RESONANT BEAM POSITION MONITOR FOR LOW INTENSITY ION BEAMS

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Abstract

The SPS-accelerator at CERN has been used in 1986/87 to accelerate ion beams for fixed target experiments at 200 GeV per nucleon. The low beam 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 resonant stripline has been increased to > 1000 ohms. 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 a reproducibility of ± 0.5 mm over an intensity range of 20 nA - 2 mA. The resolution of the relative intensity of the 200 MHz signal is better than 10^{-3} of the intensity range 100 nA - 2 mA selected by the programmable gain 0-86 dB of the RF-amplifiers [1]. The sum signal of the resonant monitor has been used also for setting the servospill of the slow beam extraction of 4.10^7 sulphur ions.

Design Considerations

A monitor with two resonant striplines in the vertical plane has been installed in the SPS accelerator at a place where the vertical aperture of the machine is only Ø 40 mm (fig. 1). Because of the small vertical aperture required for the beam, the striplines in the vertical plane can be mounted close to the beam and far from the vacuum chamber, so that the stripline 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 coaxial feedthroughs (fig. 2). For a resonant stripline, only one feedthrough is required towards the resonator, whereat the other end of the stripline is left open. By virtue of the reciprocity theorem for electromagnetic fields, the voltage induced in the stripline by the beam is proportional to the dot product of the beam current and the longitudinal electric field produced by the stripline when excited externally [2]. 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 a stripline of length $\ell = \lambda/4$, where λ = 1.5 m is the wavelength of the dominant spectral line of the beam (200 MHz). The horizontal stripline loops C and D of the monitor (fig. 1, 2) have been retained from an earlier version BPCR, and serve as test lines for exciting the resonators.

Cable Resonators

In order to enhance the electro-magnetic interaction between the beam and the monitor, a resonance is set up in the stripline. By this resonance, the voltage at the open end of the stripline acting back on the beam is multiplied, and more signal power is extracted from the beam. The resonators are made of semi-rigid coaxial cables, which have an attenuation constant α = 0.008 Np/m at 200 MHz providing a quality factor $Q_o = \pi/\alpha\lambda_o$ = 400 for an unloaded cable resonator (λ_o = 1 m). The load resistance of the hybrid junction (fig. 1) is matched to the resonator by means of a short-circuit stub ℓ_1. The length of the individual cables of the resonator has been adjusted for maximum power output from the resonant striplines when excited by a test line. The resonator including the stripline has a loaded Q-factor Q_L = 130 measured from the 3 dB-bandwidth Δf = 1.5 MHz of the resonator output. The hybrid junction provides the sum and difference signal of the two resonators : Σ and Δ. If both resonant striplines are excited equally by a test line, the equality 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.

Transfer Impedance of Stripline Monitor

The transfer impedance indicates the output voltage U_o of a stripline for a given beam intensity I_b located at the centre of the monitor. If the stripline is loaded by its characteristic impedance, the transfer impedance Z_L of a matched

