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BEAM TRANSPORT MAGNET MEASUREMENTS AT DESY

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Summary

A number of standard beam transport magnets are in use at DESY, which were designed for high field linearity and acceptance. In order to facilitate full use of these magnets, it is intended to determine from field measurements the precise optical transformation coefficients up to third order for the quadrupoles and up to second order for the bending magnets. For this purpose, a precise semiautomatic Hall probe measuring system has been put in operation which will enable us to take, within a few days, on the order of 40000 data for each magnet prototype on punch cards. The system and preliminary results characterizing the magnet performance are described. The accuracy in probe position is ± 0.02 mm, and in field strength ± 0.5 G.

Introduction

For spectrometers and beam transport, several types of standard quadrupoles and deflecting magnets have been developed at DESY[1], including a synchrotron type deflecting magnet. In view of the increasing demand for precise large aperture systems, the design of these magnets is aimed at the field which, in a wide range of excitation, deviates from the linear field distribution by not more than a few parts in 10^{-3} over the full magnet aperture. Table I gives the main parameters of these magnets. The quadrupole aperture is cross-shaped[2], increasing the acceptance by a factor greater than 2 as compared to the circular aperture. The maximum rectangle inscribed in the aperture of the largest quadrupole is 50 cm • 12,5 cm without vacuum chamber. All magnets have linearized end field with hyperbolically rounded pole ends and magnetic mirror plates[2].

In order to facilitate full use of these magnets, we plan to determine the optical properties of each type from extensive field measurements at an accuracy of ± 0.5 G. For this purpose, a precise semi-automatic Hall probe measuring system has been built and put in operation.

Precision coordinate system

The Hall probe is mounted at the end of a 1.5 m long aluminium arm which is suspended by a precision Cartesian coordinate transfer system (see Figure 1). This system allows to move the probe within a volume 1.6 m long, 0.7 m wide and 0.5 m high with an accuracy of ± 0.02 mm. Due to the size of this volume and the length of the arm, which translates small angular changes into large position errors, this accuracy could be achieved only by using a very rigid concrete foundation and very careful alignment techniques which included manual scraping of guiding rails and were controlled by an autocollimation telescope and a precision coincidence level. Fig. 2 shows the final deviations of the probe from a straight motion, where s is the logitudinal coordinate, and z and x are the vertical and the horizontal transverse coordinates, respectively. The angular deviations from 90° between the coordinate axes are smaller than 0.3 mrad.

For probe positioning, all three coordinates can alternatively be hand- or motor-driven. The longitudinal motion has an additional slow motor drive of 200 mm/min for the automatic measuring procedure. The probe position is read with an accuracy of 0.01 mm by 3 commercial scale and readout systems$^{3)}$. An additional commercial precision glass scale with photoelectric readout$^{4)}$ gives the longitudinal probe position in digitized form for the automatic mode of operation. For the transverse coordinates, a quantized digitized position is given by photoelectrically viewed slotted disks, while the probe can be rotated about its axis, and the angular position can be read with an accuracy of 0.1 mrad.

The room temperature is stabilized within ± 0.5° C. The magnets to be measured are placed on a separate concrete foundation in front of the coordinate system such that their full aperture can be covered by the probe.

Hall probe circuit

We have preferred Hall probes to rotating coils since the latter require a more complicated mechanical and electrical system. We are using Siemens probes of type FC 32$^{5)}$ which are especially suited for precise measurements in inhomogeneous fields due to their small sensitive area. They are operated at a stabilized current of 100 mA. Their temperature coefficients are about $6 \cdot 10^{-4}$ per degree for the Hall voltage and $2 \cdot 10^{-3}$ for the internal resistance, necessitating a compensating system which, in our case, employs an NTC-resistor[6)] in thermal contact with the probe and matched for field strengths above 10 KG. Fig. 3 shows the temperature coefficient with and without compensation as a function of field strength. At 2 KG, the remaining temperature coefficient is $2 \cdot 10^{-4}$ per degree and thus sufficient to measure the field with an accuracy of ± 0.5 G at all excitations.

The Hall voltage is measured either by a commercial digital Voltmeter, which is used in the automatic measuring mode, or, with an improved accuracy of 2 μV, by comparison with a compensating voltage which is derived from a constant voltage supply by means of a commercial Kelvin-Varley-decade[7)] (see Fig. 4).

Hall probe calibration

The Hall probe is calibrated against a commercial nuclear magnetic resonance fluxmeter[8)] in a calibration magnet. This magnet can be moved on rails into the region of the probe (see Fig. 5).

Nonlinear Hall probe effects

In our magnet measurements, we observed the following two nonlinear effects which must be taken into account:

1. Every probe has a characteristic zero-field Hall voltage which can be measured in a Mu-metal chamber. Upon bringing the probe into a uniform field and adjusting its direction for this zero-field voltage output, the

angular orientation ϕ_o of the probe will depend on the strength and polarity of the field. At a field strength of 20 KG, we measured an angular deviation of 3.5 mrad between the two field polarities. Fig. 6 shows the zero-field angle ϕ_o as a function of field strength.

2. Upon rotating the Hall probe in a uniform field, one would expect a sinusoidal field variation. In fact, however, one always finds a component which is somewhat larger than expected and which, in addition, strongly depends on the field strength. Fig. 7 shows the relative deviation of the field from the sinusodial distribution as a function of the angle ϕ for different field strengths. This means that field components can only be measured precisely by introducing a correction which depends on the field strength and on the angle between probe and field direction.

Magnet alignment

Before measuring a magnet, it is aligned with respect to the coordinate system. Each magnet rests on a standard mount which facilitates a precision adjustment under load. For magnets weighing over 5 t the load is partially relieved by a hydraulic system during alignment (see Fig. 8).

In the uniform field bending magnets, the pole surfaces are not covered by the vacuum chamber, and they can thus be aligned mechanically. The quadrupoles, however, must be aligned magnetically. This is done by finding the magnetic symmetry planes $B_z = 0$, $B_x = 0$ and $B_z = \pm B_x$, taking into account the nonlinear dependence of the zero-field angle on the field strength. These measurements also determine the coordinates of the probe position relative to the rotational axis of the arm on which it is mounted.

The alignment procedure is used at the same time to position within ± 0.1 mm on top of each magnet the optical targets and horizontal reference planes which are provided for beam setup. Quadrupoles have two fixed targets, while bending magnets have three, which can be moved sidewise on a scale to account for a given deflecting angle (see Fig. 9).

Automatic data collection

For one magnet of each standard type, we intend to take a three-dimensional plot of the two transverse field components in about 10000 measuring points at 2 - 3 different excitations. In addition, reduced data plots will be taken for individual magnets to determine the fluctuation within each series. In order to cope with such a program, the following semi-automatic measuring system 9) has been developed:

After manually setting the transverse probe position and starting the slow longitudinal motor drive, the Hall voltage is automatically registered on IBM punch cards at preselected intervals of 1, 2, 10 or 20 centimeters. At a trigger signal from the longitudinal coordinate counter, a fast mercury relay disconnects the Hall probe from a storage capacitor, and the capacitor voltage is digitized by the voltmeter and transferred to the summary punch 10). It is thus possible to take on the order of 40000 data within 3 days.

Preliminary measurements for determination of design parameters

Before carrying out the systematic measuring program, some magnet prototype measurements have been done to determine certain final design parameters.

Fig. 10 shows the relative deviation from the ideal quadrupole field in the median plane of quadrupole QA$^{11)}$ for two different shim profiles, of which the one shown at right was chosen.

The linearized quadrupole end field shown in Fig. 11 agreed so well with expectation that parameter changes were unnecessary. The integrated end field length decreases by 2 mm when going up from a small to maximum excitation, and its transverse distribution is constant at all excitations within ± 1 mm over the full quadrupole aperture.

The window frame bending magnets have shimming holes in the yoke near the sides of the aperture, which correct the field distribution at saturation$^{12)}$ (see Fig 12). Size and position of these holes could be varied in the prototype, and the corresponding transverse field distributions are shown in Fig. 13. The linearized fringe field and the deviation of its integrated length for different aperture points are given in Fig. 14.

Final measuring program and evaluation of optical magnet properties

The final measuring program aims at determining the precise optical transformation coefficients up to second order for the bending magnets and up to third order for the quadrupoles which, due to their symmetry, have only chromatic nonvanishing second order terms.

