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MEASUREMENT OF THE MAGNETIC FIELD OF THE CDF MAGNET

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Abstract

The magnetic field of the CDF (Collider Detector at Fermilab) superconducting solenoid has been measured using a newly designed field mapping device. NMR probes and a system of three orthogonal search coils were used as sensing elements. The central uniform region inside the solenoid coil and the fringing field in the conical end plugs were measured. The detailed field distribution and its characteristics are described.

I. Introduction

The central part of the CDF detector is structured by a 2000 ton magnet[1] which is excited by a superconducting solenoid[2]. In April, 1985 the magnet was turned on for the field measurement. At that time, the magnet was in its final configuration with the exception that the central calorimeters were not present. It is estimated that about 10% of the total return flux goes through the steel structure of the central calorimeters. The flux distribution inside the solenoid is not expected to change drastically when the central calorimeters are present.

The magnet is composed of the outside return yoke, an end plug and end wall steel structure at each end, and the superconducting solenoid. The central magnetic volume is about 3 meters in diameter and 4.5 meters long. This volume has a fairly uniform magnetic field except near the openings to the end plugs. The fringing field volumes inside the end plugs are conical in shape, and the magnetic field is drastically changing, as shown by a computer calculation[3].

II. General Features of the Field Measurement

For most of the measurements, the magnet was operated at its nominal field of 15 kilogauss, corresponding to 5000 A. The details of the CDF field mapping device "ROTOTRACK" are described elsewhere[4]. The setup of ROTOTRACK with respect to the magnet is shown in Figure 1. The coordinate system used is shown in Figure 2. The outer surfaces of the end plugs are at $z = \pm 372$ cm. The inner surfaces of the end plugs are at $z = \pm 226.5$ cm. The conductor winding is at $r = 149$ cm for z between -239 and 239 cm at liquid helium temperature. Note that the axial field component is directed toward negative z; this is the direction of antiprotons.

The field distribution near the center of the magnet was scanned in detail with NMR probes. Nonuniformities in the field due to joints in the conductor and to the solenoid return lead were studied extensively. The residual field, present when the magnet is turned off, was also measured. In general, the measurements were found to agree well with the results of calculations based on the TRIM program[3].

The field was measured on the boundary of a cylindrical surface and these data were then used to perform a fit based on Maxwell's equations. The fit coefficients were used to calculate values of the magnetic field inside the cylinder. These calculated values were then compared to measurements of the field within the cylindrical surface. The method of fitting the magnetic field has been described elsewhere[5]. Detailed results of the fit for the CDF magnet will appear in a future note[6].

III. Field Distribution on the Magnet Axis

The field distribution near or on the axis of the magnet was measured using search coils, a Hall probe and an NMR probe. Figure 3 shows the axial component of the field on the magnet axis, as measured by a set of search coils. The positions of the inner and outer surfaces of the end plugs are indicated with arrows. The central uniform region was measured in detail with an NMR probe; the results are shown in Figure 4. The peak of the field is 25 cm away from the geometrical center. Several factors may contribute to this shift, including a nonuniform distribution of the conductor joints, nonuniform windings of the conductor over the length of the solenoid, or a slight displacement of the solenoid relative to the center of the iron structure.

IV. Central Solenoid Volume

The central part of the solenoid volume was scanned in detail with NMR probes. Measurements were taken at z = 0, ±10, ±20, ±30 cm with r = 0, 5, 10, and 15 cm for each z value. Additional data points were taken at z = 0 for r = 20, 25, and 30 cm. The results are shown in Figures 5a and 5b. Note that the central field value at r = 0 is always lower than other field values at the same z coordinate. The data also show that the minimum field point is at z = -25 cm. The field distribution in the central region may be parametrized as follows:

$$B = 15083.86 - 7.46 \times 10^{-3}(z + 25)^2 + 3.75 \times 10^{-3}r^2,$$

where B is in gauss and z and r are in cm. This gives the magnitude of the field B, but it is essentially equal to B_z as the radial and azimuthal components of the field are small. This point is discussed in Reference 4.