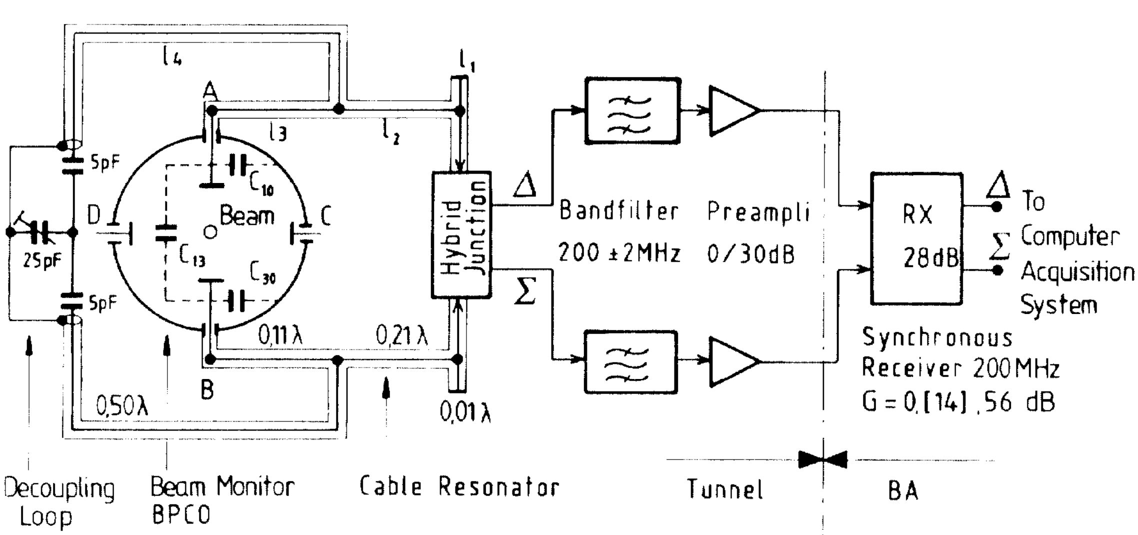

Fig. 1 - Schematic Layout of Resonant Beam Monitor and Synchronous Receiver 200 MHz

stripline is given for the BPCO-monitor by [3] :

$$Z_t = U_o/I_b = 60\Omega \, \ln(R/a)\, \sin(2\pi \ell/\lambda) = 48\ \Omega$$

for R = 86.5 mm, a = 38.5 mm, ℓ = 0.25 λ, where "R" means the radius of the vacuum chamber and "a" is the distance of the resonant striplines from the monitor centre (fig. 3).

Since the characteristic impedance Z_c = 139 Ω of the BPCO-stripline is considerably higher than the load resistance R_o = 50 Ω, the stripline can be matched to the load by a lossless impedance transformer. In the case of a resonant impedance transformation, more signal voltage $U_m = m\, Z_t\, I_b$ is gained from the monitor, and the transfer impedance is enhanced by a factor $m = \sqrt{Q_L R_o/Z_c} = 7$ by the interaction of the resonator with the beam.

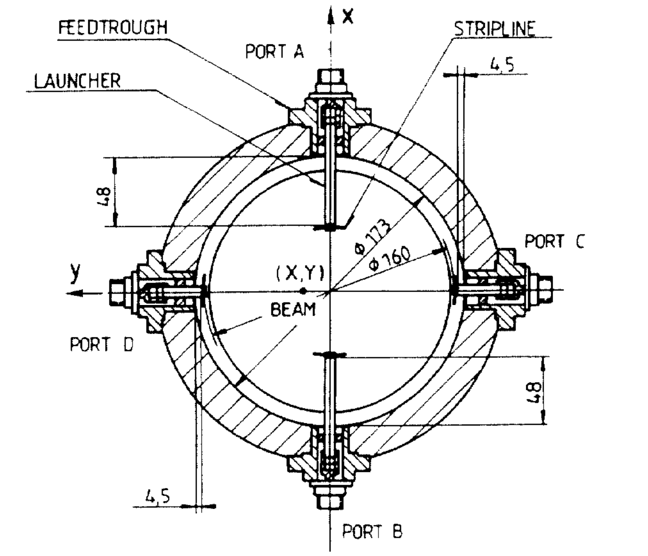

Fig. 2 - Cross section of resonant coupler BPCO

Logarithmic Beam Potential

The output signal of a stripline versus beam position can be derived from the logarithmic potential of ultrarelativistic beams. For the ion beams of the SPS (10<γ<200), the transverse electric field induced by an ultrarelativistic beam (v≈c) can be readily derived from the potential field of the beam. The electric potential V created in a circular cylinder of radius R by a ultrarelativistic beam of electrically charged particles propagating parallel to the cylinder axis at the source point T(x,y) (see fig. 3) is given by [3] :

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

where r is the coordinate of the field point P on the x-axis, at which the electric potential is measured along the launcher of the stripline. The RF-voltage induced by an ultrarelativistic beam of charged particles is negligible along the stripline, because the longitudinal electric field vanishes and so does also the magnetic induction $d\emptyset/dt$, except for the radial launchers at both ends of the stripline. The voltage U_ℓ induced in the launchers is obtained from :

$$U_\ell = \int_a^R E_x dr + d\emptyset/dt = 2V(r{=}a), \text{ since}$$

$$d\emptyset/dt = \mu_o \int_a^R H dr (dz/dt) \simeq \mu_o c \int_a^R H dr = \int_a^R E_x dr = V(r{=}a).$$

