For Low Beam Intensity

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Abstract

The SPS-accelerator at CERN has been used recently to accelerate ion beams for fixed target experiments at 200 GeV/c per nucleon. The low intensity of a few microamperes in the accelerator ring cannot be monitored by the standard beam diagnostics equipment. One of the directional couplers used for closed orbit measurement has been modified and equipped with two 200 MHz resonators, so that the shunt impedance of the beam monitor has increased by a factor 200 x reaching 100 Ω. Using the standard 200 MHz receivers and acquisition system of the closed orbit measurement, the beam position can be measured by the resonant monitor with an accuracy of ± 0.5 mm over an intensity range of 0.1 µA - 10 mA. The resolution of the intensity measurement at 200 MHz is typically 5 nA for intensities up to 2-4 µA. The sum signal of the resonant monitor has been used also for setting the servospill of the slow beam extraction of $4 \times 10^7$ sulphur $^{32}$S-ions.
INTRODUCTION AND DESIGN CONSIDERATIONS

A monitor with two resonant loops in the vertical plane has been chosen for installation near to the quadrupole QF 214 where the vertical aperture of the accelerator is 40 mm. Because of the small vertical aperture occupied by the beam at this place, the striplines of the vertical loops can be mounted close to the beam and far from the vacuum chamber, so that the loops embrace a maximum of the magnetic flux produced by the beam. The two ends of the striplines are supported by two radial launchers mounted on two coaxial feedthroughs of the vacuum chamber (fig. 1). For a resonant monitor the upstream feedthroughs with respect to beam propagation are connected to the resonators, whereas the downstream feedthroughs are left open. By virtue of the reciprocity theorem for electromagnetic fields, the voltage induced in the loop by the beam is proportional to the dot product of the beam current and the longitudinal electric field produced by the loop when excited externally 2,3). A strong longitudinal electric field along the beam path is created by long vertical launchers coming close to the beam. Maximum voltage is gained from the loop if the two vertical ends are located at a distance l which equals one quarter of the distance $\lambda$ between subsequent bunches: $l = \lambda/4$. Since the ion-beams are bunched at 200 MHz by the RF-acceleration cavities, the resonant monitor is tuned to 200 MHz.

The horizontal loops of the monitor (fig. 1) have a characteristic impedance of 50 $\Omega$, and can be used as a test line for exciting the resonators and for checking the accuracy of the electromagnetic centre of the monitor. It should be remembered that the resonant monitor BPCO has been derived from the mechanical design of the directional coupler BPCR 4), which has a coaxial feedthrough at either end of the 50 $\Omega$-stripline in order to monitor two colliding beams separately at their upstream ports.
EXTERNAL RESONATORS

In order to increase the electromagnetic interaction between the beam and the monitor, external resonators are connected to the feedthroughs of the monitor loops, so that the voltage of the loops acting back on the beam is increased and more signal power is extracted from the beam. The bunch frequency of the beam being 200 MHz, cable resonators made of semi-rigid 50 Ω cables have been used. Two stubs are connected to the signal line at an interval of \( l_2 = \lambda/4 \), see fig. 3. The first stub is short-circuited (\( l_1 = 0.14 \lambda \)), the second is open (\( l_3 = 0.075 \lambda \)). The length of the cable stubs has been adjusted to gain maximum power out of the resonators when excited by test line C. The resonator including the loop has a bandwidth of 5.5 MHz at -3 dB, when loaded by the hybrid junction by 50 ohms.

The hybrid junction provides the sum and difference signal of the two resonators. If both resonators are excited equally by the test line C or D, the uniformity of the loops and resonators can be checked. In fact a ratio \( \Delta/\Sigma \leq 0.005 \) has been measured corresponding to an electrical error of the beam position monitor of less than 0.2 mm, if the beam is located exactly in the mechanical centre of the monitor.

IMPEDANCE OF MONITOR LOOP

The monitor loop can be characterized by different measurements of the output voltage at the upstream feedthrough. Without any beam in the monitor, the characteristic impedance \( Z_c \) of the loop can be measured as the ratio between the voltage \( U_c \) and the current \( I_c \) of a wave travelling in or out of the loop: \( Z_c = U_c/I_c \). The measurement is carried out by a network analyser or reflectometer, which monitor the forward and backward waves.
If the loop is loaded by a resonator which reflects nearly the totality of the wave coming out of the loop, a standing wave is built up in the loop with a large voltage which reacts against the beam at the two vertical legs of the loop extracting more signal power from the beam than a matched stripline. The power $P$ extracted from the beam is expressed by the shunt impedance $Z_s$ by:

$$ P = \frac{1}{2} Z_s I_o^2, $$  \hfill (1)

where $I_o$ is the amplitude of the beam intensity measured at 200 MHz.

