The New Directional-Coupler Pick-Up for the HERA Proton Beam Position Monitoring System

W. Schütte M. Wendt K.-H. Meß
DEUTSCHES ELEKTRONEN SYNCHROTRON
Notkestraße 85, D-2000 Hamburg 52, FR-Germany

Abstract

For the $820 GeV$ HERA Proton Storage Ring Accelerator a new directional-coupler pick-up is beeing developed. This cryogenic device is part of the superconducting quadrupole module. It determines either the horizontal or the vertical position of the beam. The pick-up is designed to operate under various conditions: $1 \ldots 210$ bunches per turn, $10^9 \ldots 10^{11}$ particles per bunch and bunch-lengths of $0.3 \ldots 2m$. The monitoring system is able to measure a selected single bunch with or without integration over several turns. It will also be used for beam-loss warning and calculation of tune, tune spread and some other machine parameters. Two $40cm$ long 50Ω transmission-line electrodes of the coupler are placed in indentations of the vacuum pipe in order to reduce parasitic mode losses. Special cryogenic RF-feedthroughs and very high pressure fabrication techniques are used. The electrode/beam coupling is 8% and the sensitivity is $1.2dB$ per mm. The pick-up is read out by a $104MHz$ broadband high-speed analog electronics.

Introduction

At DESY in Hamburg the 35-820 GeV e-p storage ring HERA is being built. For the superconducting proton arcs a beam position monitoring system is being developed. For each of the 220 quadrupoles the position is measured in its focussing direction. This enables one to steer the beam through the inaccessible cold part of the ring at startup. In the normal storage operation the system permits a precise alignment of the beam along the quadupole axis. The pick-up is designed to get maximum sensitivity with minimum disturbance of the beam, in particular with minimum power losses. A directional-coupler pick-up type is chosen.

Requirements for the Beam Position Monitoring System

The main task of the beam position monitoring system is the measurement of the orbit and the position of a single specified bunch. The beam position has to be determinated for two operation modes of the machine, the *comissioning* and the standard *storage* operation. During the comissioning phase a low intensity pilot bunch has to be surveyed on a single pass through the pick-ups. In storage mode a high resolution is required.
An option for the evaluation of tune, tune-spread and chromaticity exists. For selected pick-ups a modified digital electronics allows the position measurement of every passing bunch (*beamscope*).

Since the superconducting magnets are very sensitive to a beam impact, an advanced feature to minimize this risk has been implemented into the digital part of the monitoring system. This socalled *quench protection* initiates a controlled beam dump, if a sufficiently large deviation of the beam from the pick-up center is detected. For any beam loss the last 1024 positions and 256 orbits are stored for a *post mortem* analysis.

The beam position monitoring system consists of 220 directional-coupler pick-ups in the four arcs. They measure the two transverse planes separately: each horizontal pick-up is precisely aligned to a horizontal focussing quadrupole and correspondingly for the vertical case. All pick-ups are ultra-high vacuum devices and are mounted within the $4\,K$ cryostat. This restricts the selection of materials and fabrication methods. Furthermore the introduced heat, especially that due to the mode losses, has to be minimized [1]. The pick-ups are part of the quadrupole module and a maximum length of $530\,mm$ was available. In addition the device is not allowed to limit the aperture, therefore the beampipe diameter of $55.3\,mm$ has to be kept clear.

The pick-up is built to measure properties of the HERA proton bunches. These bunches are between $0.3\,m$ and $2\,m$ long and of parabolic shape in phase space[1] [2]. One bunch contains between 10^9 and 10^{11} protons[2]. Up to 210 bunches with a minimum spacing of $96\,ns$ are circulating in the machine.

The Directional-Coupler as Beam Position Pick-Up

The beam position measurement consists of the determination of the beam location with respect to the vacuum chamber center, which in turn is usually carefully aligned to the quadrupole axis. The beam position is reconstructed with the aid of two or four distance-sensitive elements (electrical sensors), see Figure 1. The use of two elements allows only position measurement in one dimension.

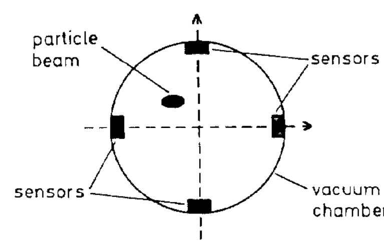

Figure 1: Principle of the beam position measurement with distance-sensitve elements

There are four types of distance sensors:

- Current Pick-Ups
- Inductive Pick-Ups
- Capacitive Pick-Ups and
- Directional-Coupler Pick-Ups.

The former type utilize the image current of the beam. The latter types couple to the magnetic-, the electric- or the electromagnetic field of the beam respectively.

