СООБЩЕНИЯ
ОБЪЕДИНЕННОГО
ИНСТИТУТА
ЯДЕРНЫХ
ИССЛЕДОВАНИЙ
Дубна

E13 - 6659

W.Gajewski, Z.Guzik, A.D.Kirilov, L.Kh.Komolov,
R.Krasowski, B.Niczyporuk, T.S.Nigmanov,
W.Popielski, E.N.Tsyganov, M.Turala, M.I.Yatsuta
E.Dally, D.Drickey, J.Kieffer, A.Liberman,
P.Shepard, J.Tompkins

ЛАБОРАТОРИЯ ВЫСОКИХ ЭНЕРГИЙ

MAGNETIC MEASUREMENTS FOR π^--e EXPERIMENT AT 50 GEV

1972

E13 - 6659

W.Gajewski, Z.Guzik, A.D.Kirilov, L.Kh.Komolov,
R.Krasowski, B.Niczyporuk, T.S.Nigmanov,
W.Popielski, E.N.Tsyganov, M.Turala, M.I.Yatsuta
E.Dally,* D.Drickey,* J.Kieffer,* A.Liberman,*
P.Shepard,* J.Tompkins*

MAGNETIC MEASUREMENTS FOR π^--e EXPERIMENT AT 50 GEV

* University of California, Los Angeles

Гаевски В., Гузик З., Кириллов А.Д., и др.

E13 - 6659

Магнитные измерения в эксперименте по $\pi^- - e$-рассеянию при энергии 50 Гэв

Представлено детальное описание измерительной аппаратуры, обработка данных и анализ измерений магнитного поля в магните СП-12. Магнит использовался как спектрометр в эксперименте по измерению радиуса заряженного пиона на серпуховском ускорителе 76 Гэв.

Сообщение Объединенного института ядерных исследований
Дубна, 1972

Gajewski W., Guzik Z., Kirillov A.D et al.

E13 - 6659

Magnetic Measurements for $\pi^- - e$ -Experiment at 50 GeV

A detailed description of the measurement apparatus, data taking and subsequent data analysis for a set of magnetic measurements at the Dubna magnet SP-12 is presented. The magnet was used as a spectrometer in an experiment to measure the pion-charge radius performed at the 76 GeV proton synchrotron at the IHEP, Serpukhov.

Communications of the Joint Institute for Nuclear Research.
Dubna, 1972

I. Introduction

The magnetic field for the Dubna magnet SP-12 was measured to an absolute precision of 0.1% using a temperature stabilized Hall probe which was calibrated by nuclear magnetic resonance. This magnet was used as a spectrometer in an experiment to measure the pion radius that was performed at the 70 GeV proton synchrotron of the Institute of High Energy Physics (Serpukhov) in 1970-71 by a collaboration of physicists from the Joint Institute for Nuclear Research (Dubna) and the University of California at Los Angeles (United States). In this experiment, incident pions of 50 GeV/c were scattered by the electrons in a liquid hydrogen target. The recoil electron and pion were deflected by the SP-12 magnet, and their momenta were calculated by reconstructing the trajectories from sparks in the wire spark chambers which flanked the magnet. The magnetic measurement precision of 0.1% meant that the spectrometer resolution was determined by the errors in the spark coordinates and not by the uncertainties in the measurements of the magnetic field.

The magnet was operated at an excitation current of 1300 amperes. It is an "H" type, with a 3 m long gap, and aperture 20 cm high and 50 cm wide. The measurements of the field were made in a volume that was 4.25 m long, 16 cm high and 50 cm wide. The measurements beyond the pole pieces were done in order to have the field mapped in the entire region through which the particles pass. The recoil pion and electron momenta were in the range of 14 to 36 GeV/c. In addition, the kinematics of the process and the geometric detection efficiency limited the angles of the recoil particles to less than 10 milliradians. As a result, the trajectories of the particle through the magnet were always inside the measured volume and there was no need to extrapolate the field.

Magnetic measurements were made using a Hewlett Packard computer, model HP 2116 B, connected on-line to the measurement system. The data were recorded on magnetic tape for subsequent analysis, and various checks were made on the data while it was being taken to guard against possible systematic errors and apparatus malfunction.

The magnetic field measurements were used to compute the coefficients in a formula that gave the momentum of a particle in terms of explicitly measured quantities only. Having such a formula represents an enormous saving in both computer time and storage compared with the method of integrating each trajectory through the field when the momentum of many thousands of particles must be calculated.