The characteristic impedance of a single stripline inside a parallel cylinder can be approximated by 5)

$$ Z_c = 60 \Omega \arg \cosh \left( \frac{D^2 + d^2 - 4e^2}{2 d D} \right) = 153 \Omega $$  \hfill (2)
$$ d = (w + t)/2 = 11 \text{ mm}, \quad D = 173 \text{ mm} $$
$$ e = (D - 2h - t)/2 = 37 \text{ mm}. $$

For a smooth transition of the characteristic impedance from 50 $\Omega$ at the feedthrough up to about 140 $\Omega$ at the end of the launcher (photo 2), the diameter $b$ of the launcher has been chosen for $b = 8 \text{ mm}$. The mean value of the characteristic impedance $Z_L$ of the launcher is given by the ratio $h/b$ 5):

$$ Z_L = 60 \Omega \ln (1.15 h/b) = 116 \Omega $$  \hfill (3)
for $h = 48 \text{ mm}$ and $b = 8 \text{ mm}$. 

The characteristic impedance of the stripline has been measured with the network analyser. The measurement of the reflexion coefficient at the inner side of the upstream coaxial feedthrough is shown by the Smith diagram in fig.2. The circle described by the reflexion coefficient in the Smith diagram is a direct measurement of the characteristic impedance of the loop formed by the stripline, the two vertical launchers and the vacuum chamber:

$$ Z_c = \sqrt{Z_1 Z_2} = 132 \Omega. $$  \hfill (4)
The frequency $f_0 = 334$ MHz at $Z_0$ in the Smith diagram (fig.2) indicates the electrical length $\lambda$ of the loop:

$$\lambda = \frac{\lambda}{2} = \frac{c}{2f_0} = 449 \text{ mm}$$  \hspace{1cm} (5)

where $\lambda$ is the wavelength at frequency $f_0$ and $c$ is the speed of light.

The characteristic impedance along the loop can be observed in detail with a fast sampling scope used as a reflectometer. The reflectometer emits a fast step pulse towards the loop, which reflects back a fraction of the signal at every discontinuity of the characteristic impedance. The sampling scope monitors the total of the emitted step voltage and the reflections from the device under test. In the centre of photo 1, the top of 3 ns duration reveals the reflexion ($r = 0.47 \pm 0.03$) of the stripline, which has a characteristic impedance of:

$$Z_c = \frac{1 + r}{1 - r} \cdot 50 \ \Omega = 139 \pm 10 \ \Omega.$$  \hspace{1cm} (6)

The very short reflexions from the upstream feedthrough and launcher are shown in photo 2. The short negative reflexion before the rise from 50 Ω to 140 Ω along the launcher is caused by the capacitance of the diaphragm in the coaxial vacuum feedthrough.

**TRANSFER IMPEDANCE OF MONITOR LOOP**

The voltage induced in the pick-up loop by the beam in the centre of the monitor can be derived easily from the electric and magnetic fields of the beam. For ultrarelativistic beams, the same field distribution exists as for electrostatic line charges located at the centre of mass of the beam. For ultrarelativistic beams ($v = c$) travelling through the centre ($\rho = 0$) of a circular monitor, the transverse electric field strength $E_r(r)$ induced by the beam current

$$I_b = I_o \sin 2\pi (ft - z/\lambda)$$  \hspace{1cm} (7)

at distance $r$ from the centre amounts to:

$$E_r(r) = \frac{I_b}{2\pi \varepsilon_0 r} = \frac{I_b \cdot 60 \ \Omega}{r}$$  \hspace{1cm} (8)
where

$I_0$ : amplitude of beam intensity at signal frequency $f$
$t$ : time
$c = 3.10^8$ m/s , $c_0 = 8.86 \cdot 10^{-12}$ As/Vm
$z$ : axis of beam propagation
$\lambda$ : wavelength of signal frequency $f$, $f \lambda = c$.