The uniformity of the magnetic field in the central region is of interest for track reconstruction. The CDF Central Tracking Chamber (CTC) occupies a cylindrical volume about 320 cm long with the outermost sense wires located at a radius of 132 cm. Figures 6 and 7 show respectively histograms of our measurements of the axial (B_z) and transverse (B_T) components of the magnetic field ($B_T = \sqrt{B_r^2 + B_\phi^2}$). Figures 6a and 7a, are the results of scanning the plane at z = 0. Measurements were taken every 20 cm in r out to r = 120 cm, and every 10 degrees in ϕ. The average value of B_z is 15090 gauss with an RMS of 20 gauss. The average value of B_T is 28 gauss with an RMS of 14 gauss. Figures 6b and 7b shows the result of scanning the cylindrical surface at $r = 121$ cm for z between -160 and 160 cm. Measurements were taken every 20 cm in z and every 10 degrees in ϕ. The average value of B_z is 15080 gauss (RMS = 74 gauss) and the average value of B_T is 88 gauss (RMS = 63 gauss).

V. Residual Magnetic Field Distribution

The field distribution was measured with a Hall probe when the excitation current was zero. Figure 8 shows the axial component B_z measured at $r = 8.9$ cm. The positions of the inner and outer surfaces of the end plugs are again indicated with arrows. The axial component has its maximum value at points 40 cm inside the surfaces of the end plugs. The residual field has its (local) minimum value at the magnet center where it is about 7 gauss. Inside the end plug regions, the axial component of the residual field reverses polarity. The residual fields are due to the saturation of the iron so the field is strongly localized near the inside edges of the end plugs.

VI. Effect of Conductor Joints

The CDF solenoid has 1174 turns wound on a single layer. The conductor of the superconducting solenoid has ten joints along its length and they are distributed fairly evenly. The average distance between the joints is about 50 cm. Two full turns are welded together to make each joint. For the field distribution, this is equivalent to a missing turn, so the effective turn number is reduced to 1164. The calculated effect for uniformly distributed joints is shown in Figures 9a and 9b. Note that a field value of 10 kG was used for the calculation. The calculation indicates that the axial component decreases near the joints and the radial field component changes polarity at the joints.

The measured data near the conductor are shown in Figure 10. The positions of the innermost 8 joints are shown with arrows. These data were taken at r = 121 cm; the conductor is at r = 149 cm. There are several clear dips in B_z corresponding to the joints. B_r also shows the expected behavior, changing its magnitude and polarity at the joints. From Figure 9a, one finds that the expected value of the decrease in B_z is about 23 gauss at a radial distance of 28 cm from a joint. This is in good agreement with the observed value of 15-30 gauss.

VII. Effect of Return Lead

The solenoid has a return conductor at r = 152.7 cm just outside the solenoid winding at the top of the coil. The return lead runs parallel to the axis of the solenoid near ϕ = 90°. With the approximation that the return current is infinitely long, and neglecting the effect of nearby steel, the field due to the return lead may be estimated with a simple equation:

$$B_{ret.\ lead} = I/(5R)$$

where R is the distance from the return conductor. Here B is in gauss, I is in amperes and R is in cm. The observed effect is shown in Figure 11. The azimuthal component of the magnetic field B_ϕ was measured with a search coil at r=121 cm at several z positions throughout the magnet. B_ϕ shows a strong peak at ϕ = 84°, where the return conductor is placed. The peak is roughly 40 gauss. Based on the equation above, one would expect about 32 gauss, so the agreement is fairly good.

Acknowledgements

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4. R. Yamada, et al. "The CDF Field Mapping Device - ROTOTRACK", Fermilab TM-1358 and CDF Note No. 345, August, 1985.

