RESULTS OF MEASUREMENTS ON THE HERA PROTON BEAM POSITION MONITORS

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Abstract: A beam position monitoring system has been designed for the 820 GeV HERA proton storage ring accelerator. There will be 243 pickups of the directional coupler type in the ring. The vacuum, mechanical and electrical properties of each must be measured. These measurements ensure good quality and form the basis for determination of the beam orbit position relative to the corresponding quadrupole axis. The results of the measurements and the alignment procedure are described.

Introduction

HERA, now under construction at DESY in Hamburg, is a pair of storage rings in which 820 GeV protons will be collided against 30 GeV electrons. The proton bunches will be between 0.3 and 2.7 m long and each will contain between 10^9 and 10^{11} particles. Up to 210 such bunches will be placed in 220 equispaced RF buckets. The orbit of the proton beam must be measured with an accuracy considerably better than 1 mm with respect to the corresponding quadrupole axes [1]. For this task a position monitoring system is under construction. It consists of 243 directional coupler pickups. The readout uses the method of amplitude ratio to phase difference conversion [2]. The position of a single preselected bunch will be digitized with an accuracy of 8 bits.

In HERA there is a strong distinction between the straight sections and the arcs: the straight sections use conventional technology while the arcs are totally equipped with superconducting magnets. There are only 23 pickups in the straight sections [3]. They differ from the cold monitors in mechanical design details and will not be considered further in this paper. Each of the arcs consist of a very long cryostat built of dipole and quadrupole modules. In each quadrupole module sits a position monitor, separated from the quadrupole magnet by more than a meter. This is due to the correction dipole magnet, the second major element of the module. Next to a horizontally (vertically) focussing quadrupole one measures the position in the horizontal (vertical) direction only.

The pickup is part of the UHV beam pipe and is located inside the isolation vacuum of the module. It is fixed to the beam pipe of the module with a precision fitting which is part of a conflat flange. The beam pipe itself is tightly welded inside the helium vessel of the cryostat as basic mechanical reference. The vessel has a good connection to the quadrupole magnet.

The beam will induce electromagnetic losses (of less than 0.2 W) due to standing waves inside the pickup [4]. The pickup is also electroplated with copper to avoid unnecessary heating due to the beam image current on the vacuum chamber. The beam induced heat is transported into the liquid helium via thermal conduction in the beam pipe and via a copper braid connection between the pickup and the two phase liquid helium pipe[1)]. This reduces mechanical stresses on the vacuum system due to thermal expansion of the pipe, feedthroughs and flanges.

1) Heat transportation by radiation is reduced to a negligible amount by the superisolation directly around the pickup.

The pickup itself is a 530 mm long directional coupler (Fig. 1) [5]. It consists of two 395 mm long $\lambda/4$ antennas, covering 36° in azimuthal angle. They are fitted into bulges in the sides of the round beam pipe to keep the losses due to beam induced electromagnetic waves as low as possible [4]. This geometry leads to 8% coupling. The monitor constant is expected to be 1.2 dB/mm [6] because of the small pipe radius of 55.3 mm and the low coupling.