The radial electric field $E_r$ of the beam induces a source voltage $U$ in the radial legs of the loop at $z = 0$ and $z = \lambda$:

$$U(z=0) = \int_R^R \frac{R}{\ln \left( \frac{R}{R-h} \right)} \sin(2\pi ft)\, \frac{E_r}{R-h} \, dr = I_0 \times 60 \Omega \ln \left( \frac{R}{R-h} \right) \sin(2\pi ft)$$ (9)

$$U(z=\lambda) = \int_R^R \frac{R}{\ln \left( \frac{R}{R-h} \right)} \sin(2\pi (ft - \lambda/\lambda))\, \frac{E_r}{R-h} \, dr = -I_0 \times 60 \Omega \ln \left( \frac{R}{R-h} \right) \sin(2\pi (ft - \lambda/\lambda))$$ (10)

There is also a source voltage induced at the launcher by the magnetic field of the beam. For ultrarelativistic beams $v \approx c$, the magnetic induction equals the electric induction voltage, and the total voltage observed on a matched load equals half the source voltages $^2$.

The source voltages induced at both ends of the stripline split up in a forward and backward wave of half the induced voltage amplitude. At the downstream end of the feedthrough, the forward waves cancel each other. At the upstream feedthrough, the backward waves add up:

$$U_O = \frac{1}{2} \left[ U(z=0) + U(z=\lambda) \right]$$ (11)

$$U_O = I_0 \times 60 \Omega \ln \left( \frac{R}{R-h} \right) \sin(2\pi \lambda / \lambda) \cos(2\pi (ft - \lambda/\lambda))$$ (12)

For a beam passing through the centre of the monitor, the transfer impedance of the stripline terminated by its characteristic impedance is given by $^4$:

$$Z_L = U_O / I_b = 60 \Omega \ln \left( \frac{R}{R-h} \right) \sin(2\pi \lambda / \lambda).$$ (13)
If the loop is loaded by 50 Ω at both feedthroughs, the output voltage at the upstream port and the transfer impedance \( Z_m \) are reduced by the matching factor \( m \):

\[
Z_m = m Z_t , \quad \text{wherein} \quad m = \frac{1 + g}{\sqrt{1 - 2g^2 \cos(4\pi k/\lambda)} + 4g^2} = 0.45 
\]

\[
g = \frac{Z_o - Z_c}{Z_o + Z_c} = -0.45 , \quad k = 0.3 \lambda 
\]

The transfer impedance \( Z_m \) can be measured by injecting a test current \( I_t \) into the test line \( C \). Thereby the beam current \( I_o \) is replaced by the test current \( I_t \). The proportionality factor \( n = I_t/I_o \) is obtained from eq. (38) by setting \( x = 0 \) and \( y = r \) for the location of the test current, and by setting \( x = y = 0 \) for the beam in the centre position:

\[
n = \frac{2 \ln (R/a)}{\ln \left( \frac{R^2 + a^2 r^2}{R^2} \right)} = 20 , \quad \text{for} \quad \frac{R^2 + a^2 r^2}{a^2 + r^2} 
\]

\( R = 86.5 \text{ mm} \), \( a = 38.5 \text{ mm} \), \( r = 81.25 \text{ mm} \).

From the measurement of the voltage ratio \( U_1/U_2 = -35 \text{ dB} = 0.018 \) between the test line \( C \) and the loop \( A \) terminated by 50 Ω at both feedthroughs, the transfer impedance \( Z_m \) is obtained by:

\[
Z_m = 50 \Omega \left( \frac{U_1}{U_2} \right) n = 18 \pm 2 \Omega . 
\]
This measurement agrees with the theoretical value calculated from:

\[ Z_m = 60 \, \Omega \ln(R/a) \sin(2\pi l/\lambda) \]
\[ m = 20 \, \Omega. \]  \hspace{1cm} (19)

In order to check the substitution of the beam current by a test current in the test line, the transfer impedance of the directional coupler BPCR has been measured also. This coupler has four striplines 50 \, \Omega identical to the test lines of the monitor BPCO. The dimensions of the coupler BPCR are:

\[ R = 86.5 \, \text{mm}, \quad r = a = 81.25 \, \text{mm}, \quad l = 375 \, \text{mm} = \lambda/4. \]

The voltage ratio caused by the coupling between two orthogonal striplines \( Z_c = 50 \, \Omega \) of the coupler BPCR has been measured and is:

\[ U_1/U_2 = -47 \, \text{dB} = 0.0045 \] providing a transfer impedance

\[ Z_t = 50 \, \Omega \left( U_1/U_2 \right) n = 3.6 \pm 0.4 \, \Omega, \] wherein \hspace{1cm} (20)

\[
 n = \frac{2 \ln(R/r)}{\ln\left(\frac{R^4 + r^4}{2R^2 r^2}\right)} = 16 \] for BPCR  \hspace{1cm} (21)