5. H. Wind, IEEE TRANSACTIONS Magnetics 5, 269 (1969); H. Wind, Nuclear Instruments and Methods 84, 117 (1970); Paul R. Ganci, "Fitting a Magnetic Field from Boundary Observations in Cylindrical Coordinates", CERN Computer Centre Program Library Long Writeup W1029/W1030; P. Ganci and A. C. Melissinos, "The Field Map of the CLEO Magnet (Warm Coil)", CBX-80-53, September, 1980.

6. C. Newman Holmes, "Fitting the Magnetic Field of the CDF Solenoid", CDF Note No. 361, November, 1985.

List of Figures

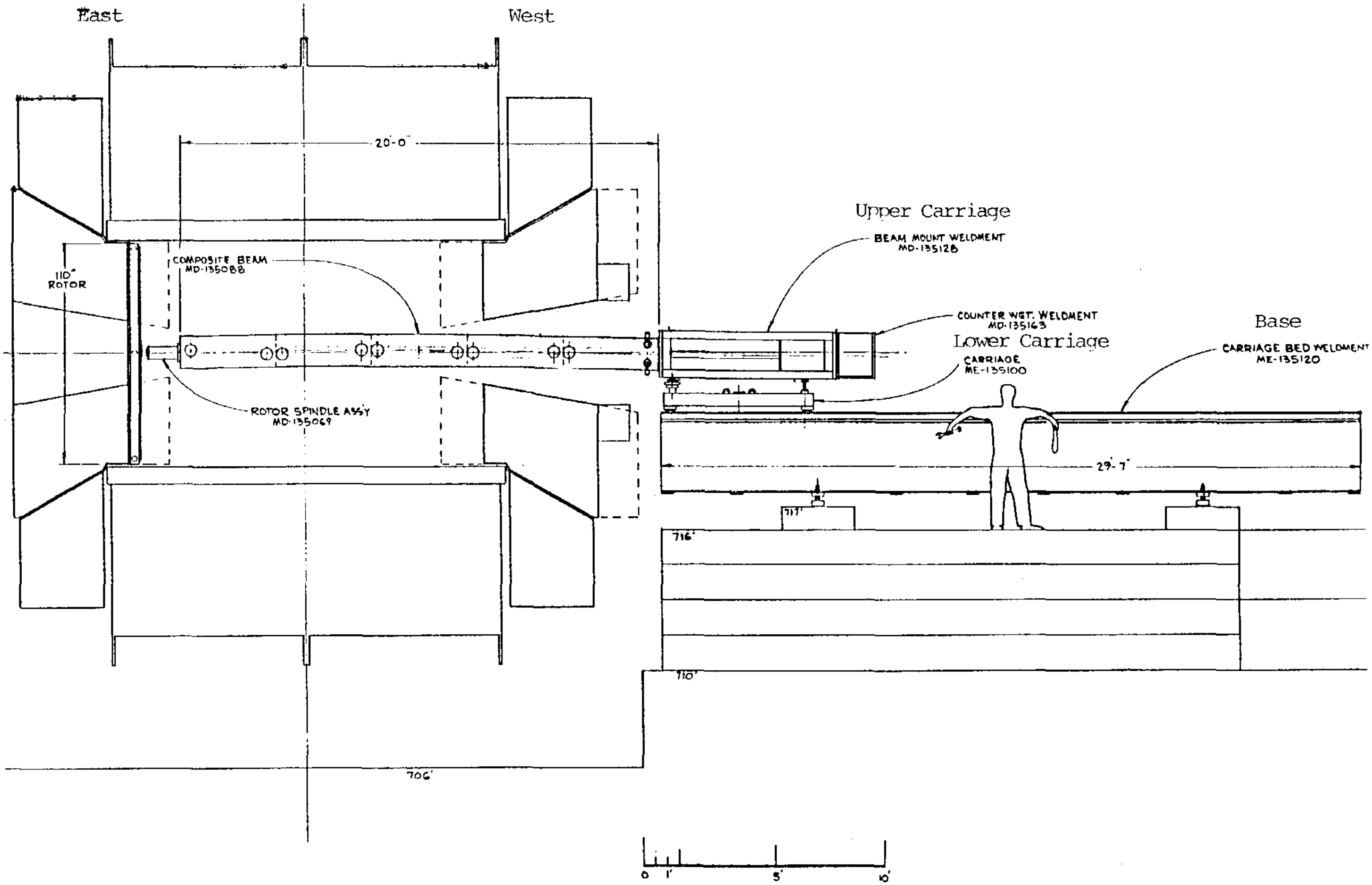
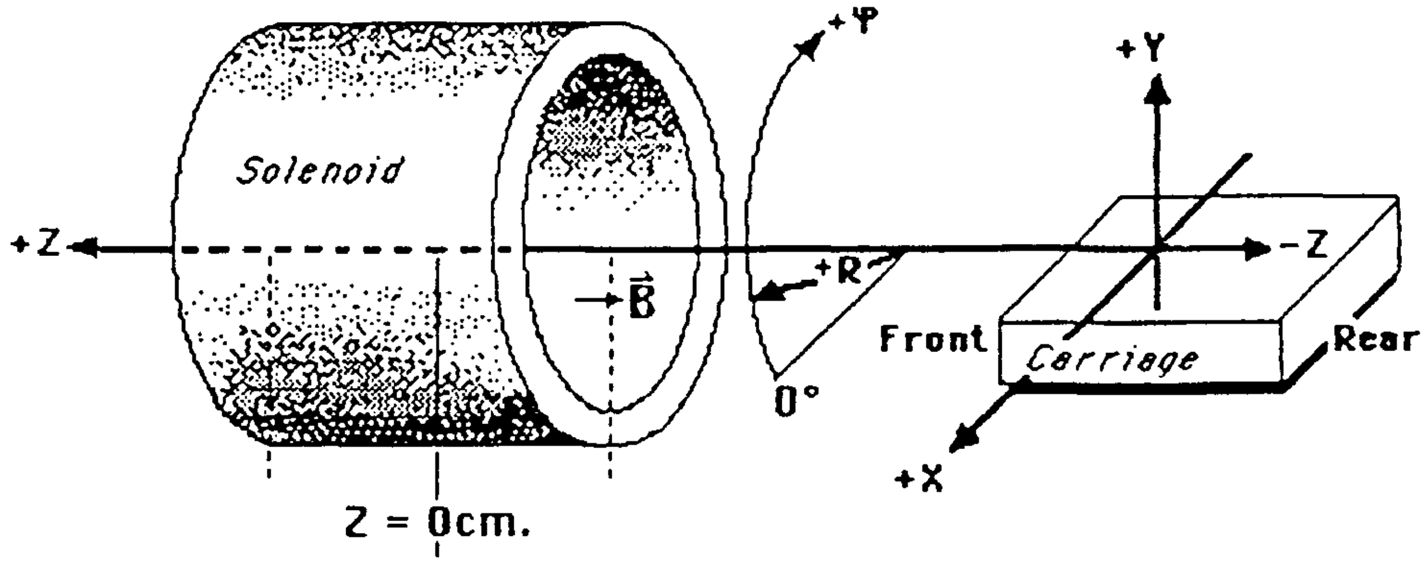


Fig. 1
CDF Field Mapping Device "Rototrack"