II. Equipment and Measurement Technique

The Hall probe was rectangular 2 mm by 7 mm and 1/2 mm thick. The box containing the probe was fixed to a bar on a carriage which in turn moved through the length of the magnet aperture on rails that were supported and aligned at either end. The box could be moved along the bar in horizontal steps of 2 cm, and the bar itself in 1 cm intervals vertically. The orientation of the probe could also be changed so as to permit successive measurements of the 3 field components. The guiding rails for the carriage were aligned parallel to the magnet axis to within an accuracy of several tenths of a millimeter. There was an adjusting screw on the box for precise positioning of the probe. This was important for the measurements of the two components transverse to the main (verticl) component; the adjustment was done so that the probe gave a null reading at the center of the magnet.

The Hall probe voltage output is proportional to the Hall current and also to the temperature, and so both of these parameters had to be carefully monitored in order to achieve the desired measurement precision. The Hall probe current came from a power supply that was regulated to 0.01% and it was checked continuously while the field measurements were being made. The Hall probe was heated by a resistor and its temperature was controlled by a mercury thermometer switch; fluctuations in the temperature caused changes in the central field reading of less than 0.02%.

A motor moved the carriage along the guide rails at a constant speed of 4 cm/sec. Data were taken with the carriage moving in both directions to compensate the measurement hysteresis. A wide brass belt with slits every 2.5 cm was made to pass between a photo-transistor switch, positioned on the guide rails, and a collimated light source. When the light triggered the photo-transistor, a pulse was sent to the electronic readout system directing it to make a voltage measurement.

The electronic readout system consisted of 5 parts: (1) Dynamco model DM 2022S self-calibrating digital voltmeter, capable of digitizing the Hall probe voltage in 10 milliseconds with 0.01% precision; (2) photo-transistor switch, described above, which signalled the voltmeter when to make a voltage measurement; (3) a system of sequentially closing relays which sent various voltage signals to the voltmeter at the beginning of each measurement series; (4) the motor control which remotely started and stopped the carriage motor and automatically reversed its direction when it reached the end of the 4.25 m guide rails; (5) a diode matrix that decoded the decimal output of the voltmeter and sent the data to the computer interface. A series of data consisted of the initial voltage levels (Hall current, shunt voltage, voltage from a second, fixed Hall probe that shared the same current supply as the moving probe, vertical and horizontal position indicating voltages that came from 2 chains of resistors on the carriage), plus measurements of the field at the 171 positions along the magnet axis. For each of the three components of the field there were (26 x 17) x 342 such measurement series, so that the field was measured at some 450000 points.

The data taking was under computer control. A signal from the computer indicating a state of readiness enabled the readout system; the measurements were then started by pushing a button of the readout control panel. When the correct number of data points was received by the computer, the motor control was automatically switched off. Following a short analysis period, described below, and an examination of the data, the ready signal was sent from the computer to prepare the electronics for the next series of measurements.

The purpose of the analysis routines was to insure that the data were satisfactory and that the apparatus was performed normally. The operator at the computer console had the option of viewing on a storage scope either one of 2 displays. The first display was the average of the 2 measurements at each point, plotted against the measurement position; the second and more useful of the 2 was a plot of the difference between the 2 sets of measurements. Any errors in timing, measurement sequence, or unusually large noise interference was very easily detected. The operator made the decision of writing the data onto tape by a switch on the computer panel.

III. Treatment of the Data

The Hall probe was calibrated by comparing its output voltage with the field measured by a nuclear magnetic resonance probe at the same point in the magnet for various values of magnet excitation current. A least square fit to these data was made to a polynomial of the form:

$$\text{kilogauss} = C_1 \times \text{Hall voltage} + C_2 \times (\text{Hall voltage})^2 + C_3 \times (\text{Hall voltage})^3 + \\ + \text{higher order terms.}$$

It was found that with 3 coefficients, the average deviation, using 20 data points, was negligible and the average absolute deviation between the data and the fit was 7 gauss.

Before converting to kilogauss, the voltage measurements for the 2 passes were averaged. In the fringe field region, the averaged result was kept, but in the central field region some smoothness criteria were applied to eliminate measurements with large noise. No correction was applied for the measurement hysteresis since the difference between the simple average of the results of the two passes and a fit using the field shape was only 0.05% at the most, and that much only in a small region where the field was rapidly changing.