This measurement agrees with the definition of the transfer impedance of the directional coupler BPCR:

\[ Z_t = 60 \, \Omega \ln(R/r) \sin(2\pi l/\lambda) = 3.75 \, \Omega. \]  \hspace{1cm} (22)
SENSITIVITY OF POSITION MONITOR

An important design characteristic of beam position monitors is the sensitivity \( S \) of the monitor signal \( U \) versus a small beam displacement \( \delta x \) from the centre position \( (x=0) \):

\[
S(x=0) = \frac{\delta U}{\delta x} \cdot \frac{1}{I_0} 
\]

(23)

If the beam is located in the \( xz \) plane which contains also the two loops of the beam monitor (fig. 1), the output voltage \( U_{1,3} \) of loop A and B with resonators is given by:

\[
U_1(x) = m I_0 \cdot 60 \Omega \ln\left(\frac{R^2 - ax}{R(a-x)}\right) \sin(2\pi k/\lambda) 
\]

(24)

\[
U_3(x) = m I_0 \cdot 60 \Omega \ln\left(\frac{R^2 + ax}{R(a+x)}\right) \sin(2\pi k/\lambda) 
\]

(25)

\( R \) is the radius of the vacuum chamber, \( x \) is the beam position in the median plane \( (y=0) \), and \( a \) is the mechanical aperture of the monitor in the median plane : \( a = R - h \). The matching factor \( m \) represents here the transformation ratio between the source voltage \( U_0 \) and the output voltages \( U_{1,3} \). For a matched impedance transformer between the characteristic impedance \( Z_c \) of the stripline and the output load \( Z_o \), the factor \( m \) is given by:

\[
m = \sqrt{Q Z_o / Z_c} 
\]

(26)

where \( Q \) is the loaded Q-value of the resonator \(^3\).

The beam position \( x \) is measured from the difference \( \Delta = U_1 - U_3 \) and the sum \( \Sigma = U_1 + U_3 \) of the output voltages of two opposite loops using the linear approximation:

\[
x = d \cdot \Delta / \Sigma, 
\]

(27)

where \( d \) is the aperture factor of the monitor depending on the height \( h \) of the monitor loop.
The aperture factor \( d \), the sensitivity \( S \) and the transfer impedance \( Z_m \) of a beam position monitor are related by

\[
S = Z_m / d. \tag{28}
\]

The sensitivity \( S \) of the monitor is calculated from eq. 23 and 24 and amounts for a beam in the centre:

\[
S = m \cdot 60 \, \frac{\Omega}{R^2 - a^2} \, \frac{R^2 - a^2}{R^2 a} \sin(2\pi l / \lambda). \tag{29}
\]

The mechanical aperture \( a \) and the aperture factor \( d \) for a beam displacement along the axis \( x \) (fig. 5) are related by:

\[
d = \frac{a \, R^2}{R^2 - a^2} \ln \left( \frac{R}{a} \right) = 38 \text{ mm for BPCO.} \tag{30}
\]

For a monitor with \( a \ll R \), the sensitivity is defined only by the mechanical aperture \( a \) of the striplines:

\[
S \ (a \ll R) = (m \cdot 60 \, \frac{\Omega}{a}) \sin(2\pi l / \lambda) \tag{31}
\]

The analysis presented here has been derived using the assumption that the propagation delays in the launchers between the feedthroughs and the striplines can be neglected for a given signal wavelength \( \lambda \), and that the height \( h \) of the loop is therefore limited to \( h < \lambda / 10 \). It has also been assumed that the beam is ultrarelativistic so that the electric field distribution matches closely that for an electrostatic line charge.
LINEARITY OF POSITION MONITOR

The response of the loop monitor versus beam position is not linear, and is different for a beam located either in the median plane or outside of it. The exact response of the loop monitor for any beam position for ultrarelativistic beams can be derived from the logarithmic potential of electrostatic line charges. For relativistic beams $v < c$, the field distribution in the monitor is expressed by Bessel functions $^2$. Both methods provide the same result for the ion beams of the SPS ($10 < \gamma < 200$), because the arguments of the Bessel functions are very small.