It is intended to proceed as follows:$^{1)}$

1. For 7 prototype magnets, collect about 20000 data each at 2 - 3 excitations and derive from these data a set of prototype field distributions which are "smoothed" using

Maxwell's equations and the magnet symmetries. For all magnets within a series, we expect a sufficiently identical field distribution according to the achieved mechanical precision.

2. From the quadrupole prototype fields, calculate the following parameters:
   a) The linear transformation matrix or, equivalently, the effective focusing strength and length as a function of field gradient per unit momentum.
   b) The chromatic second and third order and the geometric third order transformation coefficients.
   c) The strength of higher order terms in the multipole expansion of the inner as well as the integrated field including the end fields.

3. For the bending magnets, the first and second order transformation coefficients depend not only on the field strength, but also on the angle of deflection. They will, therefore, be calculated for a representative set of these angles. The linear transformation of the symmetrically operated magnet will be expressed in terms of three parameters: an effective length, an effective deflecting strength, and an effective focusing strength.

As a result of this program which is carried out as a general laboratory service, beams and spectrometers can be calculated with high accuracy by simple consecutive application of the transformations thus predetermined for each magnet type.

References

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3) CM-Ablesegeräte, Hensoldt, Wetzlar

4) Dr. Johannes Heidenhain, Traunreut

5) Siemens & Halske, Nürnberg

6) T.S. Dahlstrom, H.A. Howe, W.M. Mallet and W.E. Smith, USNRDL-TR-559, San Francisco (1962)

7) ESI, Portland, Oregon

8) F8 - NMR - Fluxmeter, Varian Associates, Palo Alto, California

9) W. Flauger and K. Holm, DESY E4,5 - 11 (1964)

10) IBM summary punch 526

11) manufactured by MFO, Zürich

12) M. Foss, private communication

Table I: DESY standard magnets

Type	approximate dimensions			field values at 1500 A
	Aperture of vacuum chamber		magnetic length	
	Ø	max. rectangle		
Quadrupoles QD	15 cm	20 cm x 5 cm	0.5 m	1.75 KG/cm
QB	15 cm	20 cm x 5 cm	1 m	1.83 KG/cm
QA	27 cm	37 cm x 9 cm	1 m	0.98 KG/cm
QC	34 cm	47 cm x 12 cm	0.6 m	0.81 KG/cm
Bending Magnets MB		30 cm x 11 cm	1 m	22.4 KG
MA		48 cm x 17 cm	1.3 m	20.7 KG
Synchrotron-type magnet MC		40 cm x 10 cm	1 m	0.4 KG/cm