The voltages induced in the launchers split up in a forward and backward wave propagating in opposite directions. The total RF-voltage U_o available at the upstream end of the stripline terminated by its characteristic impedance is given by the vector sum of the backward waves from the two ends of the stripline, taking into account their relative phase difference $\Delta\varphi = 4\pi\ell/\lambda$: $U_o = V(x,y,a)\sin(2\pi\ell/\lambda)$.
Since the output of the stripline is loaded by a resonator, a standing wave is set up in the stripline, and the output voltage $U_m = mU_o$ is multiplied by the interaction of the standing wave with the beam.

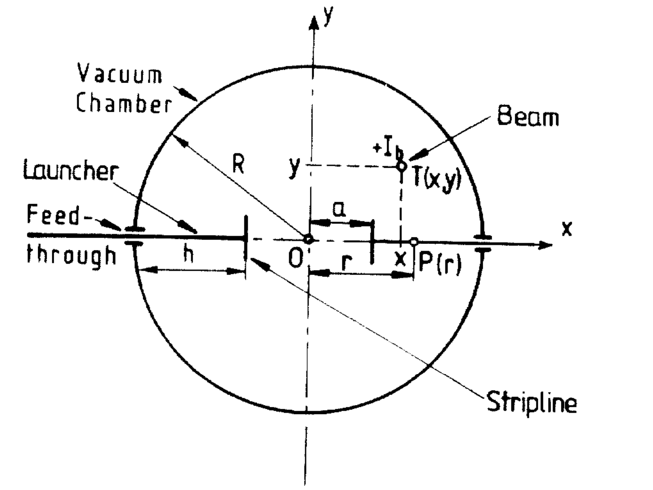

Fig. 3 - Schematic cross section of monitor cylinder, rotated by 90°

Beam Position Measurement

The output voltages U_1 and U_3 of the resonators connected to the vertical ports A and B of the monitor amount to :

$$U_1(x,y) = mU_o = 30\Omega\, m\, I_b \,\ln\left(\frac{(R^2-ax)^2 + a^2y^2}{(Ra-Rx)^2 + R^2y^2}\right) \sin(2\pi\ell/\lambda)$$

$$U_3(x,y) = 30\Omega\, m\, I_b \,\ln\left(\frac{(R^2+ax)^2 + a^2y^2}{(Ra+Rx)^2 + R^2y^2}\right) \sin(2\pi\ell/\lambda)$$

As usual in beam position measurements, the output voltage U_1 and U_3 of a position monitor are combined in a hybrid junction, which provides the vector difference voltage Δ and the vector sum voltage Σ of the monitor signals U_1 and U_3. The beam position T (x,y) is contained implicitely in the normalized difference $\Delta/\Sigma(x,y)$:

$$\frac{\Delta}{\Sigma}(x,y) = \frac{U_1 - U_3}{U_1 + U_3} = \frac{L(x,y,a) - L(x,y,-a)}{L(x,y,a) + L(x,y,-a)} , \text{ with}$$

$$L(x,y,a) = \ln \frac{(R^2-ax)^2 + a^2y^2}{(Ra-Rx)^2 + R^2y^2} .$$

The function $\Delta/\Sigma(x,y{=}cst)$ is plotted in fig. 4 for the resonant coupler BPCO. For y = constant, the function is about linear, but its slope depends strongly on the parameter y. In order to determine the beam position by a nonlinear monitor, two measurements are required, one in the horizontal plane : $p = \Delta H/\Sigma H$, and the other in the vertical plane : $q = \Delta V/\Sigma V$. The horizontal and vertical beam coordinates x and y can be calculated from the two measurements p and q by :

$$\frac{x(p,q)}{a} \simeq c_1 + \frac{p-q}{c_2} - \sqrt{\left(c_1 + \frac{p-q}{c_2}\right)^2 - \frac{4p}{c_2}}$$

$$\frac{y(p,q)}{a} \simeq c_1 - \frac{p-q}{c_2} - \sqrt{\left(c_1 - \frac{p-q}{c_2}\right)^2 - \frac{4q}{c_2}}$$

where a is the distance of the striplines from the centre of the monitor. The constants c_1 and c_2 depend on the geometry of the monitor and for a = 0.445 R give c_1=1.333, c_2=1.836.