Following the simpler approach for ultrarelativistic beams with practically the speed of light $c$, the field distribution in a circular and conducting cylinder is usually derived with the help of an image line charge $-I_0/c$, which reproduces the same boundary conditions as the vacuum chamber. As it is well known from electrostatics, two parallel line charges located at source point $T (x, y)$ and $T'$ create a logarithmic potential $V(r)$ at field point $P(r)$, (fig. 4):

$$V(r) = \frac{-I_0}{2\pi \epsilon_0 c} \ln \left( \frac{r_1}{r_2} \right) + C,$$

where $C$ is a constant. (32)

$$r_1^2 = \rho^2 + r^2 - 2\rho r \cos \varphi,$$

(33)

$$r_2^2 = R^2/\rho^2 + r^2 - 2(R^2/\rho) r \cos \varphi,$$

(34)

$$\rho \cos \varphi = x, \quad \rho \sin \varphi = y,$$

(35)
The constant C must be chosen so that \( V = 0 \) on the cylinder wall \((r = R)\). Combining the equations 22 - 25, the logarithmic potential at field point P \((r)\) is expressed by:

\[
V(r) = I_b \ 30 \ \Omega \ \ln \left( \frac{R^4 - 2R^2rx + r^2(x^2 + y^2)}{R^2(r^2 - 2rx + x^2 + y^2)} \right),
\]

where \(x\) and \(y\) indicate the beam position.

The voltage \(U\) induced in the upstream launcher \((z = 0)\) is obtained from equations (9) and (36)

\[
U = \int_{a}^{R} E_x \ dx \ = \ V(r=a).
\]

The total output voltage from the upstream and downstream port is given by eq. (12) for a beam in centre position. Applying (11) for a beam at position \((x, y)\), the output voltages \(U_{1,3}\) of two opposite loops 1 and 3 are:

\[
U_1 = m I_o \ 30 \ \Omega \ \ln \left( \frac{(R^2 - ax)^2 + a^2y^2}{R^2(a - x)^2 + R^2y^2} \right) \sin(2\pi l/\lambda)
\]

\[
U_3 \ (x, y) = U_1 \ (-x, y)
\]

\[
U_3 = m I_o \ 30 \ \Omega \ \ln \left( \frac{(R^2 + ax)^2 + a^2y^2}{R^2(a + x)^2 + R^2y^2} \right) \sin(2\pi l/\lambda).
\]

As usual in beam position measurements, the output voltages \(U_1\) and \(U_3\) of two opposite striplines are combined in a hybrid junction, which provides the difference voltage \(\Delta\) and the sum voltage \(\Sigma\) of two loops:

\[
\frac{\Delta}{\Sigma} \ (x, y) = \frac{U_1 - U_3}{U_1 + U_3}.
\]
The function $\hat{A}^{\pm}(x)$ is plotted in fig. 5 for the resonant coupler BPCO, with the ordinate $y$ of the beam position as parameter. The function $\hat{A}^{\pm}(x)$ is about linear, but its slope depends strongly on $y$. In order to determine the beam position horizontally and vertically with better precision, two measurements are required, one in the horizontal plane: $p = \Delta H/I H$, and the other one in the vertical plane: $q = \Delta V/I V$. By means of the two measurements $p$ and $q$, the beam position can be determined from the following expressions:

$$\frac{x(p,q)}{a} = c_1 \pm \frac{p-q}{c_2} - \sqrt{\left(\frac{c_1 + p-q}{c_2}\right)^2 - \frac{p}{c_3}}$$

(41)

$$\frac{y(p,q)}{a} = c_1 \mp \frac{p-q}{c_2} - \sqrt{\left(\frac{c_1 - p-q}{c_2}\right)^2 - \frac{q}{c_3}}$$

(42)

where $a$ is the distance of the striplines from the centre of the monitor. The constants $c_1$, $c_2$ and $c_3$ depend on the geometry of the monitor and are for $a = 0.445$ R (BPCO):

$c_1 = 1.333$, $c_2 = 1.836$, $c_3 = c_2/4$, $c_1 = 0.344$. 

(43)

The accuracy of the approximations given in eq. 41 and 42 for the geometry of the monitor BPCO is better than $\pm 0.06\cdot a$ for $x^2 + y^2 < 0.8a^2$.