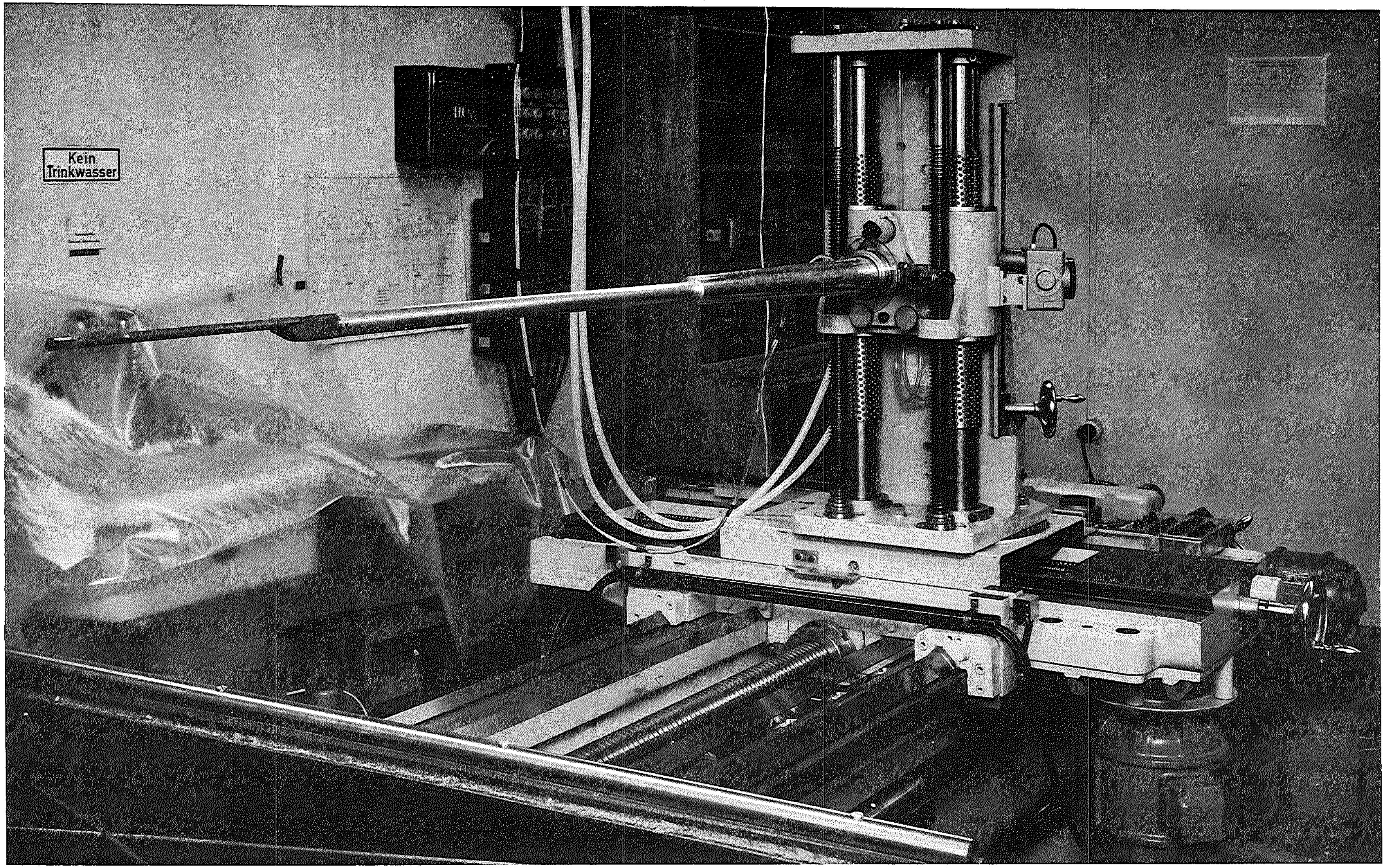

Fig. 1 Precision cartesian coordinate transfer system

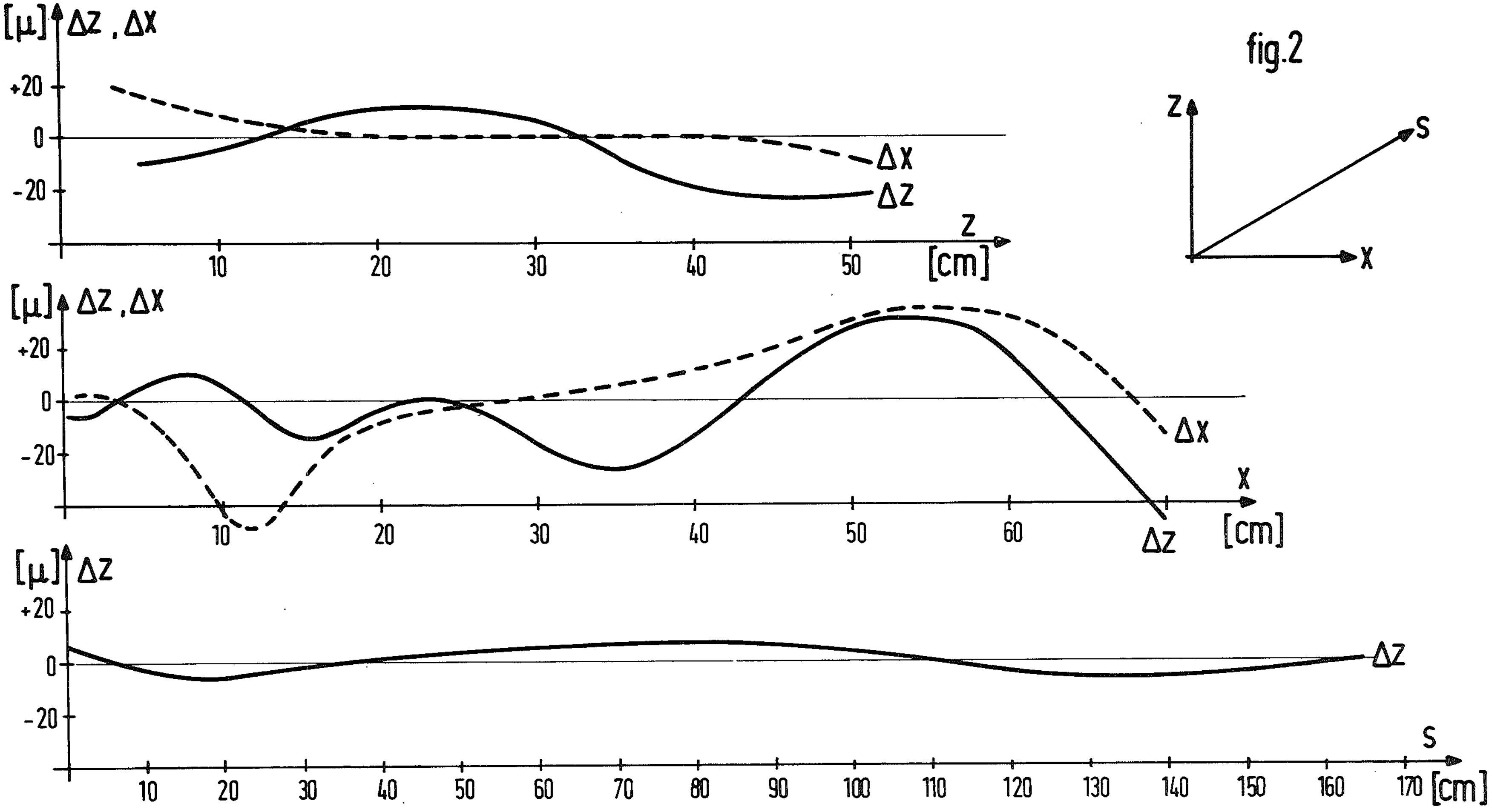

Fig. 2 Deviations of the probe from straight motion

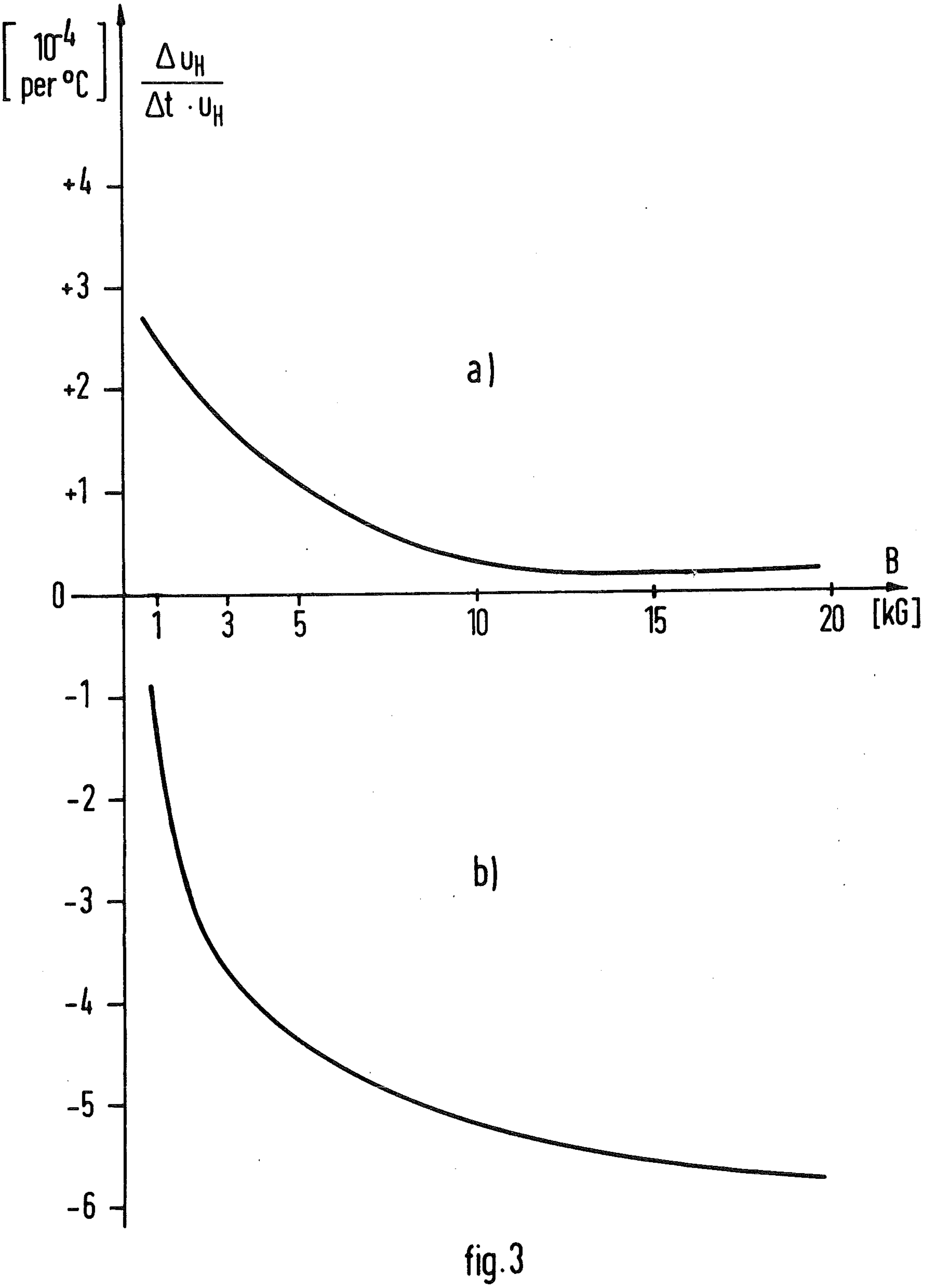

Fig. 3 Temperature coefficient of Hall probe
a) with temperature compensation
b) without temperature compensation