Only a directional-coupler is able to meet the conditions discussed in the previous section. The current (*resistive wall*) pick-up has intolerably high heat losses for a $4\,K$ environment. Inductive (*transformer*) pick-ups are slow, complicated and lossy. Capacitive (*button*) pick-ups are unsuited for the long HERA bunches [3].

The heart of a directional-coupler sensor is a $\lambda/4$ antenna which couples electromagnetically to the frequency spectrum of the beam.

[1] In real space the shape has the form: $i_{norm}(t) = 16\,c\,[1-(2\,c\,t/\ell)^2]^{3/2}/(3\,\pi\,\ell)$

[2] Especially the pick-up has to be sensitive to a $2\,m$ long pilot bunch with less than 10^9 particles.

CH2387-9/87/0000-1725 $1.00 © IEEE

PAC 1987

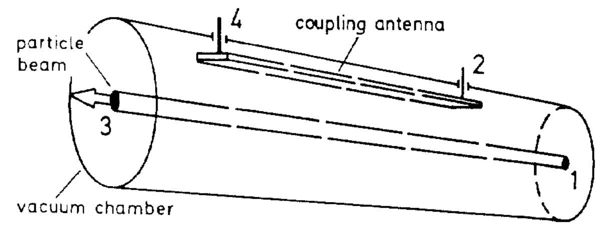

Figure 2: directional-coupler principle

The distance-sensitive signal emerges only on the upstream port (2) of the antenna (B), see Figure 2.

In electrical terms this device is a four-port transmission-line directional-coupler with coupled lines of unequal characteristic impedances, where the beam (A) is one of the transmission-lines. The theory of this coupler is extensively discussed in [4]. The admittance matrix is given by:

$$\mathbf{Y} = j \cdot c \cdot \begin{pmatrix} \mathbf{C} \cdot \frac{1}{\tan\Theta} & \mathbf{C} \cdot \frac{1}{\sin\Theta} \\ \mathbf{C} \cdot \frac{1}{\sin\Theta} & \mathbf{C} \cdot \frac{1}{\tan\Theta} \end{pmatrix}, \tag{1}$$

with the *capacitance matrix*[3]

$$\mathbf{C} = \begin{pmatrix} C_A + C_{AB} & -C_{AB} \\ -C_{AB} & C_B + C_{AB} \end{pmatrix},$$

the *electrical phase* $\Theta = \omega\, l/c$ (l: antenna length),

and the speed of light $c = 2.998 \cdot 10^8\, m/s$.

From the relation $\mathbf{I} = \mathbf{Y} \cdot \mathbf{U}$ and the termination of the ports $2 \dots 4$ in their characteristic impedances one finds for a beam current i_1 and the output voltage v_2:

$$\frac{v_2}{i_1} = \frac{k}{c\sqrt{C_A C_B}} \cdot \frac{j \tan\Theta}{\sqrt{1-k^2} + j \tan\Theta}, \tag{2}$$

where $k = \frac{C_{AB}}{\sqrt{C_A C_B}}$ is the *coupling coefficient*.

Obviously the coupling coefficient k increases with decreasing distance between beam and antenna. Formula (2) as a function of frequency is called the *transfer function* between the output (measuring) port and the incoming beam.

The HERA beam position pick-up consists of two antennas in juxtaposition (now labeled with index B and C). Together with the beam A we have a six port device, which is called a *dual* directional-coupler. It is described correspondingly to the four port case (1) with the capacitance matrix

$$\mathbf{C} = \begin{pmatrix} C_A + C_{AB} + C_{AC} & -C_{AB} & -C_{AC} \\ -C_{AB} & C_B + C_{AB} + C_{AC} & -C_{BC} \\ -C_{AC} & -C_{BC} & C_C + C_{AB} + C_{AC} \end{pmatrix}$$

The derived capacitances are computed numerically by a SOR-method [5]. The characteristic impedances of the antennas are cross checked with a time-domain reflectometer measurement. Finally the signal ratio of the output ports is determined as a function of the beam position in one and two dimensions (see last section).

Technical Implementation

The major design decisions are the antenna length, width and shape. For the detailed construction a multitude of aspects – ultra-high vacuum, cryogenic temperatures, high frequencies, etc. – have to be considered. The problems of series fabrication were studied in an early stage.