**COUPLING BETWEEN LOOPS**

The loops of the beam monitor are coupled to each other by the electromagnetic interaction. If a current flows through loop $A$, it induces a voltage $V_1$ in loop $A$ and a much smaller voltage $V_3$ in loop $B$ (fig. 3). The maximum coupling between parallel striplines occurs when the lines are a quarter wavelength long. In this case, the coupling coefficient $k$ is defined as the voltage ratio between the $\lambda/4$-striplines

$$k = \frac{V_3}{V_1} \ll 1.$$

(44)
For a beam position monitor, it is necessary that the coupling between the
different loops or electrodes is as small as possible, otherwise the
sensitivity $S$ of the monitor is reduced to $S_k$:

$$S_k = \frac{1 - k}{1 + k} \cdot S. \quad (45)$$

The coupling factor can be evaluated either by measurement or by
calculation. The most reliable method is the measurement of the
electrostatic capacitances of the striplines. The coupling coefficient
$k_{13}$ between a pair of striplines is given by $^6,^7$:

$$k_{13} = \frac{C_{13}}{\sqrt{(C_{10} + C_{13})(C_{30} + C_{13})}}. \quad (46)$$

The line capacitances $C_{10}$ and $C_{30}$ are the partial capacitances of line
1 and 3 to ground, and $C_{13}$ is the partial capacitance between the two
lines 1 and 3.

The line capacitances are related also to the coupled transmission line
impedances $Z_e$ and $Z_0$ by $^6,^7$:

$$Z_{e1} = \frac{1}{c \ C_{10}}, \quad c = 3.10^8 \text{ m/s} \quad (47)$$

$$Z_{01} = \frac{1}{c \ (C_{10} + 2 \ C_{13})}, \quad (48)$$
where \( Z_e \) and \( Z_o \) are the even and odd line impedance, when two lines are excited by a voltage source either in phase (even mode) or in antiphase (odd mode). The beam in centre position excites only the even mode in all striplines of equal height. However, if the beam is not in centre position, there is a voltage difference between the striplines, and for this voltage difference, the line impedance is \( Z_o \). The characteristic impedance \( Z_c \) of a coupled transmission line is lowered by the coupling \(^{6,7}\):

\[
Z_{c1} = \sqrt{\frac{Z_{e1} Z_{o1}}{C_{10}}} = \frac{1}{C_{10}} \sqrt{\frac{1}{1 + 2 C_{13}/C_{10}}} \tag{49}
\]

In the case of four coupled striplines, the different coupling factors can be derived from the static capacitance matrix \((4 \times 4)\) \(^8\). For reasons of simplicity we consider only the coupling between the two strongly coupled loops A and B (fig. 1), and neglect the weakly coupled loops C and D.

The static line capacitances of the four striplines of length 0.375 m have been measured:

Stripline A and B : \( C_{10} = C_{30} = 22.4 \pm 0.8 \) pF/m
Stripline C and D : \( C_{20} = C_{40} = 66.7 \pm 2.7 \) pF/m
\( C_{13} = C_{31} = 2.560 \pm 0.013 \) pF/m
\( C_{12} = C_{23} = C_{34} = C_{14} = 0.900 \pm 0.005 \) pF/m. \( \tag{50} \)

The characteristic impedance \( Z_c \) of the mutually coupled striplines A and B calculated from the static line capacitances amounts to:

\[
Z_e = 149 \pm 5 \, \Omega \quad \text{without coupling},
\]
\[
Z_c = 143 \pm 6 \, \Omega \quad \text{with coupling}. \tag{51}
\]

The coupling factors between striplines measured from the static line capacitance are

\[
k_{13} = 0.103 \pm 0.004 \quad \text{striplines A-B}
\]
\[
k_{12} = k_{23} = k_{34} = k_{14} = 0.023 \pm 0.001. \tag{52}
\]
The strong coupling $k_{13}$ between striplines A and B reduces the sensitivity of the position monitor by 20%. The weak coupling between the test lines C or D and the monitor striplines A and B allows for testing the monitor and the electronics of the position measurement by a calibrated test signal at 200 MHz CW.

**NEUTRALIZATION OF COUPLING BETWEEN LOOPS**

The coupling between loops modifies the position measurement. In the case of four equal striplines placed at 90° intervals around the circumference of the monitor, the coupling between horizontal and vertical loops introduces an additional term between horizontal beam position and vertical position measurement. This effect can be neutralized by injecting the same fraction of signal but with opposite polarity at the outside of the monitor feedthroughs by means of an attenuator with the ratio $k$.

In the case of the position monitor BPCO, only the striplines A and B have been decoupled by a capacitive signal divider. In order to get more signal power out of the monitor, external resonators have been connected to the striplines A and B. In this case the coupling between resonant striplines increases and must be neutralized experimentally.