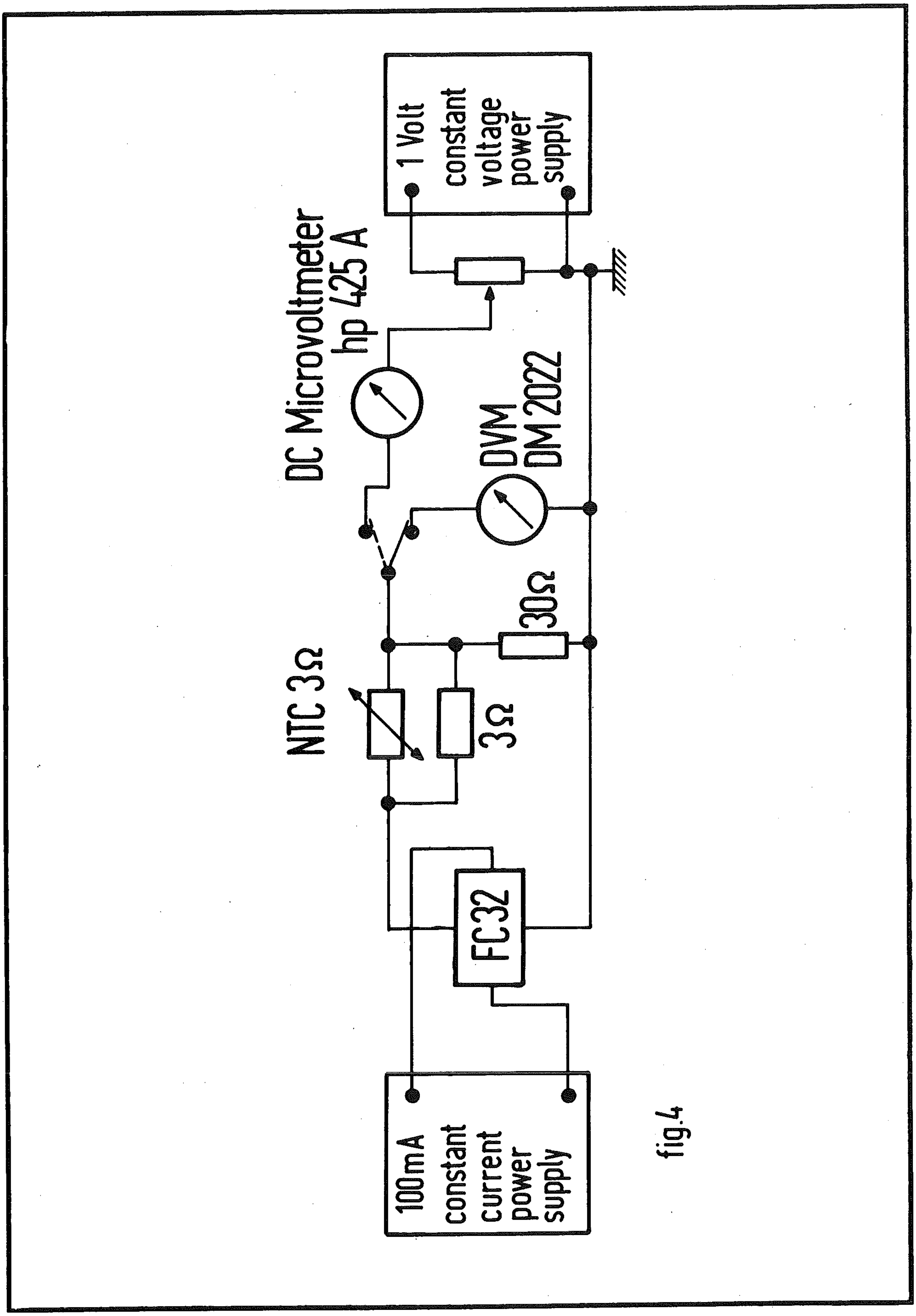

Fig. 4 Schematic diagram of Hall probe circuit

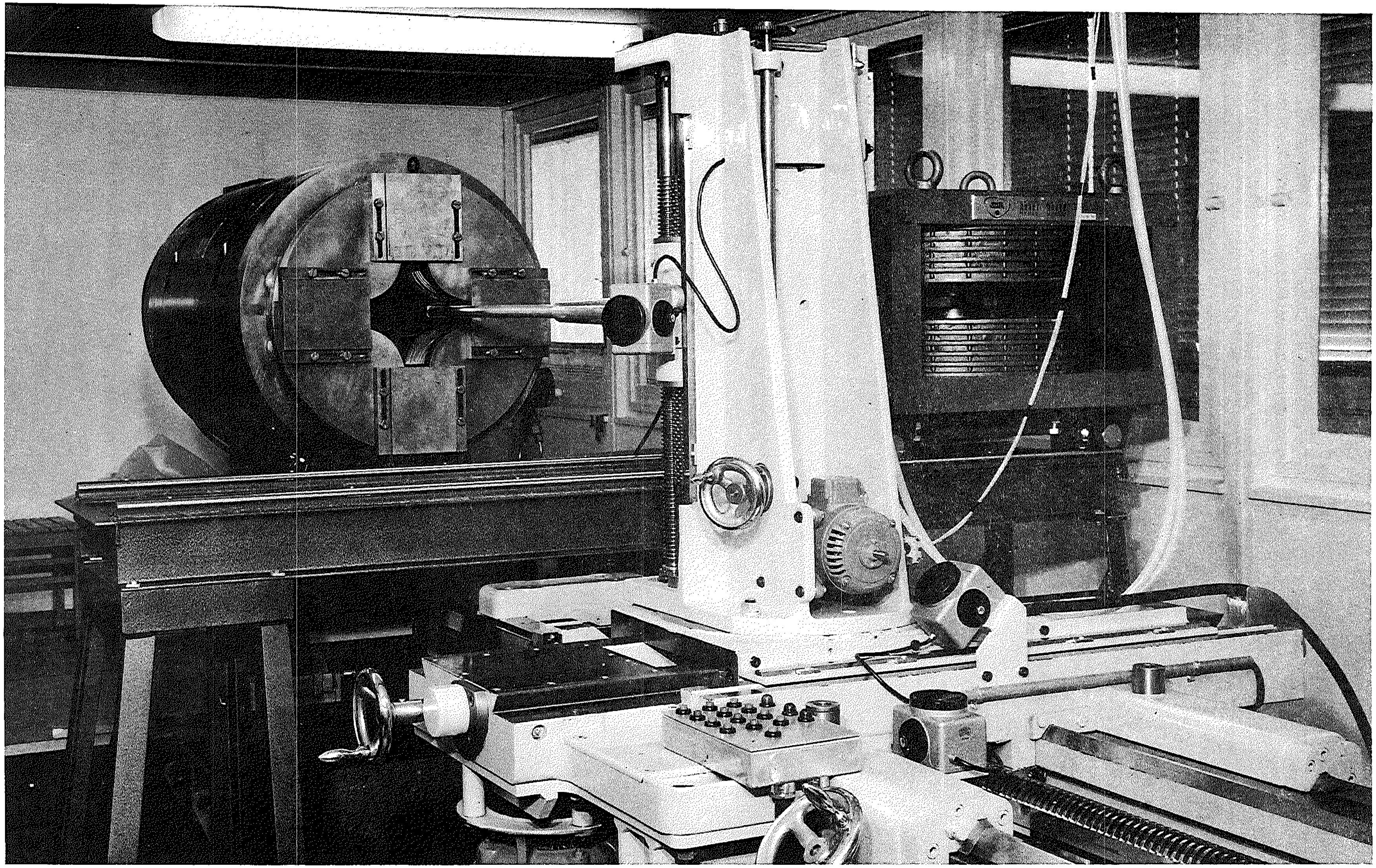

Fig. 5 Coordinate system with calibration magnet and prototype quadrupole QB

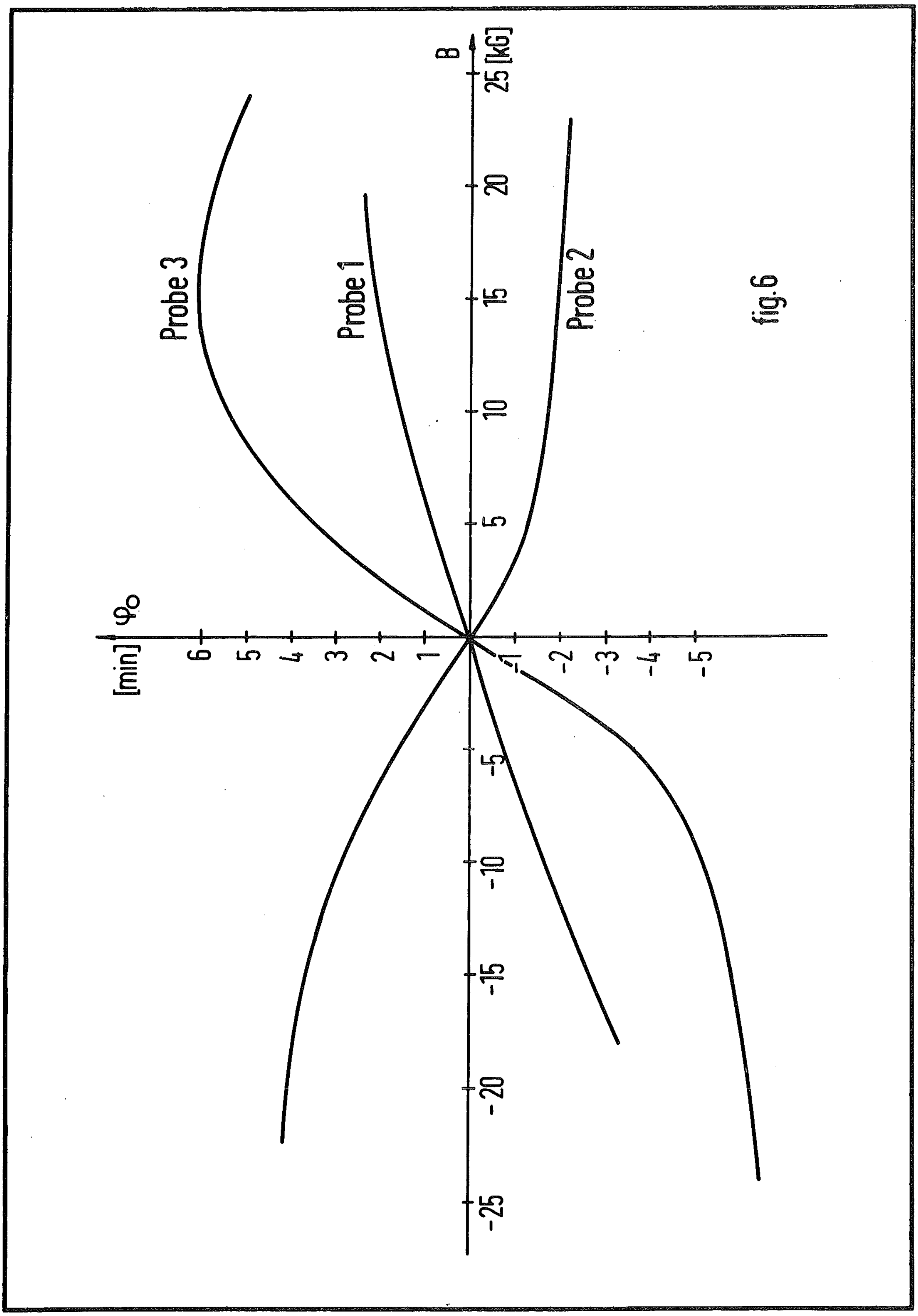

Fig. 6 Zero-field angle ϕ_o as a function of field strength for 3 different Hall probes (Siemens FC 32)