C. D. F. Coordinate System

Fig. 2

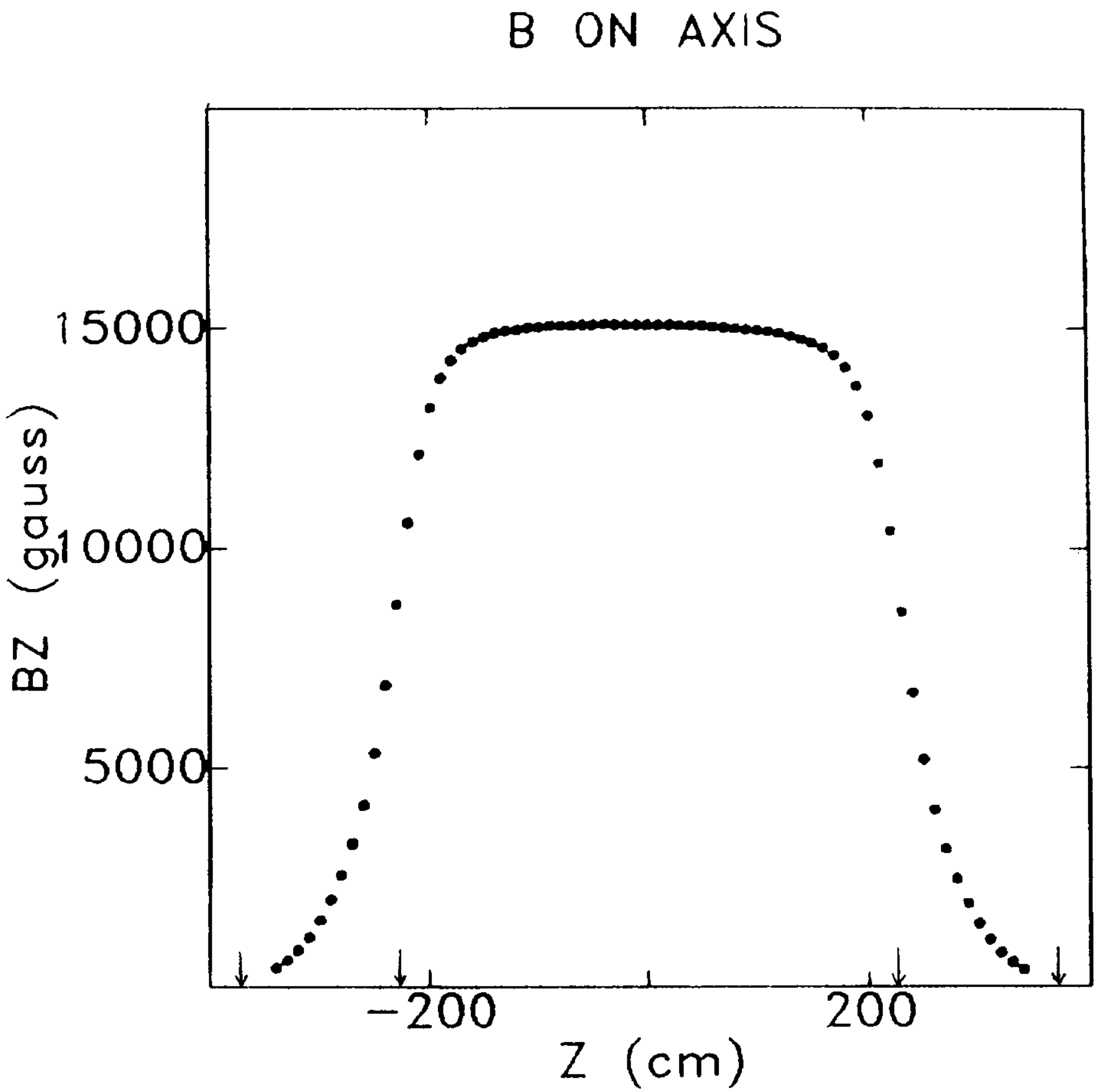


Fig. 3