IV. Analysis of the Measurements Using the Univac 1108 Computer

The magnetic field measurements were treated in 2 different ways by different analysis programs. The first program used only the values of the field on the boundary of the measurement volume, and then reconstructed the magnetic field throughout the volume using a Fourier series expansion (ref.1). An expansion in Fourier series has the advantage for numerical work that there is no limitation of computational accuracy as the functions for equidistant measurements. It can also be shown that the reconstructed field values are more precise in the volume than the volume measurements themselves because the fluctuations of the measurements are averaged out by making the Fourier series expansion. Three programs were used for the reconstruction of a full field map from the boundary observations. The first program calculated the coefficients for each component of the field expanded in Fourier series. The second used the coefficients and calculated the field at some specific points for comparison with measurements made in the volume at the same points. The third program constructed the grid, for each component separately, at a specified number of X,Y and Z points. A total of 13500 coefficients were calculated for each component, but many coefficients were small and not needed for the subsequent calculation of the field; for B_y, the main component, only 2300 coefficients were used and no difference was noted by using all the coefficients to the 1 gauss level. The number of coefficients may seem surprisingly large, but a field of the type of magnet SP-12, 3 meters of approximately flat field and then a rapid fall off in a relatively short distance, is difficult to expand in a Fourier series and convergence for some symmetry classes was slow. The calculation of the coefficients and the reconstruction of the entire field map each took about 4 minutes on the UNIVAC 1108 computer.

The second analysis method used the volume measurements directly. The comparison of the two values of the magnetic field at the same points in the magnet provided a valuable check of errors in the measurements (notably the Hall current variation which is the principal source of error). The calculated field was found to be systematically larger than the measured field in the center of the magnet by 0.1%.

V. Momentum Calculation

Hypothetical particle trajectories were traced through the magnet using a program which numerically integrated the field equations. The step size along the trajectory was arbitrary, and the magnetic field used at each point came from linearly interpolating the surrounding measurements. The step size used in the integration (that is to say the magnetic field grid interval) was chosen on the basis of two considerations. The first was the approximation in the integration of keeping only terms up to the second order. The error goes as B^3/P^3, where B is the main component central field value, and P is the momentum. For a 10 GeV trajectory, the most sensitive case, the total angular error in the trajectory from this approximation is less than .01 milliradians for a step size of 20 cm, and therefore completely negligible. The second factor in choosing the step size was the nonuniformity in the field, which also enters because terms higher than second order are not kept. This effect was estimated by comparing the field integral using different step sizes. The difference between a 2.5 cm step and 12.5 cm was less than 0.01% for a typical central field trajectory (a conservative 5 cm was used thereafter). Several step sizes for the field map in the direction transverse to the particle direction were tried and it was found that 5 cm was also a good choice. A smaller step gave differences for sample trajectories that were negligible compared with the measurement error itself. Thus, the number of magnetic field points actually used for each component was approximately 12000, or a factor of 6 fewer than the number of measurements. A further reduction could have been made by eliminating the transverse components of the field entirely. The difference between trajectories calculated using all 3 components and those using only the main vertical component was always negligible.

In the experimental layout, the magnet was approximately 10 m downstream from the target, and rotated by about 30 milliradians. The trajectories of particles tracked through the magnetic field were limited to -4 cm and +4 cm from both X and Y at the center of the target and -9 cm and +9 cm for X and Y at the center plane of the magnet.

Two algorithms were constructed for calculating the momentum of a particle using only the measurements of its trajectory before and after the magnet. The first algorithm was an expansion in Tchebycheff polynomials /2/ . A relatively small number of representative trajectories were computed and then used to generate the coefficients:

$$P = \sum_{a_1=1}^{N_1} \sum_{a_2=1}^{N_2} \sum_{a_3=1}^{N_3} \sum_{a_4=1}^{N_4} \sum_{a_5=1}^{N_5} C_{a_1a_2a_3a_4a_5} T_{a_1}(X_c) T_{a_2}(Y_c) T_{a_3}(X_M) T_{a_4}(Y_M) T_{a_5}(Q_{defl})$$

where $T_j(x)=\cos(j \arccos x)$ is a Tchebycheff polynomial, P is the momentum and the 5 variables are chosen to be X and Y at the center of the target (X_C and Y_C), X and Y at the center of the magnet (X_M and Y_M) and the horizontal deflection angle (Q_{defl}). The procedure for calculating the coefficients was the following:

(1) trajectories were integrated through the field with X_C, Y_C, X_M, Y_M and P as the 5-th variable, each chosen according to a Tchebycheff distribution:

$$x_a = \cos\,[2a - 1)\pi/2N] . \qquad a = 1,\dots N.$$

Each value of the momentum gave a certain deflection angle.