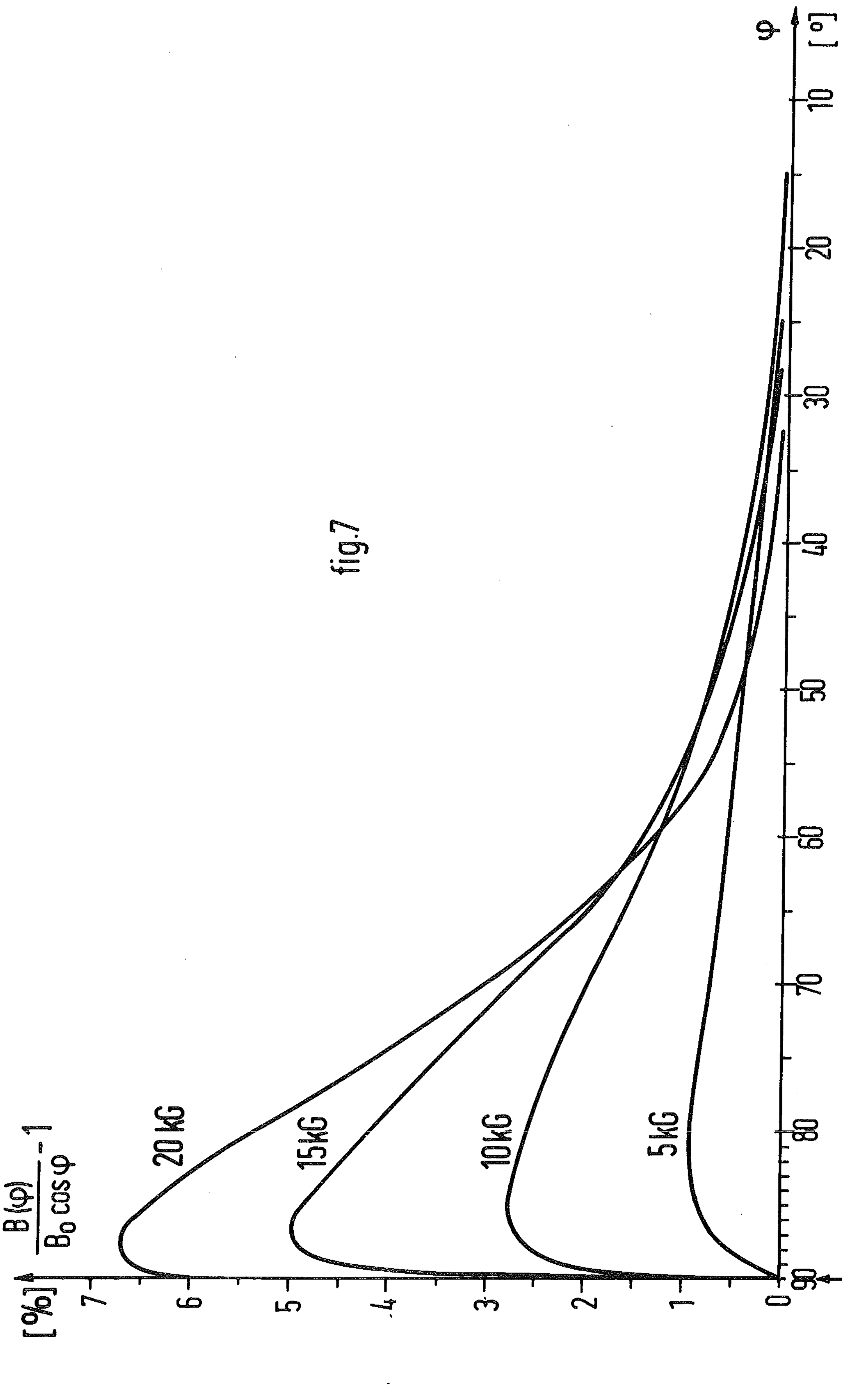

Fig. 7 Relative field deviation from a sinusoidal distribution for different field strengths

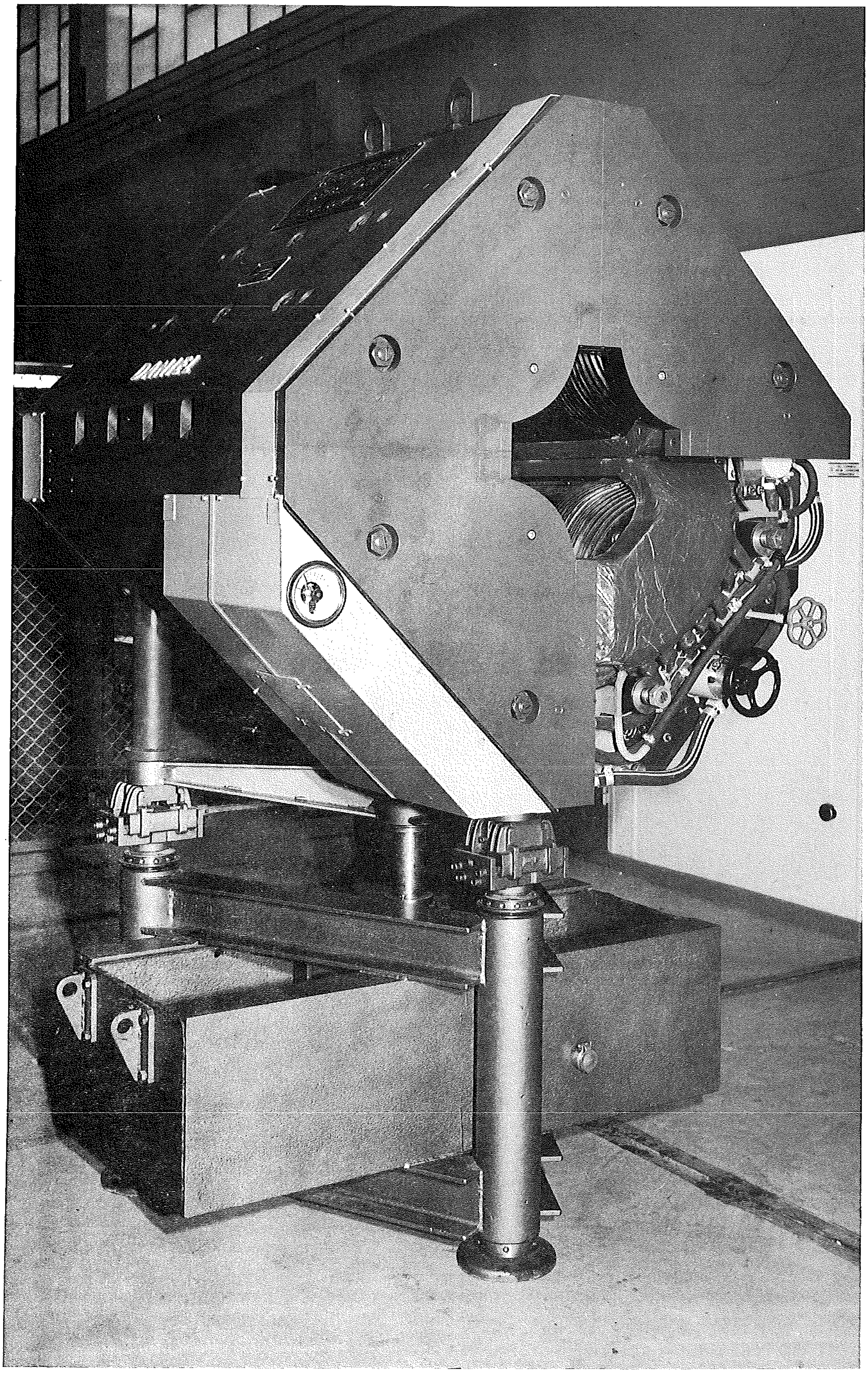

Fig. 8 Quadrupole QA on standard mount with hydraulic load relief for precision adjustment

