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A MAGNETIC BEAM POSITION DETECTOR

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Summary

In storage rings, the monitoring of the coasting beam positions at the intersections is of prime importance for luminosity optimization and control of beam-beam space charge effects. The magnetic beam position detector, developed for the CERN Intersecting Storage Rings (ISR), is mounted around the standard vacuum chamber near the intersection point. Coils above and below the beam are used to detect the beam's magnetic field. To avoid the influence of external fields, the beam is wobbled vertically at 80 Hz and only field components at this frequency are measured with synchronous detectors. A feedback system maintains a null signal by centring the probe on the beam so that the beam position is known directly from displacement transducers mounted on the probe. The precision is better than 0.05 mm vertically and 0.25 mm horizontally with a 5 A beam modulated by ± 0.1 mm. Special care has been taken to minimize the parasitic currents in the vacuum chamber which limit the precision. The beam position modulation, which is confined to the intersecting region, is obtained by two a.c. vertical bending magnets per ring and it is synchronous and in phase for the two rings. This scheme was found to have a negligible effect on the beams.

1. Introduction

In collision rings, it is of particular interest to know with precision the beam positions, especially in the intersections in order to adjust the luminosity and to control the excitation of nonlinear resonances by the beam-beam interaction. However, many of these rings have coasting beams and the usual beam position detectors work only for bunched beams. The detector developed at the ISR is intended to satisfy the following requirements:

- precision better than 0.1 mm vertically and 0.25 mm horizontally for coasting beams of 5 A or more;
- easy mounting around a 160 mm diameter arm of a standard intersection vacuum chamber. The ease of installation makes it possible to remove the detector to avoid damage during vacuum chamber bake-outs.

2. Principle

The position of the beam can be determined by observing its magnetic field. However, due to the various residual magnetic fields encountered in the ISR, such as stray fields from magnets, the earth's field, etc., it is practically impossible to detect with sufficient precision the position of a debunched, stable beam from its surrounding field. Therefore, we add an a.c. component to the beam's magnetic field by varying its position periodically by a small amount (modulation). The detector is made sensitive only to this modulation frequency which can be chosen so as not to interfere with the magnetic noise coming from other equipment.

The magnetic field of the beam is measured by a number of coils mounted on a frame around the vacuum pipe. This frame can be moved horizontally and vertically by two motors. The detection coils are connected in such a way that the output signal is zero for both directions if the frame is centred on the beam. A feedback system maintains this condition so that the position of the frame is equivalent to the beam position. The advantage of this zero-method is that the precision is not influenced by the loop gain and by the detector's linearity.

3. Modulation

At the detector, the beam position should vary periodically. In our case, we chose a vertical modulation of ± 1/10 mm at 80 Hz for a 5 A beam. For higher currents, the amplitude of modulation is reduced in proportion to the intensity. A vertical displacement was preferred since it does not affect the Q-values via the localized sextupoles. Moreover, the displacement is made in the form of a local two-magnet bump, the amplitude of which is almost constant across the aperture. In an intersection region, the beams of the two rings can be modulated in synchronism. In this way, the modulation does not affect the beam separation or the electromagnetic beam-beam interaction which governs the excitation of nonlinear resonances.

The modulation is achieved by two horizontal field magnets, one on either side of the detector. These window-frame magnets are very short (~5 cm) due to the lack of space in the ISR and are designed to be mounted directly on the side of the H-magnets used for vertical bumps for luminosity adjustments. They have a maximum integrated field of 11.5×10^{-4} Tm at 80 Hz. With this, it is possible to get a modulation amplitude of ± 0.1 mm peak-to-peak at the detector for proton energies up to 31 GeV. The residual orbit distortion outside the bump region is 15 % of the bump height and the dependence on the radial position at the detector is 4 % for $\Delta r = 40$ mm. This dependence gives rise to a small error discussed later.

The modulation frequency of 80 Hz is a compromise between a higher frequency giving more induced signal in the detector coils and a lower frequency giving lower eddy currents in the vacuum chamber with a simpler modulator design. This frequency is also at a place in the spectrum where no harmonics of the main frequency (50 Hz) occur.

4. Detection

A pencil-beam current I modulated with a peak amplitude d creates the same alternating magnetic field as an a.c. current of strength I/2 (peak) at the modulation frequency flowing in opposite directions through two fixed parallel wires separated by 2d, i.e. a periodically varying dipole field.