The phase of the internal coupling between resonant striplines has been measured at 200 MHz and has a lag of 90°. By adjusting the capacitance trimmer of the neutralization, the coupling between striplines A and B has been reduced to $k_{13} \leq 0.01$.

The neutralization of the coupling has been tested also with beam, after installation of the resonant monitor in the SPS-accelerator. The vertical closed orbit has been displaced by 4.0 mm at the monitor, and the position measurement by the closed orbit acquisition system ($\Delta z = 0.11$) has provided a beam displacement of:

$$y = d \Delta z = 4.2 \text{ mm} \quad \text{for } d = 38 \text{ mm}.$$  \hspace{1cm} (53)

This measurement confirms that the sensitivity $S$ and the aperture factor $d$ are not degraded by coupling between the resonant loops, thanks to the external neutralization.
OUTPUT POWER OF RESONANT MONITOR

The output power $P$ of the resonant loop for a beam in centre position is characterized by the shunt impedance $Z_s$, see eq. (1). The shunt impedance can be measured in the laboratory by injecting a current signal into the test lines C or D of length $\lambda/4$. Thereby the beam current $I_o$ is replaced by the test current $I_t$ at distance $r = 81.25$ mm from the monitor centre:

$$I_t = n I_o, \text{ where } n = 20 \text{ for BPCO}$$

(54)

The laboratory measurements of the output power $P$ of the resonators, when excited by a test line, have provided a shunt impedance $Z_s$ for the two resonant loops together:

$$Z_s = n^2 Z_0^P/P_t = 90 \mp 10 \Omega$$

(55)

where $P_t$ is the signal power injected into the test line ($Z_0 = 50$ $\Omega$) and $P$ is the power at output $I$ of the hybrid junction.

Beam tests have been carried out with deuton and oxygen beams. The beam intensity has been measured by the beam current transformer BCT (HS), which has a sensitivity of a few microamperes. The 200 MHz-amplitude $I_o$ of beam intensity is calculated from the BCT-measurement by:

$$I_o = b N e f_{rev}^\epsilon, \text{ where}$$

(56)

$$\begin{align*}
N &: \text{ number of particles measured by BCT, } e = 1.6 \times 10^{-19} \text{ As} \\
b &: \text{ bunching factor calculated from observed bunch length } t_o \text{ for a cosine shape of the bunch.}
\end{align*}$$

$$b = \frac{2 \cos (\pi t_o f)}{1 - (2 t_o f)^2}, \quad f = 200 \text{ MHz.}$$

(57)
The electronic equipments measuring the signals of the resonant monitor have been carefully calibrated before the beam tests and verified afterwards. Deuton beams of typically \( N = 500 \cdot 10^9 \) charges and a bunch length \( t_o = 3 \text{ ns} \) corresponding to a 200 MHz beam intensity \( I_o = 4.8 \text{ mA} \) have produced a signal \(<\xi> = 0.34 \text{ V} \) at the output of the synchronous 200 MHz-receiver in BA2.

Calibration of the electronic chain (fig. 3) comprising the 200 MHz bandpass filter and preamplifier 0 dB in the tunnel, the coaxial cable between tunnel and BA2, and the synchronous 200 MHz-receiver operating at 14 dB gain have confirmed that the output signal \(<\xi> \) of the hybrid junction of the resonant monitor BPCO was \( P = 1.12 \text{ mW} \) for a beam intensity \( I_o = 4.8 \text{ mA} \). The shunt impedance \( Z_s \) measured at the output \( \xi \) of the hybrid junction is therefore:

\[
Z_s = \frac{2P}{I_o^2} = 97 \pm 5 \Omega. \tag{58}
\]

Measurements with an oxygen beam of \( N = 33.10^9 \) charges have been carried out with the preamplifier 30 dB switched on. These measurements at low intensity have provided the same shunt impedance, confirming the linearity and calibration of the RF-amplifiers, receiver and acquisition system.