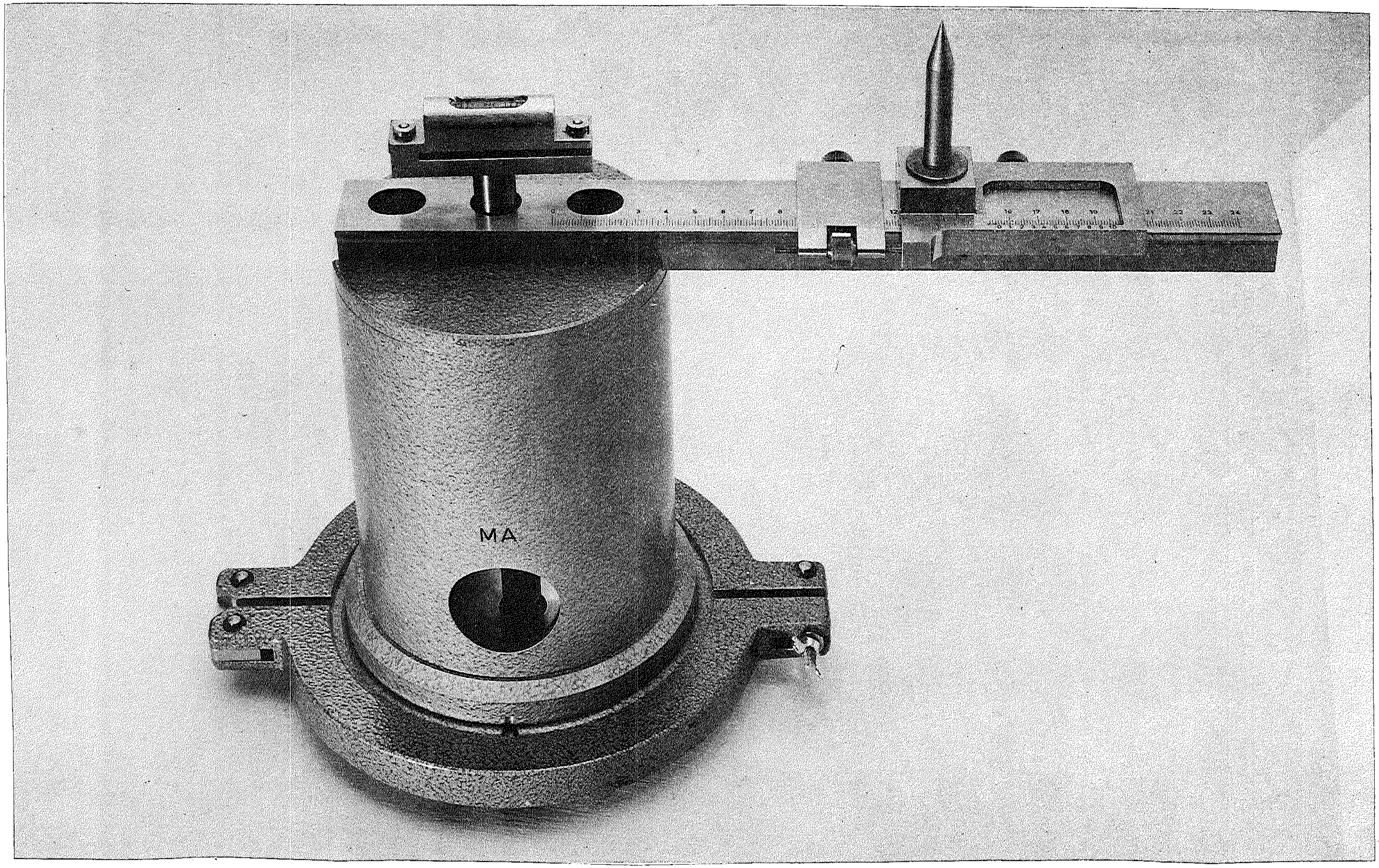

Fig. 9 Optical alignment target for deflecting magnet

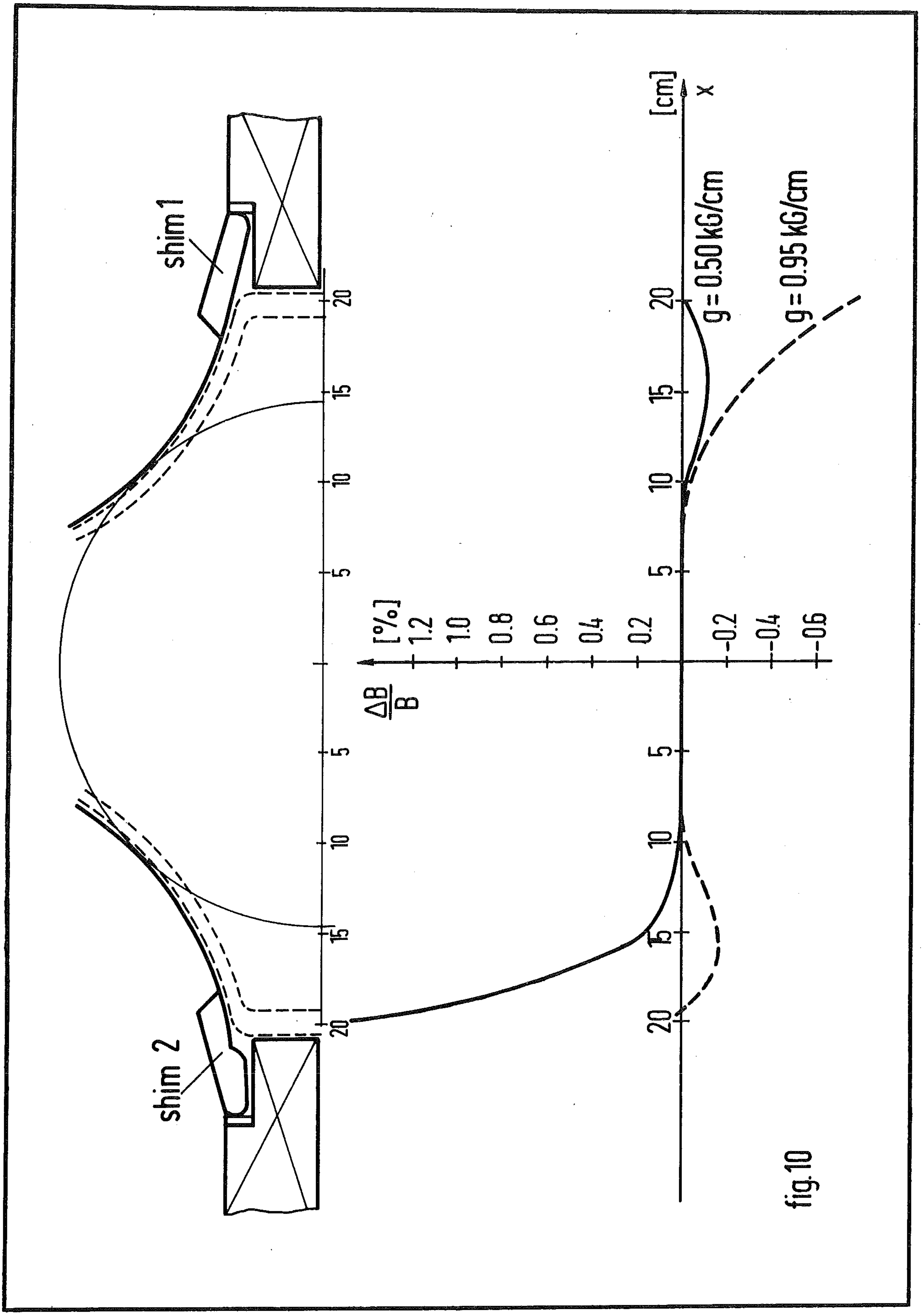

Fig. 10 Relative deviation from the ideal quadrupole field in the median plane of quadrupole QA at two field gradients for two different shim profiles.