(2) What was desired, however, was the deflection angle as the 5th variable picked according to the Tchebycheff distribution so that an interpolation was done between the originally computed values. A total of 2592 trajectories were calculated to achieve the desired precision: for 2 different values of X_C and Y_C, 6 for X_M and Y_M and 18 for P; a relatively large number of momentum points was necessary because of the inaccuracy in the interpolation.

(3) Since the variables were all chosen according to the Tchebycheff distribution, the polynomials are orthogonal:

$$\sum_a T_j(x_a) \cdot T_k(x_a) = \delta_{jk} ,$$

As a result, the coefficients, $C_{a_1a_2a_3a_4a_5}$, can be readily calculated.

The expansion was checked by comparing the known momentum of a sample trajectory with that calculated using the expansion and the observable quantities. For sample trajectories with momentum in the range of 10 to 40 GeV/c, the (P_{known} $-P_{calculated}$) $/P_{known}$ values were distributed about 0 with an error of 0.05% (the P_{known} – $P_{calculated}$ differences had a width of 12 MeV/c).

The second algorithm was the simple effective length approximation, P = constant/ deflection angle; for P in GeV/c and deflection angle in milliradians, the constant is 1625.4, corresponding to a field integral of 54.22 kilogauss centimeters. The distribution of (P_{known} - $P_{calculated}$)/P_{known} was 0.15% in width.

VI. Sources of Error

The most serious uncertainty came from the variation of the Hall probe current; the current was read on a meter which calibration drifted during the measurements, and unfortunately, the current was changed to keep the reading constant. This was corrected using the second, fixed Hall probe since the current for the two Hall probes came from the same supply. This problem contributed an absolute uncertainty to the momentum calculation of 0.1%, or larger that the error in the momentum calculation from the Tchebycheff expansion. Shifts in the Hall probe calibration, and tensor effects in the probe were hard to estimate but might be of the same size.

The sensitivity of the momentum calculation to some geometrical effects was estimated. The position of the magnet was shifted by 5 mm in X,Y and Z and the results showed that the momentum changed by less than 5 MeV/c. The finite size of the probe was not important. For the worst case, when the second derivative of the field d^2 by dZ^2 was the largest, the error was .035%.

We would like to express our gratitude to the physicists and engineers from IHEP, Drs. V.J.Kotov, Yu.S.Khodyrev, P.V.Makeev, A.A.Lednev, B.B.Splukhin, who aided us during the measurements.

We are also grateful to M.Davier for his invaluable advices and to Prof. A.Lagarrigue who kindly made the computing services at Orsay available to us.

References

1. H.Wind. Nuclear INSTRUMENTS AND Methods, 84,117-124 (1970).
2. G.Lechanoine, M.Martin and H.Wind. Nuclear Instruments and Methods, 69,122-124(1969).