In order to determine the beam position, the dipole field is detected by two sets of coils measuring separately the horizontal and the vertical position of the beam.

The coils are wound on coil formers above and below the beam and perpendicular to its axis (Fig. 1). Together with the inner shielding, they form a magnetic circuit with an open gap. This air gap slightly reduces the sensitivity to dipole fields but also strongly attenuates the influence of residual parasitic currents through the vacuum chamber. The coil formers are composed of laminated ANHYSTER sheets. The coils to measure the vertical position consist of one layer of 2296 turns over a length of 27.7 cm. The coils to measure the horizontal position are wound on top of the "vertical" coils at the edges of the coil former. The four "horizontal" coils have each 330 turns over a length of 4 cm. On either side of the coils, there are guard formers of the same composition as the coil formers. This is to avoid the influence of nearby ferromagnetic material on the field distribution of the beam near the detector coils.

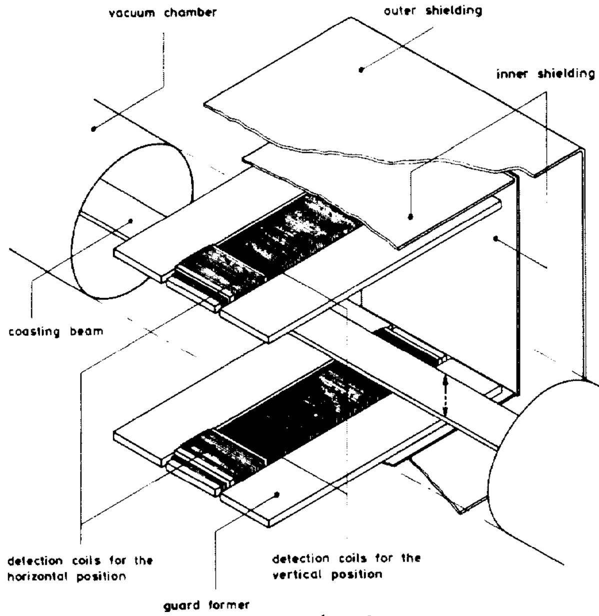

Fig. 1

For the same reason, the whole system is shielded against external fields.

For each set of coils, the geometry was chosen to give a good sensitivity and linearity along one coordinate axis and a small dependence on the other one. Figures 2 and 3 show the disposition and connection of the horizontal and vertical coils respectively. The signs correspond to the induced voltages at a given moment. Figures 4 and 5 show the sensitivities for displacements along the x- and the y-axes in a rectangle of ± 60 mm by ± 10 mm (which represents the actual limits of an ISR beam). For both directions, the output signal is zero if the detector is exactly centred on the dipole.

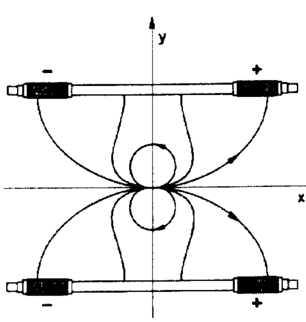

Fig. 2

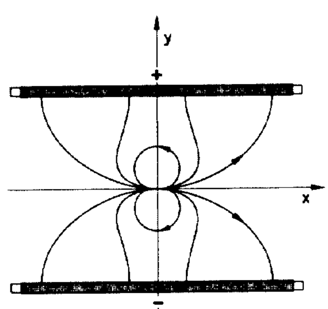

Fig. 3

The induced voltage depends on the strength I × d of the dipole field and to a good approximation linearly on the displacement, e.g. for the vertical coils,

$$U_{vert} = \text{const} \times I \times d \times y \ . \qquad (1)$$

Equation (1) holds for an ideal dipole. For the whole modulated beam, we consequently get:

$$U_{vert} = \text{const} \times I \times d \ \frac{\iint \rho(x,y)\ y\ dx\ dy}{\iint \rho(x,y)\ dx\ dy} \ , \qquad (2)$$

where $\rho(x,y)$ is the current density distribution in the beam. The integral expression on the right hand side of (2) corresponds to the y-coordinate of the centre of gravity of the beam. An analogous relation holds for the horizontal direction. Thus, the detector measures directly the position of the centre of gravity of the beam.