**OBSERVATION OF LOW-INTENSITY ION BEAMS**

The beam current of oxygen and sulphur ions amounts to 1-20 \( \mu \text{A} \) in the SPS and is much smaller than the intensity of continuous proton beams reaching 100-300 mA during fixed target operation. Beam intensities over such a large range can be measured only by switching the gain of programmable RF-amplifiers. The homodyne 200 MHz-receivers developed for the closed orbit measurement \(^{10}\) allow to adjust the gain of the receivers in steps of 14 dB over a range of 70 dB. In front of the receiver, there is a low-noise 200 MHz preamplifier with a gain of 30 dB installed at the output of the resonant monitor in the tunnel. By means of this amplifier chain, beam intensities as low as 0.5 \( \mu \text{A} \) can be measured with a signal-to-noise ratio of 30 dB at the output of the homodyne receiver. Reducing the bandwidth of the receiver output to 1 KHz improves the signal-to-noise ratio of the measurement by another 30 dB.
The reproducibility of the position measurement by the resonant coupler BPCO has been checked with a beam of $2-4 \times 10^7$ sulphur ions. The reproducibility of the beam position measurement was $\pm 0.3$ mm including the fluctuations of the beam over 10 cycles. This measurement has been carried out at high energy with the closed orbit acquisition system integrating the sum and difference signals during 1 ms.

The sum signal $\Sigma$ of the receiver can be used also for monitoring the beam intensity via an integrator with 20 ms time constant used otherwise for the beam current transformer BCT. Since the RF-signals of the beam depend on the length of the bunch, this is only a relative measurement of beam intensity, however very sensitive due to RF-amplification and its narrow bandwidth. In photo 3, the 4 injections of bunched beam are visible, but the sum signal disappears immediately after debunching, when the beam spreads out over the whole circumference of the SPS during the injection flat bottom. One second after the fourth injection, the RF-cavities are switched on and the beam is rebunched at 200 MHz. At this instant, the intensity signal $\Sigma$ of the RF-receiver reappears, see photo 3 and 4. The sum signal $\Sigma$ is not constant at the beginning of the acceleration ramp, because the bunch length changes during the front porch of the acceleration cycle and stabilizes after transition only. The dependance of the RF-signal on the bunch length of the beam clearly shows the limitations of the RF-intensity measurement.

For the extraction of $2-5 \times 10^8$ oxygen ions in 1986, the RF-cavities have been switched off, and the beam has been debunched immediately afterwards, photo 3. In 1987, sulphur beams of only $2-4 \times 10^7$ ions have been accelerated in the SPS, and the RF-cavities were on during the slow extraction, in order to provide an intensity signal from the resonant monitor. At this very low beam intensity of 2-4 $\mu$A, the intensity signal $\Sigma$ of the 200 MHz-receiver was used to set up the extraction rate of the servospill, photo 4.
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Photo 1: Reflexion coefficient $r$ [0.25/div] of the loop versus propagation time $t$ [2 ns/div] or distance $l$ [0.3 m/div] from the feedthrough (negative dip of the reflexion factor). Length of loop: 0.45 m.

Photo 2: Reflexion coefficient $r$ [0.25/div] of the launcher versus propagation time $t$ [200 ps/div].

1: diaphragm of feedthrough
2: front end of stripline
Photo 3

RF-intensity signal $I(t)$ of $4 \times 10^8$ oxygen $^{16}\text{O}$-ions. Signal increases during acceleration because of shorter bunch length.

\[ 0 \quad 1.2 \quad 2.4 \quad 3.6 \quad 4.6 \quad 5.2 \quad 10 \quad 15 \quad t \]

Cycle Time

1. 2. 3. 4. Injection and Acceleration

Debunching at 10 GeV/n.
(RF Off)

Capture RF

Extraction at 200 GeV/n.
(RF On)

Debunching (RF Off)

Photo 4

RF-intensity signal $I(t)$ of $4 \times 10^7$ sulphur $^{32}\text{S}$-ions accelerated and extracted at 200 GeV/nucleon.

\[ 0 \quad 4.6 \quad 12.2 \quad t \]

Cycle Time
Loop 1 terminated by 50 Ω

\[ Ze = \sqrt{Z_1 Z_2} = 132 \ Ω \]
FIG. 3 - Schematic Layout of Resonant Beam Monitor and Synchronous Receiver 200 MHz.

FIG. 4 - Polar Coordinates of Beam Position $T (\mathcal{S}, \varphi)$ in the Vacuum Chamber and of its Image at $T' (R^2/\mathcal{S}, \varphi)$.

$OT = \mathcal{S}$

$OT' = R^2/\mathcal{S}$

$TP = r_1$

$T'P = r_2$

$x = \mathcal{S} \cos \varphi$

$y = \mathcal{S} \sin \varphi$
FIG. 5 - Normalized response $\frac{\Delta}{\Sigma}$ of monitor BPCO ($R = 86.5$ mm, $a = 38.5$ mm) versus beam position $x$ and $y$. 