The explicit formulae for calculating the beam position have been obtained from a linear approximation of the plots in fig.4. The accuracy of the above formulae has been checked and is better than ± 0.06·a inside the aperture $\sqrt{x^2+y^2}<0.9a$ of the BPCO-monitor. If only one measurement p is available in plane x alone, the measurement error is less than ± 0.06a inside a restricted aperture $\sqrt{x^2+y^2}<0.5a$.

Shunt Impedance of Resonant Monitor

The signal power P extracted from the beam by a stripline is calculated from the shunt impedance Z_s by $P = ½Z_s I_b^2$, where I_b is the amplitude of the beam intensity measured at 200 MHz. The shunt impedance of a resonant stripline is related to the transfer impedance by :

$$Z_s = m^2 Z_t^2/R_o = 2100\ \Omega.$$

In practice the measured shunt impedance is lower because of mismatch losses due to the feedthrough and the neutralisation of the stripline coupling. The two resonators are strongly coupled by their striplines, but it is possible to decouple them by an external decoupling loop [4], which causes some losses (2 dB).

The shunt impedance of the resonant stripline has been determined in the laboratory by measuring the coupling factor between the test line 1 (C or D) and the resonant stripline 2 (A or B). The coupling factor k_{12} between striplines 1 and 2 with a matched output load is obtained from the electrostatic measurement of the partial capacitances of the striplines :

$$k_{12} = C_{12}^2/C_1C_2 = 0.00044$$

wherein C_{12} is the partial capacitance between stripline 1 and 2, and C_1 and C_2 are the total capacitance of lines 1 and 2 to ground (with all other lines connected to ground).

The ratio between the RF-power in the test line (P_1) and in the resonating stripline (P_2) has been measured at 200 MHz : $P_2/P_1 = 0.032$. Since $P_2/P_1 = k_{12}Q_m$, the measured quality factor Q_m of the resonant stripline with the decoupling loop amounts to : $Q_m = 70$. Because of the losses of the decoupling loop, the measured shunt impedance Z_s is reduced to :

$$Z_s = Q_m Z_t^2/Z_c = 1200\ \Omega.$$

The shunt impedance can be measured also from the beam, if the beam intensity is known. In the SPS, the intensity of the deuteron beams of 50 µA can be measured with good precision from the beam current transformer. The shunt impedance of a different resonator than in fig.1 has been measured with a deuteron beam [3]. The measurement with beam agrees perfectly with the laboratory measurement using the weakly coupled test line.

Acknowledgements

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References

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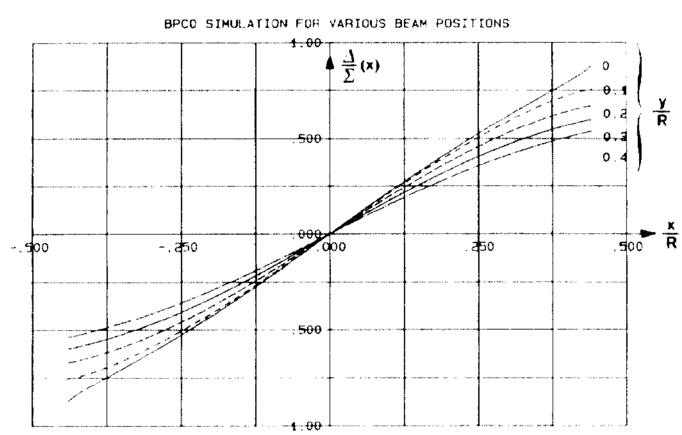

Fig. 4 - Normalised response Δ/Σ (x,y) of monitor BPCO versus beam position x , y = cst.