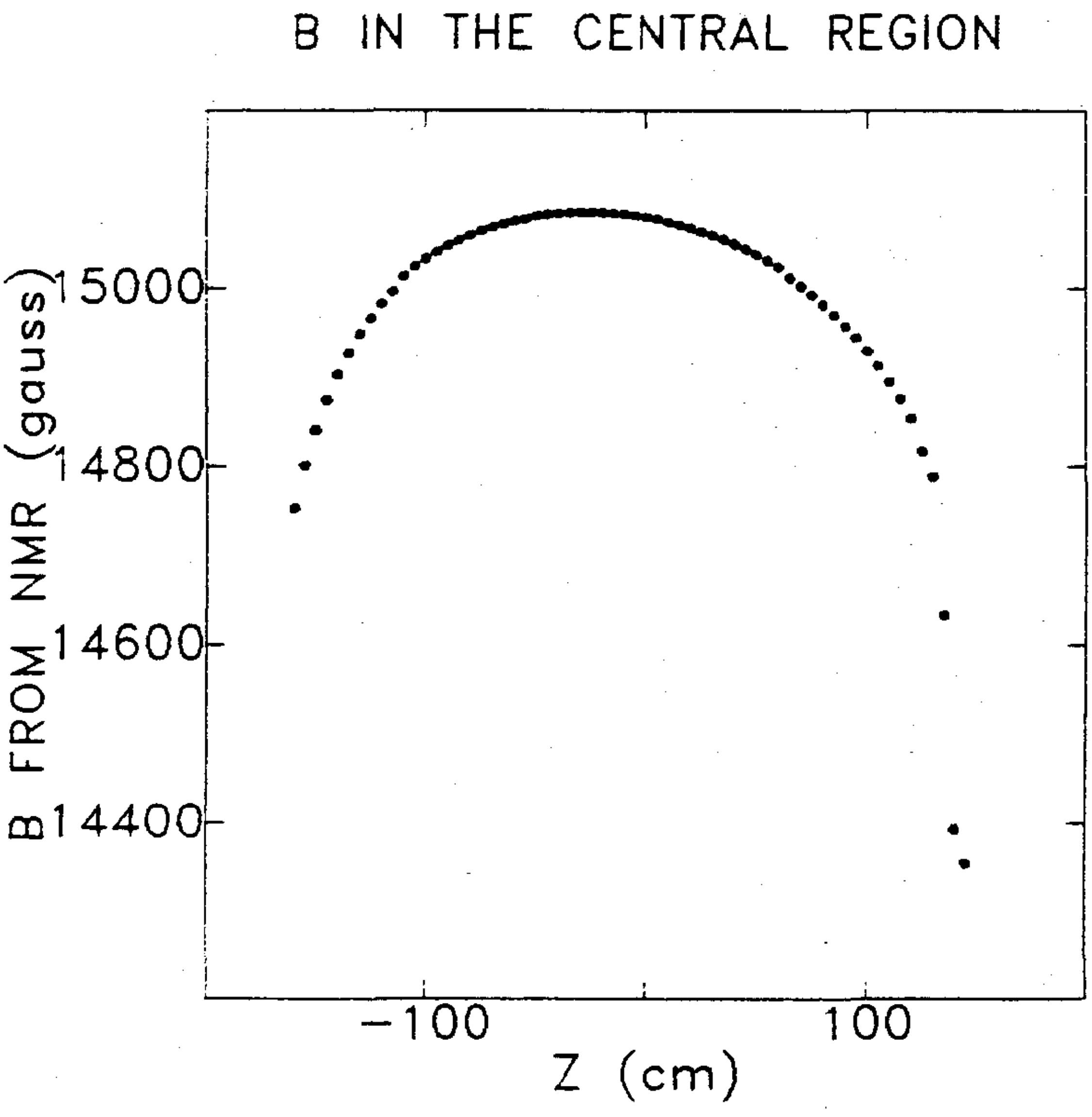

B IN THE CENTRAL REGION
B FROM NMR (gauss)
15000
14800
14600
14400
−100
100
Z (cm)