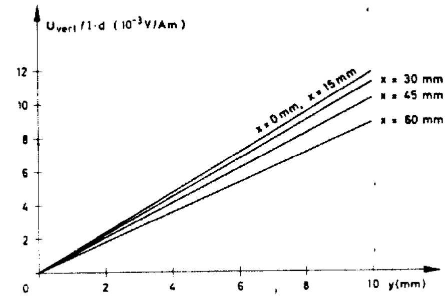

Fig. 4

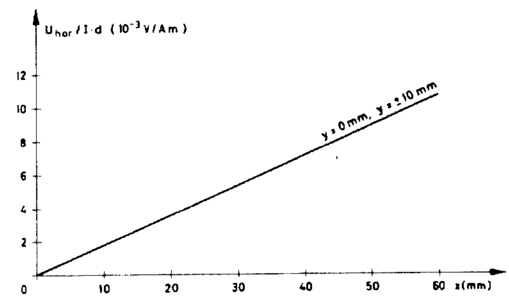

Fig. 5

The maximum errors in the determination of the centre of gravity are 0.5 % of the stack width in the horizontal plane and less than 0.01 mm in the vertical plane. They are due to the nonlinearity of the detector (Fig. 4), the non-uniformity of modulation (4 % at 40 mm), the inclination of the modulation plane (<10 mrad at the detector) and the inclination of the beam's median plane (<10 mrad).

The frame with the coils is mounted on a support, which allows horizontal and vertical displacements of ± 50 mm and ± 10 mm respectively. The movements are driven by two stepping motors giving resolutions of 0.05 mm and 0.01 mm for one step in the horizontal and vertical planes respectively. The position of the frame is measured with two inductive displacement transducers.

5. Electronic System (Fig. 6)

The voltage induced in the coil by the modulated beam is very small. For instance, a stacked beam of 5 A and a modulation of ± 0.1 mm at the detector induces 10 μV_{rms} in the vertical coil for a displacement of 10 mm. As a precision of 0.02 mm is wanted, signals of 20 nV must be measured. This is done with a lock-in amplifier preceded by a selective amplifier. The reference signal is derived from the modulator current. The output signal of the lock-in amplifier is converted into a train of pulses acting on the positioning stepping motor. In order to avoid spurious signals induced by

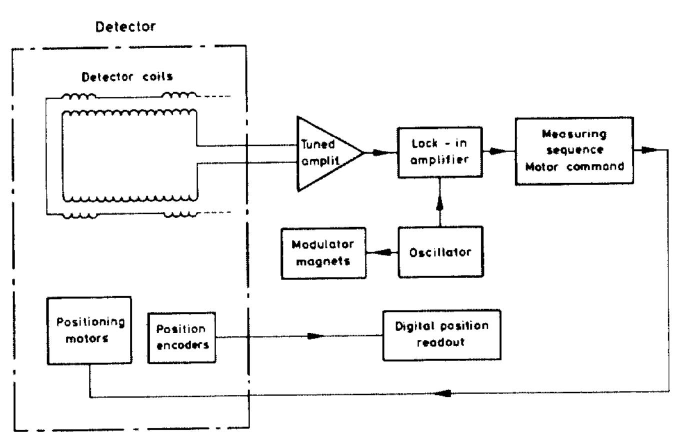

Fig. 6

by the stepping motor during the positioning of the detector, the measurement of the induced voltage and the positioning are done in two consecutive phases not disturbing each other. Thus, one adjustment cycle consists of a measurements of 8 seconds followed by the positioning of the detector. It was found that with this method the final position is reached after two or three cycles for a maximum initial displacement error.

6. Precision and Measurements

Two beam detectors have been installed in the two rings of the ISR (Fig. 7) close to the intersection point I5, which is the reference for luminosity measurements. They are mounted around the standard 160 mm diameter stainless steel vacuum chamber. Prior to their installation in the rings, the precision of the two detectors was measured in the laboratory. The two parallel wires simulating a beam of 5 A modulated by ± 0.1 mm were precisely positioned inside a standard vacuum chamber tube. The readings of the detector mounted outside were compared to the positions of the wire (see Table 1). The discrepancies between these values, which are less than 0.05 mm for both planes, are due to the imperfections in the geometry of the detector and to the influence of eddy currents in the vacuum chamber. For a stack, they contribute to the overall precision of the system together with the error involved in the determination of the centre of gravity. In the ISR rings, an unexpected complication occurred due to the parasitic currents induced by the modulators which are distributed in an uncontrolled way through the earth connections and the vacuum chamber tubes. The problem can be obviated either by cutting electrically the chamber at the detector or at the modulators or by a special modulator design. Since none of these solutions were possible for the ISR, local compensation was applied at the points of detection by measuring the spurious current with a toroidal transformer and by reinjecting an equal but opposite current via an electronic feedback.