Received by Publishing Department
on August 15, 1972

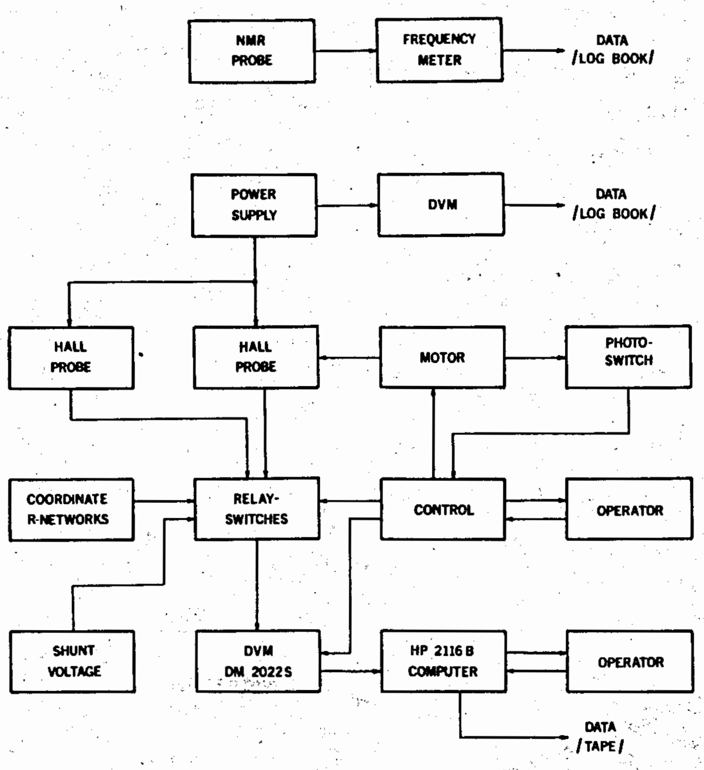

Fig.1. Functional block-diagram of the apparatus for magnetic measurements.

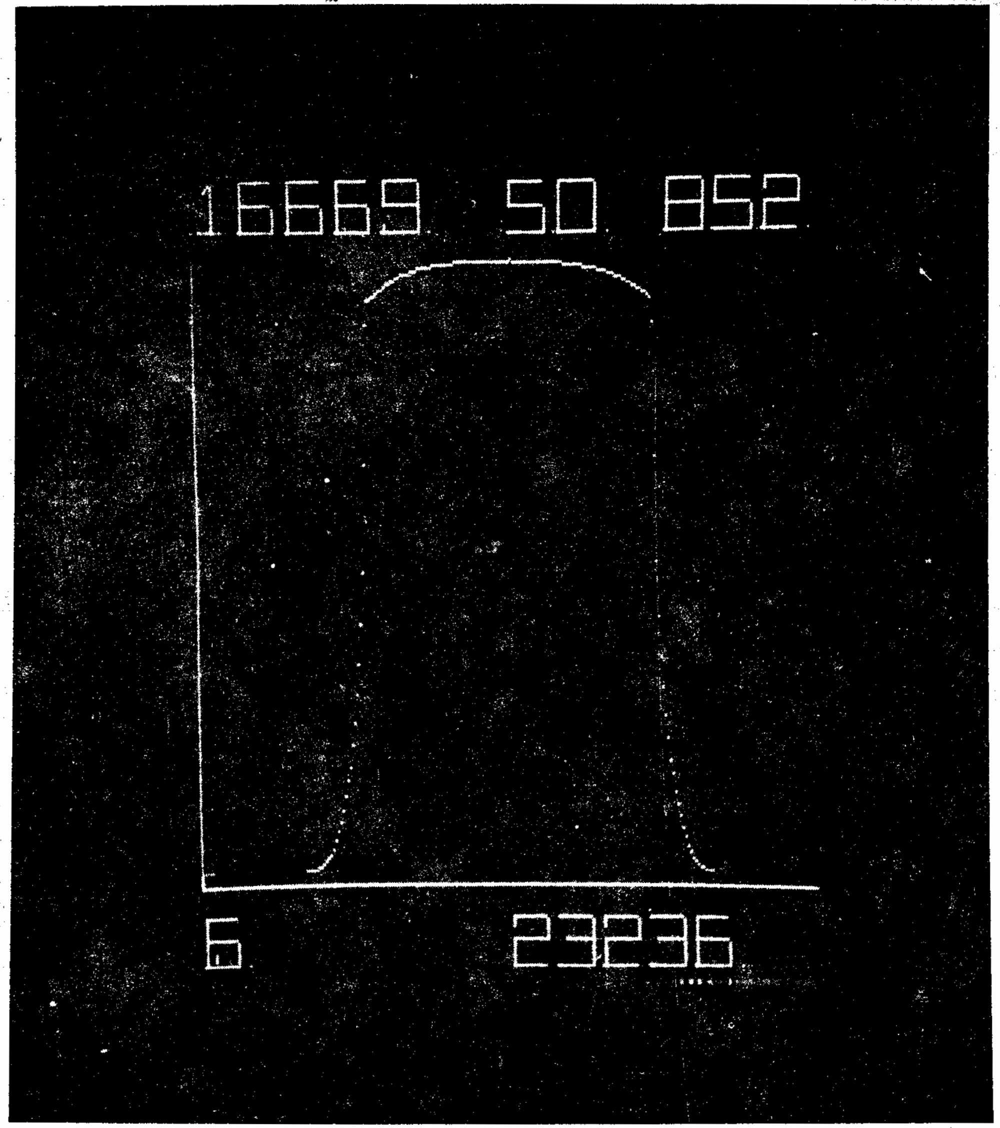

Fig.2. Average of the two measurements against the measurement position.