[3] Index A corresponds to the beam and the index B to the coupler antenna

The first antenna design parameter is its length l. It has to be matched to the frequency spectrum of the bunch. For the $0.3 \dots 2\, m$ long bunches in HERA the optimal antenna lengths are $0.1 \dots 0.8\, m$. The available space inside the quadrupole module is limited to only $0.53 m$. Due to antenna sag the length is restricted to about $0.5\, m$ in our case, while an extra support has mechanical and electrical problems of its own. We chose an antenna length of $0.395\, m$, which still gives a sufficiently high signal for $2\, m$ long bunches of 10^9 protons. The maximum sag is about $0.2\, mm$, corresponding to an impedance deviation of less than 1Ω.[4]

The width of the antenna determines the coupling k to the beam (2): wider antennas give stronger output signals. On the other hand the position sensitivity of the device decreases. A small width is highly favoured by power loss considerations in the $4\,K$ cryogenic environment. A larger antenna width leads to a bigger mechanical radius – to meet the $50\,\Omega$ transmission-line condition – and both imply higher mode losses. We chose the smallest mechanical reasonable width of $17\, mm$, which results in a coupling of $k \approx 0.08$ to the beam, assuming a circular beam of about $3\, mm$ diameter.

The shape of antenna and pick-up body must not limit the beam aperture. Furthermore the characteristic impedance has to be $50\,\Omega$. Power losses as well as fabrication costs have to be minimized. We used smoothed shapes with the antennas bulged into the pick-up body.

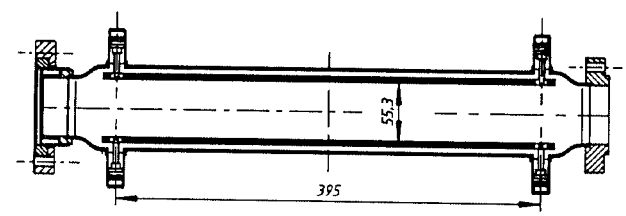

Figure 3: Technical drawing of the HERA beam position pick-up (longitudinal section)

The major construction problems are the precise alignment of the pick-up, the achievment of the $50\,\Omega$ rf transmission-line mechanical layout and the compensation of the thermal expansion of the antenna. The pick-up axis has to be aligned with the highest accuracy to the cold quadrupole axis to reach acceptable absolute position errors. A tolerance of less than $0.3\, mm$ is achieved by using a precision flange connection[5] to the quadrupole.

The $50\,\Omega$ transmission-line property is given by the arrangements of antenna and pick-up body (*ground*). A tight tolerance of $0.05\, mm$ over the entire antenna length is required, exclusive of sagging. The antenna ends are connected to the pins of $50\,\Omega$ N-type feedthroughs. These devices fulfill the ultra-high vacuum conditions even at $4\,K$ temperatures.[6]

During the machine operation, temperature differences of a few $100\,K$ will occur between the pick-up body and the antennas. This results in a relative expansion up to nearly $1\, mm$. The feedthrough ceramics can not withstand these stress forces. A special suspension with $0.1\, mm$ thick springs has been constructed to compensate for the thermal expansion.

The manufacturing of the pick-up body is of special interest, due to its complicated bulging form of high accuracy. For the series production of these bodies, stainless steel tubes are pressed at $1650\, bar$ into the precisely machined positive mould of a hydraulic apparatus. This fabrication step takes less than $1\, h$ and is done entirely at DESY. Special care has been taken in the selection of the steel and the welding and soldering alloys for their rf and ultra-high vacuum suitability down to $4\,K$ temperatures.

[4] Due to the antenna shape the sagging effect is only important for the vertical pick-ups

[5] These are ultra-high vacuum connections with good rf properties (i.e. small beampipe discontinuities)

[6] We chose *Kyocera* type *N-R*

Properties of the HERA Proton Beam Position Pick-up

In conclusion we present the measured and calculated performance of the device.

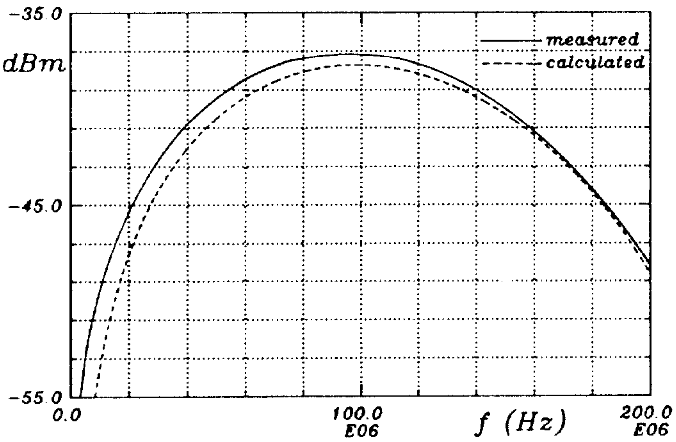

Figure 4: Frequency domain response of the HERA beam position pick-up to a $2m$ long bunchsignal

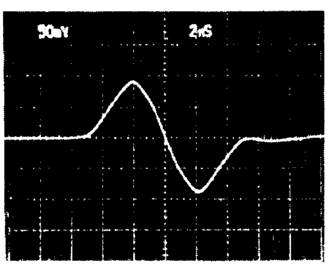

Figure 5: Time domain response of the HERA beam position pick-up to a $2m$ long bunchsignal

The actual output signal of a sensor is given by the convolution of the bunch spectrum[7] with the pick-up transfer function (2). For a $2\,m$ long pilot bunch with only 10^9 particles the output signal has $v_{out} \approx 180\,mV_{pp}$. The maximum levels are at frequencies about $100\,MHz$ with a $\pm 50\,MHz$ bandwidth.