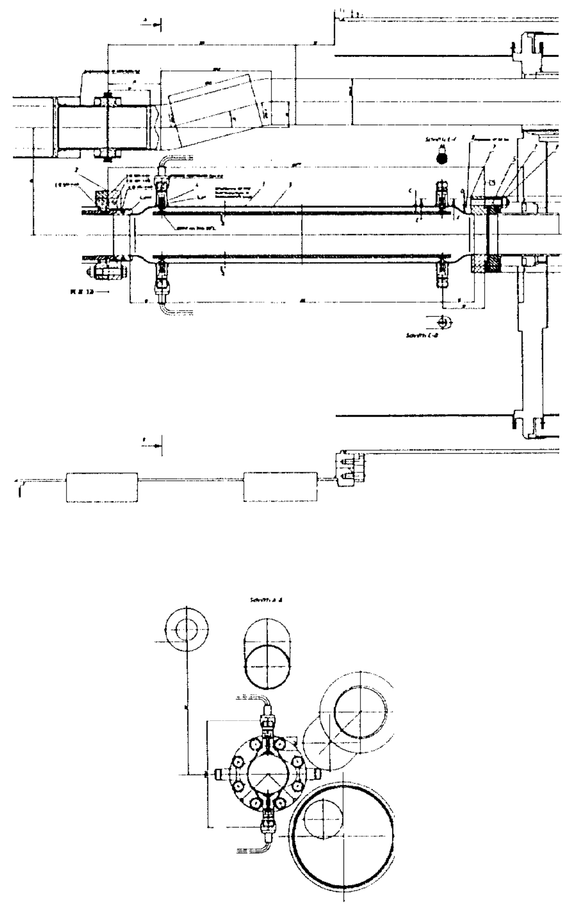

Fig. 1 Beam position pickup in its cryostat

Though the monitor body is kept close to liquid helium temperature, even with a proton beam in the machine, this is not true for the antenna. The electrical insulation results in a good thermal isolation, and heat transport with radiation is extremely small at ultra low temperatures. Therefore the antennas are suspended on small springs, which permit a relative expansion/compression of 1.5 mm, i.e. a 50% safety margin. A test showed that the springs survived easily 100000 movements. Two of the delivered pickups had to be returned to the factory because of broken springs; we assume that they were dropped during transport.

The pickups were fabricated in the following way: The 2.5 mm thick pipes were annealed and then

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hydraulically pressed at 1650 bar in a mould to form the antenna bulges. Everything except the feed-throughs with the antennas was welded together. The body was then plated with 12 μm of copper and the precision milling of the fitting in the quadrupole conflat flange was performed. The complicated cross section of the antennas was created by a drawing operation and the spring suspension and the Kyocera N-feedthroughs were Laser spot welded onto them. The feedthroughs were then welded into the pickup body. The spacing of the antennas from the body was controlled by a mechanical set-up which took into account the measured distortion due to welding of 0.7 mm. Finally, the pickup was thoroughly cleaned at 180°C at the company[2)]. At DESY the pickups were baked out totally in vacuum at 300°C and all the vacuum measurements were repeated [7].

Each pickup is connected with four ca. 3 m (17 nS) long cables to a flange in the quadrupole cryostat module. Since it is practically impossible to exchange these cables, they must be very radiation resistant. Custom made 50 Ω cables with Kapton bandages and connectors containing Vespel are used. They are only 3 mm thick due to the limited space and to keep thermal conduction low. Each is also wound around the 80 K heat shield of the cryostat, resulting in a heat load of less than 0.1 W per cable at 4 K. Finally the connection to the analogue electronics is done by cables similar to RG213.

General Properties

Each monitor was first visually inspected. On the first pickups deterioration of the copper coating near weld joints was found. This led to minor changes in the design and the welding procedure, after which no problems with the coating were observed. There was no evidence for poor adhesion of the copper due to remnant oil from the hydroforming process.

Two pickups were found to be much too long because of assembly errors during the welding process and the precision fittings at two monitors were too large. The general straightness and the parallelism of the flanges were checked by rotating the monitor on its precision fitting.

The required vacuum properties (leakage < 10^{-9} Torr•l/s, absorption < $3 \cdot 10^{-12}$ Torr•l/s cm^2) could only be reached by a 300°C vacuum bakeout, after which no problems were found due to the hydroforming oil or any other reason.

Two pickups failed the basic electrical tests. One had a feedthrough destroyed by welding. The other had an electrical connection between antenna and ground. The characteristic impedance of the antennas were found to be (49.36 ± 1.1) Ω , matching the cable quality. This corresponds to an accuracy of the distance between antenna and pickup body of (5.46 ± 0.25) mm.

Position sensitivity

The ratio of the output voltages of the two antennas is a good measure for the beam position. It is independent of the bunch shape, the selected measuring frequency and, except for threshold and saturation effects, is independent of the number of protons in the bunch. Of prime importance is the position sensitivity at the center of the monitor: the so called monitor constant, since the beam has to be steered by an iterative process onto the quadrupole axis.

The position sensitivity of the pickups was measured with a special machine which used two pairs of excenters to translate a signal wire parallel to the monitor axis. The wire with its 1 mm diameter was matched to the 50 Ω measuring system with cylindrical resistors. The output voltages were measured with a spectrum analyzer at 104 MHz.

It was very difficult to achieve a mechanically reliable system. We had many problems with wires stretching, bending and breaking until we finally used a springy steel wire. It was not possible to make a reliable absolute position calibration with respect to the monitor flange. Also, the complicated setup with the two excenters led to difficulties in completely understanding positioning errors of the machine. Comparisons with the device described in the next sections show an absolute position uncertainty of 0.4 mm.

The output voltage ratio was measured for wire positions at nearly 100 points along the line between the two antennas. The ratio as function of position could well be parametrized by a linear function in the central ± 5 mm of the monitor. Outside this region, a term of the form $a \cdot x^b$ was added. The monitor constant was found to be 1.18 dB/mm with an accuracy of better than 5%. All measured sensitivity curves were identical within the digitalization accuracy except for their offset in the monitor center. Therefore we were content with measuring only a quarter of the monitors and determining this offset independently.