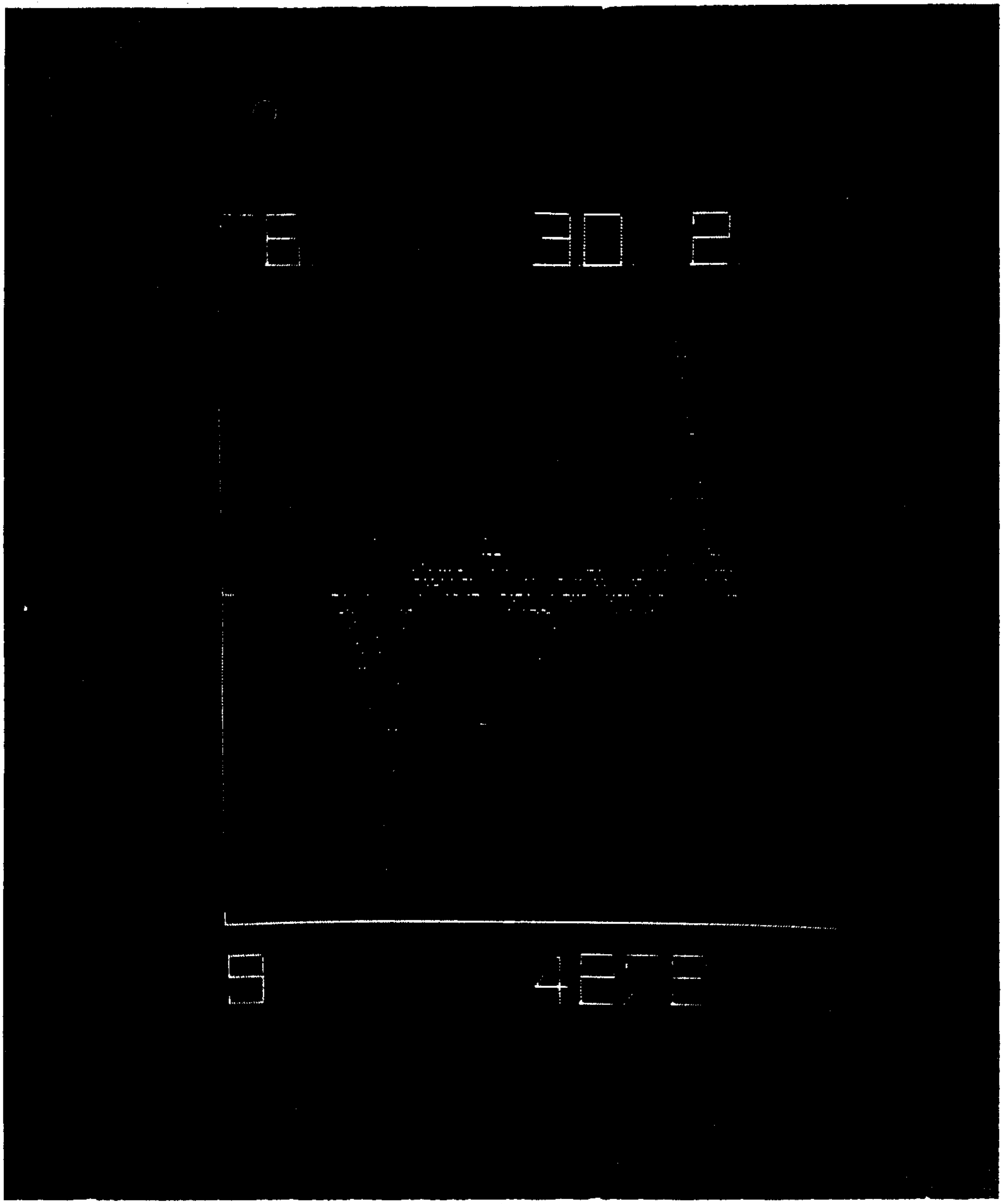

Fig.3. Difference between the two measurements against the measurement position.