[7] The fourier transformation of i_{norm} gives the normalized bunch spectrum $\rho(\omega) = 32J_2(\frac{1}{2}\omega\ell/c)/(\omega\ell/c)^2$

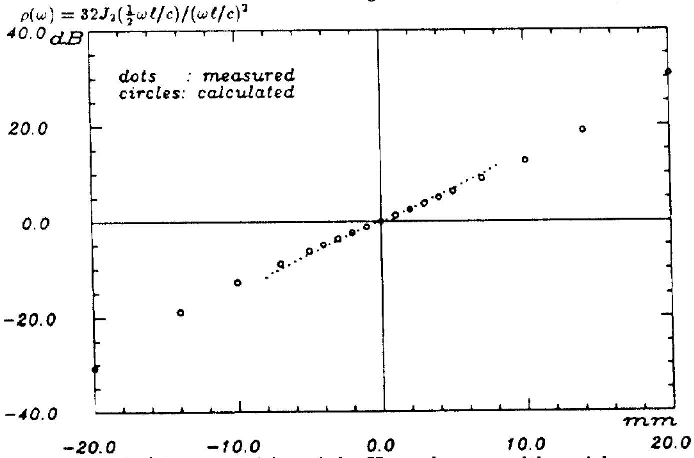

Figure 6: Position sensivitity of the HERA beam position pick-up along the major axis

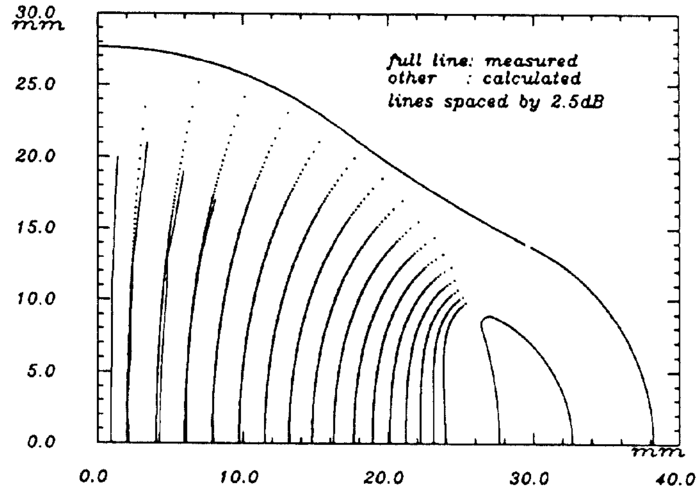

Figure 7: Position sensivitity of the HERA beam position pick-up for both axes of the transverse plane

Due to the relatively small coupling of $k = 0.08$ we get a high position sensitivity of $v_B/v_C = 1.2\,dB/mm$. The pick-up response to beam deviations is linear within $\pm 1\,cm$. Also in two dimensions the response is a monotonic function of the deviation.

The location of the narrow antennas in bulges in the pick-up body leads to small power losses. They are computed to be less than $0.2\,W$ under all HERA operation conditions [1].

Conclusions

A directional-coupler beam position pick-up with $40\,cm$ long electrodes has been developed. The prototype meets all requirements for operating in the arcs of the HERA proton storage ring. A $104\,MHz$ broadband readout electronics is currently being designed [6].

Acknowledgements

We are grateful to S. Klehn and G. Hoffmann for their technical support and to J. Bailey for checking the manuscript.

References

[1] M. Wendt, W. Schütte and T. Weiland, "Estimation of Mode Losses in Complex RF Vacuum Devices," presented at the *IEEE Particle Accelerator Conference, Washington, D.C., March 16-19, 1987*)

[2] R. D. Kohaupt, private communications

[3] W. Schütte and M. Wendt, "Estimation of the Output Signal Strength of the PETRA Beam Position Pick-Up for Proton Bunches," *DESY HERA 87-05, February 1987*

[4] E. G. Cristal, "Coupled-Transmission-Line Directional Couplers with Coupled Lines of Unequal Characteristic Impedances," *IEEE Trans. on Microwave Theory and Techniqes, Vol. MTT-14, No. 7, pp. 337-346, July 1966*

[5] I. Petrescu, Diploma Thesis on 2D-Capacitance Calculations and Measurements, *University of Hamburg*

[6] to be published