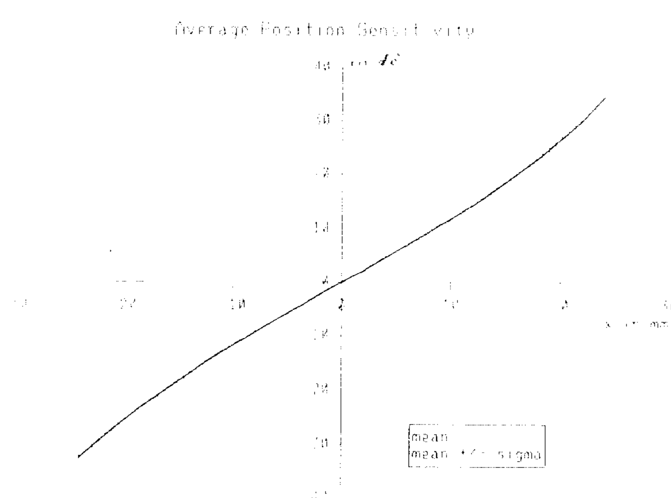

Fig. 2 Average position sensitivity of the pickup

2) A higher temperature was not possible due to the copper on the outside of the pickup turning black.

Determination of the Beam Position Relative to the Quadrupole Axis

The most important task of the position monitoring system is to allow beam steering through the quadrupole axis with an absolute accuracy of considerably less than 1 mm. This is ensured by a solid mechanical design and a chain of correction constants. The connection between the actual 8 bit digitization of the orbit position and the position of the cold quadrupole axis can be seen in the following listing:

- average over 128 turns of the position of a single bunch (defined here as orbit position)
- 8 bit digitalization
- analogue electronics
- different cable impedances
- electrical pickup center
- mechanical pickup center & monitor constant
- quadrupole module center
- quadrupole axis.

The resolution of the electronics is intensity dependent and degrades rapidly for bunches with less than 10^9 protons. The resolution degradation due to the least significant bit is 0.1 mm. The cables have an impedance uncertainty of 1.5 Ω r.m.s., which leads to different reflections on both feedthroughs, and an uncertainty of 0.12 mm.

Since the pickups are not totally symmetric, there are two distinct centers: an electrical and a mechanical. The electrical center is defined by a beam giving equal output voltages on both antennas, and the mechanical center by the precision fitting on the quadrupole flange. The relation between them is measured using a stainless steel device. It is basically a 25 mm diameter metal rod (50 Ω) fixed on a mating flange of the pickup. It is optimized for good mechanical tolerances (r.m.s. 30 μm). Electrically this bar serves as a "beam" in the same way as the wire in the position measurement machine. The "beam" here is terminated with zero impedance, resulting in a total reflection of the input current.

Next, the mechanical monitor center must be related to the quadrupole module center. This is done by optically surveying a target fixed on the quadrupole module monitor flange at the positions of both monitor ends. The reproducibility without cool down is 0.09 mm and with cool down 0.14 mm r.m.s. This includes the uncertainty of the difference in measurements at liquid helium and room temperature. For the actual connection the play of 0.03 mm r.m.s. in the slip fit of the actual monitors to the quadrupole module has also to be considered.

The total r.m.s. correction is found from:

	r.m.s. in mm
electrical-mechanical monitor center correction:	0.7
mechanical monitor center to quadrupole module axis:	0.4
quadrupole module center to quadrupole center:	0.4
total:	0.9

Since the expected correction is nearly one millimeter, it must be included in the measurement of the orbit. The correction itself leads to an uncertainty of 0.05 mm due to the 5% monitor constant error.

The sum total of the uncertainty is

	r.m.s. in 1/100 mm
least significant bit:	10
different cable impedances	
Kapton cables:	12
analogue electronic cables:	12
electrical-mechanical center relation:	3
mechanical center-quadrupole axis relation:	16
slip in precision flange:	3
correction error due to calibration constant uncertainty:	5
total:	26

The total error in measuring the position of the orbit of a proton beam of sufficient intensity with respect to the quadrupole axis is thus expected to be about 0.3 mm r.m.s. (this estimate does not include contributions from the calibration and stability of the analogue electronics, for which we do not yet have reliable measurements). This can only be reached by applying the proper calibration constants. The uncorrected system would have an error of the order of 1 mm.

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