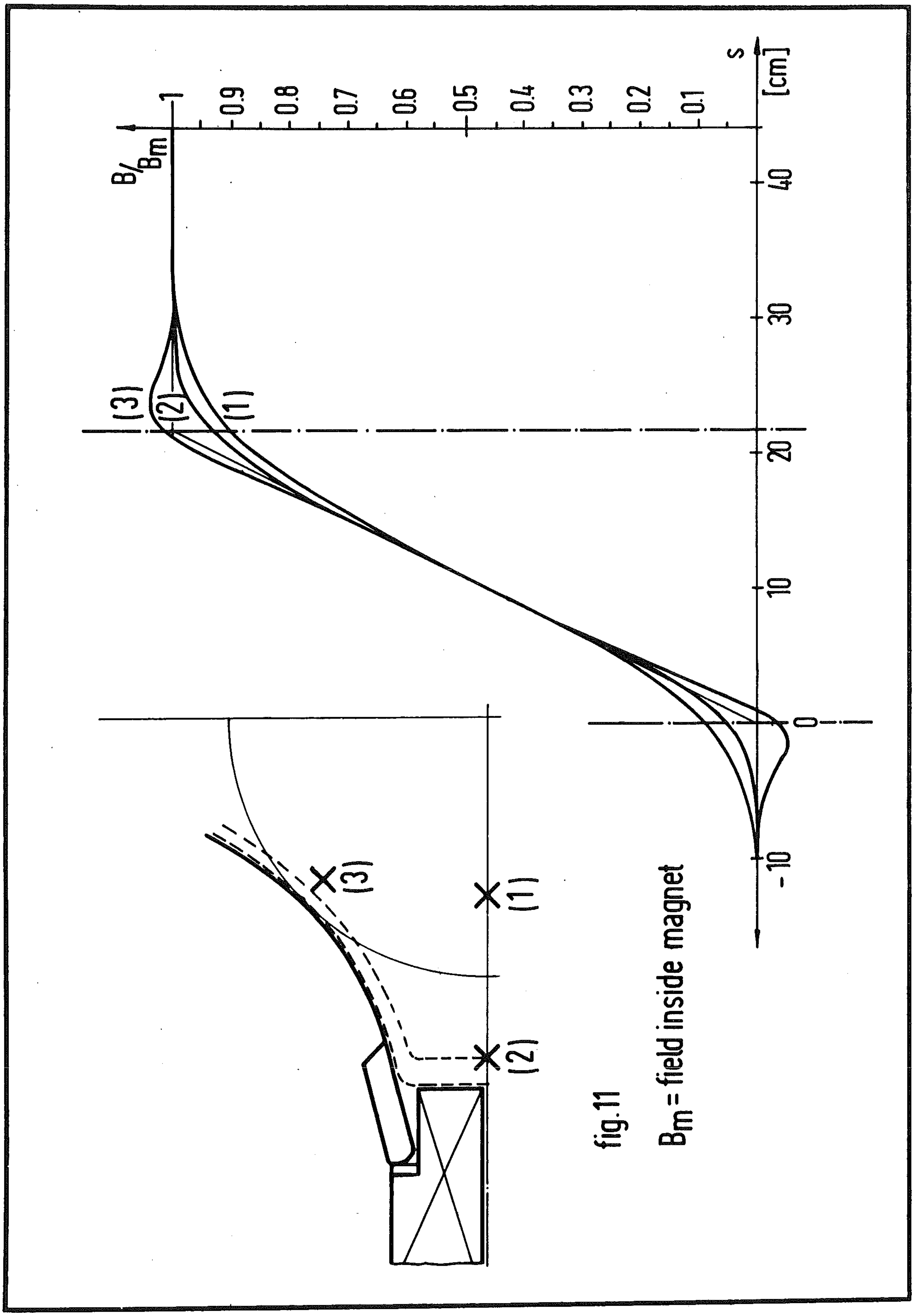

fig.11

B_m = field inside magnet

Fig. 11 Rise of end field in Quadrupole QA at different aperture positions.

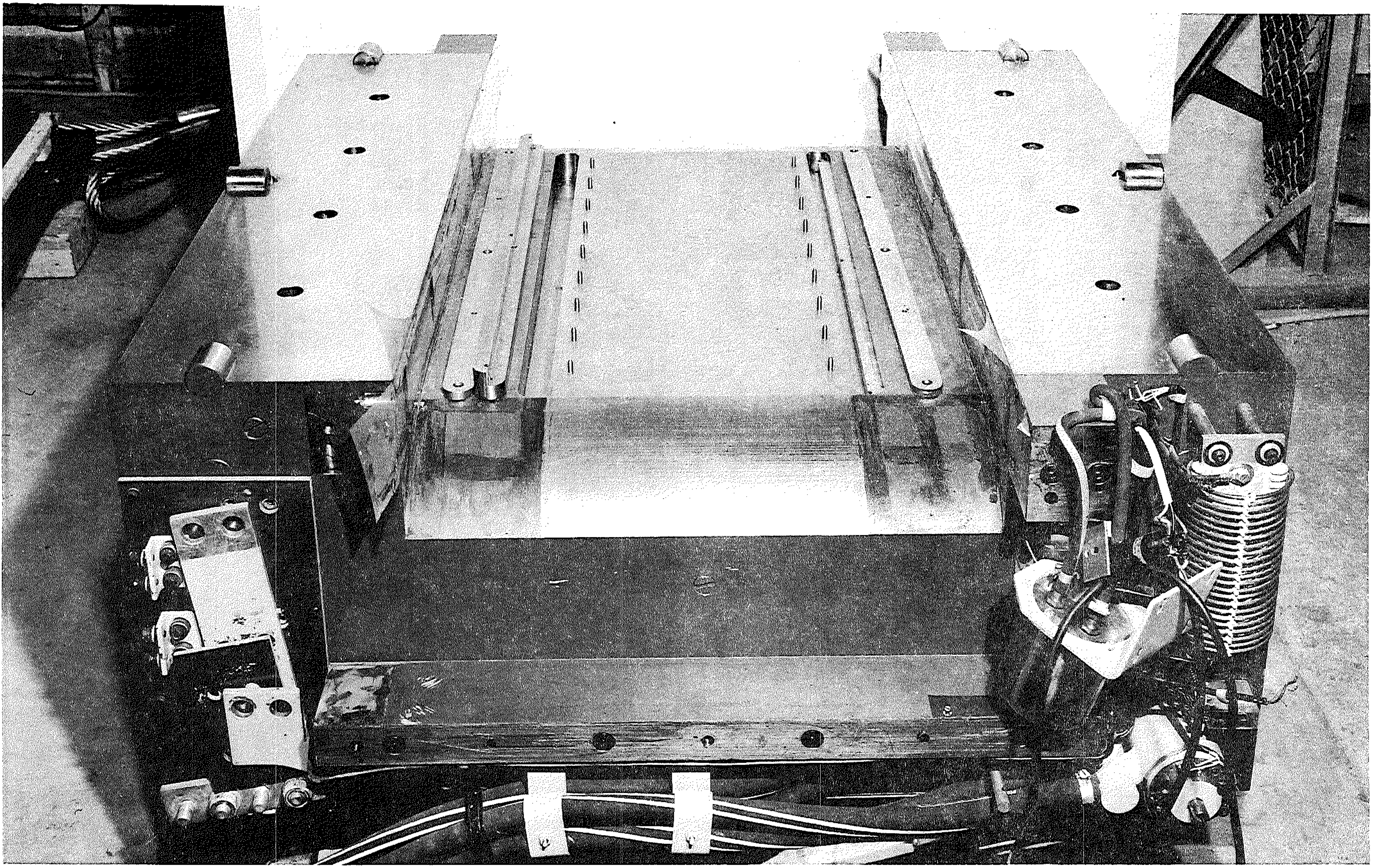

Fig. 12 Half yoke of bending magnet, showing grooves and filling pieces for shimming hole adjustment