Fig.-4

Fig. 5a B ON Z-AXIS

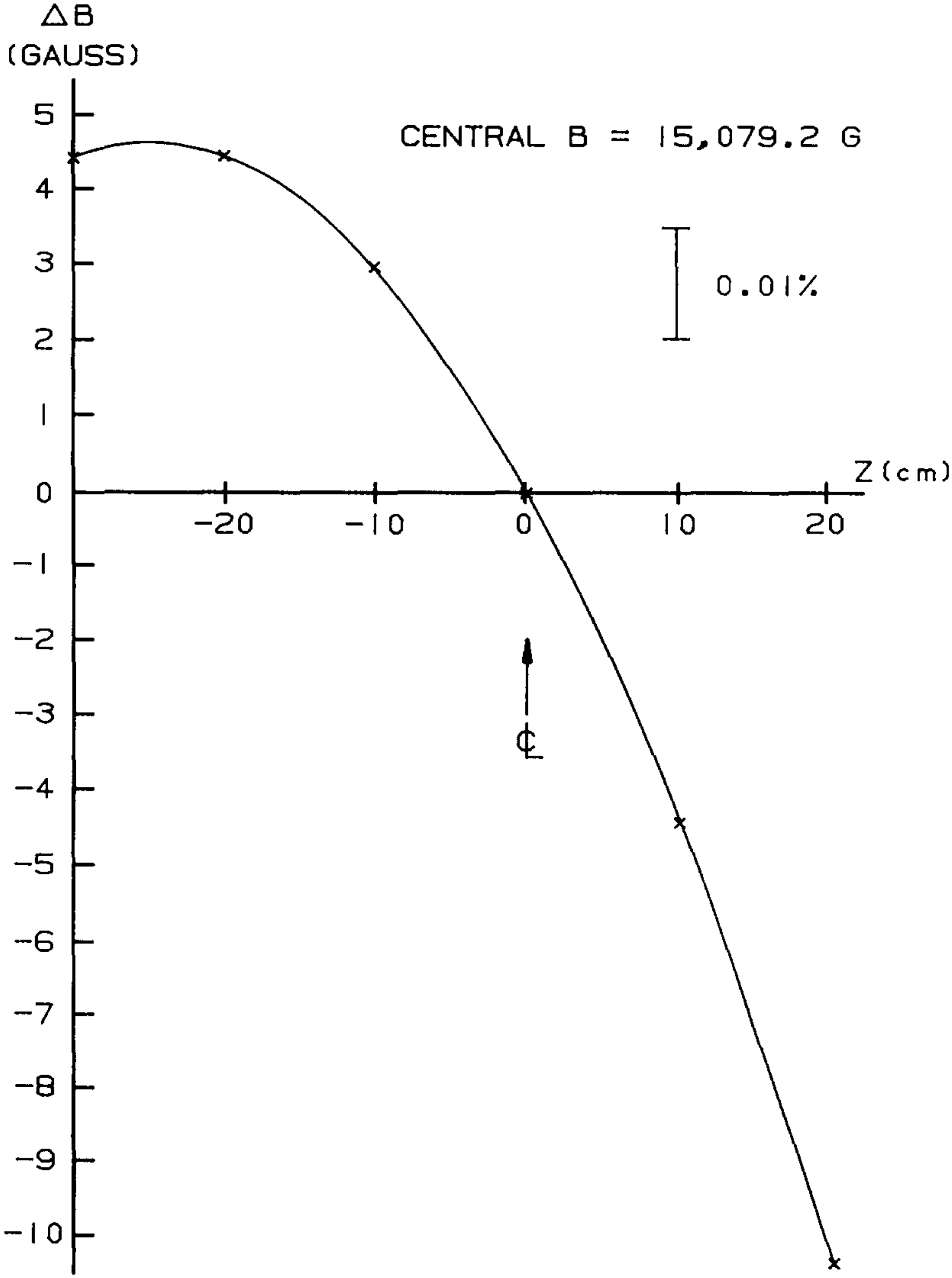