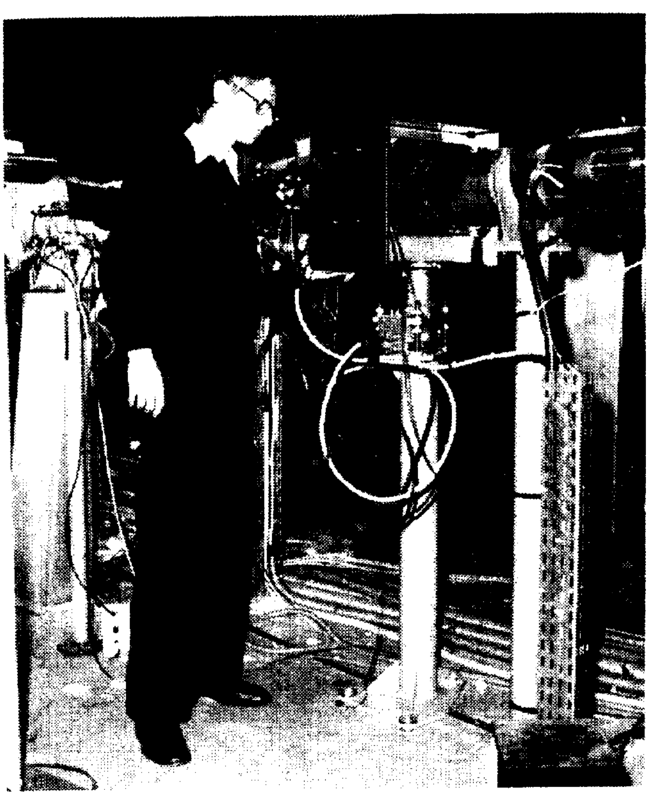

Fig. 7

TABLE 1

y	x = -60 mm	-30 mm	0 mm	30 mm	60 mm
+10 mm	0.02 -0.01	0.02 -0.02	0.02 -0.04	-0.01 -0.03	-0.01 -0.04
0 mm	0.00 0.01	0.01 0.01	0.00 0.00	-0.01 0.02	-0.01 0.02
-10 mm	0.01 0.02	0.00 0.03	0.01 0.03	-0.01 0.04	0.00 0.05

horizontal } vertical } positioning errors (in mm).

Systematic measurements were made with a 5 A proton beam at 26 GeV/c in the ISR and nominal modulation of ± 1/10 mm. The beam was moved vertically by ± 5 mm and horizontally by ± 20 mm using the standard local intersection bumps. The stability and the reproducibility of the detector readings were within 0.01 mm for the vertical position and 0.05 mm for the horizontal position. These values fully confirmed the laboratory tests. For the vertical position, an absolute calibration was done by comparing the displacements indicated by the detector to those measured by scraping off the beam with the high precision scraper installed at the intersection point. For a 10 mm displacement, the two values agree to within 0.5 %. The effect of the modulation on the beam loss rate (<0.5 ppm min^{-1}) and on the background is negligibly small. The perturbation is indeed so small that it does not depend on whether the two beams or only one beam is modulated, which makes the possibility of a simultaneous modulation of the two beams redundant.

These two detectors have already been used for physics stacks.

Conclusion

This type of position detector for coasting beams has proven to be of very high precision. It can be mounted around a normal vacuum chamber tube which makes it easy to install in the intersection regions or at any place where a measurement has to be performed. The design of the detector can be easily adapted to special requirements: for instance, a fully nonmagnetic detector has been built to measure the beam position in the gap of the ISR Split Field Magnet with a field of 1 T; an even simpler design with a fixed frame could be used in the intersections if it is only required to centre the beams in the median plane. The modulation applied to the beam is so small that it has a negligible effect. If beam position detectors were to be installed in several intersections, modulation could certainly be provided by only two programmable modulators separated by a quarter of betatron wavelength.

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