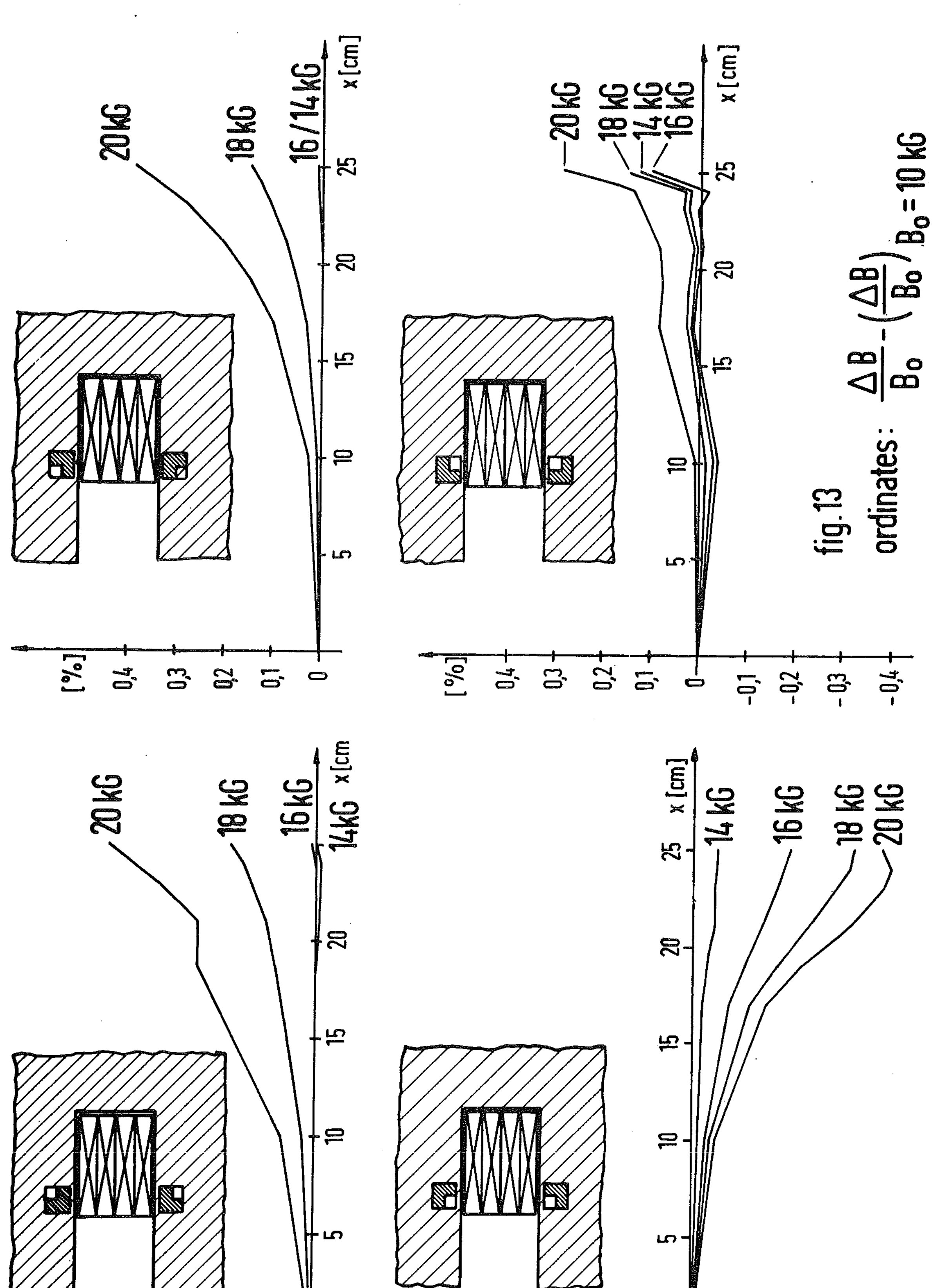

Fig. 13 Bending magnet MA, median plane:
Variation of relative*distribution below saturation,
for 4 different positions of shimming hole.

* field deviation with excitation referred to the field

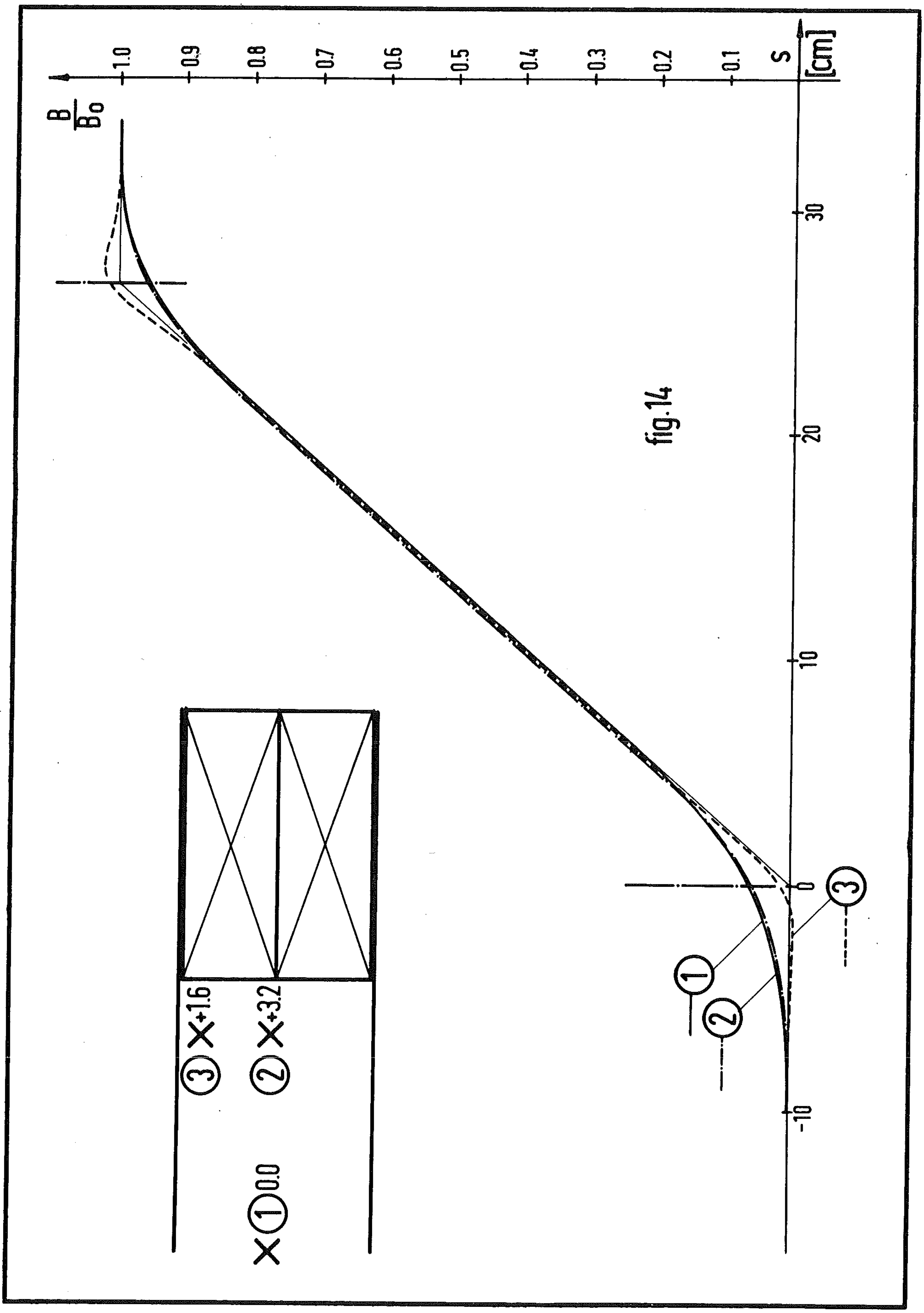

Fig. 14 Rise of end field in bending magnet MB at different aperture positions. Deviations of the integrated fringe field length (in mm) are given in the insert.