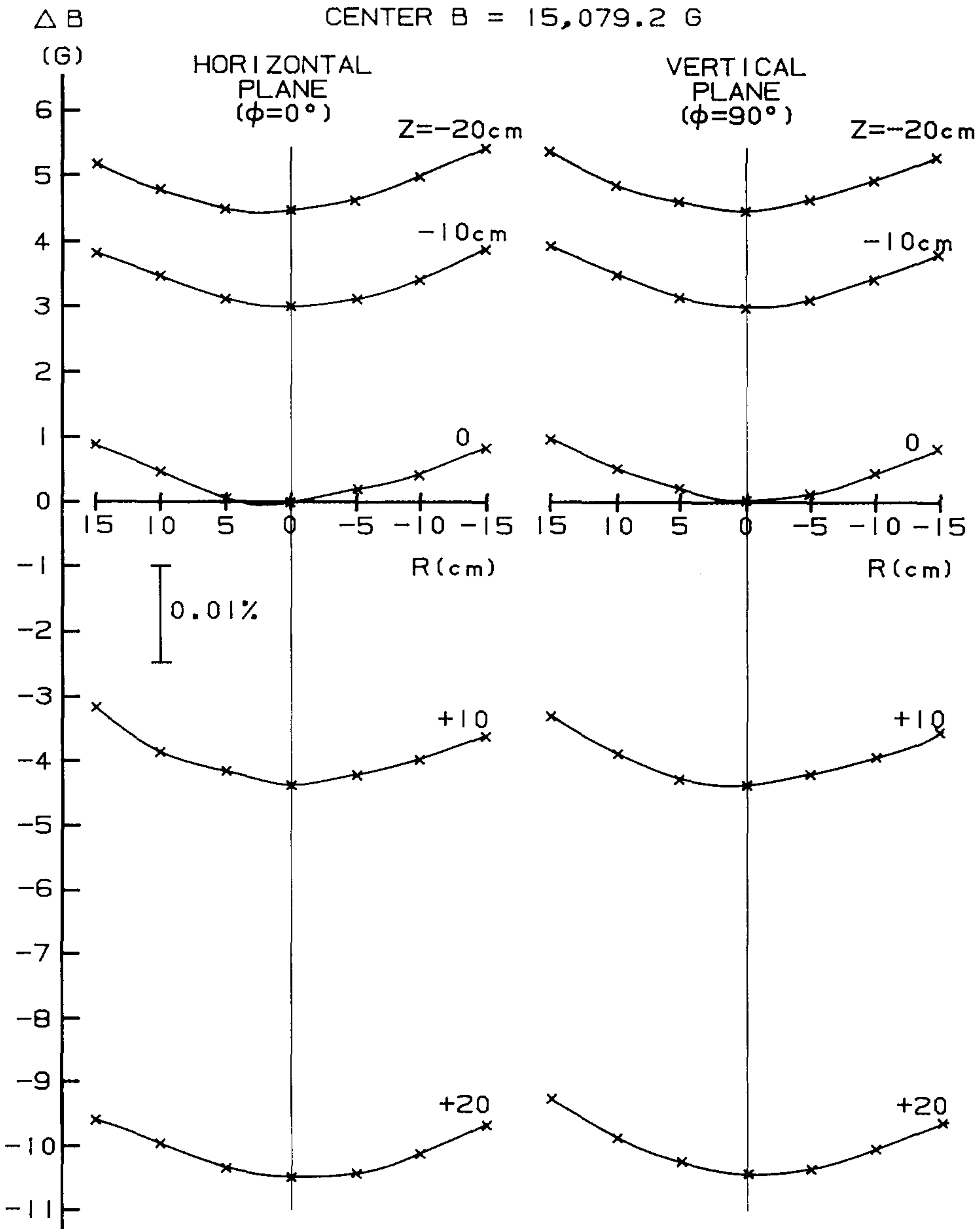


Fig. 5b ΔB AROUND CENTER



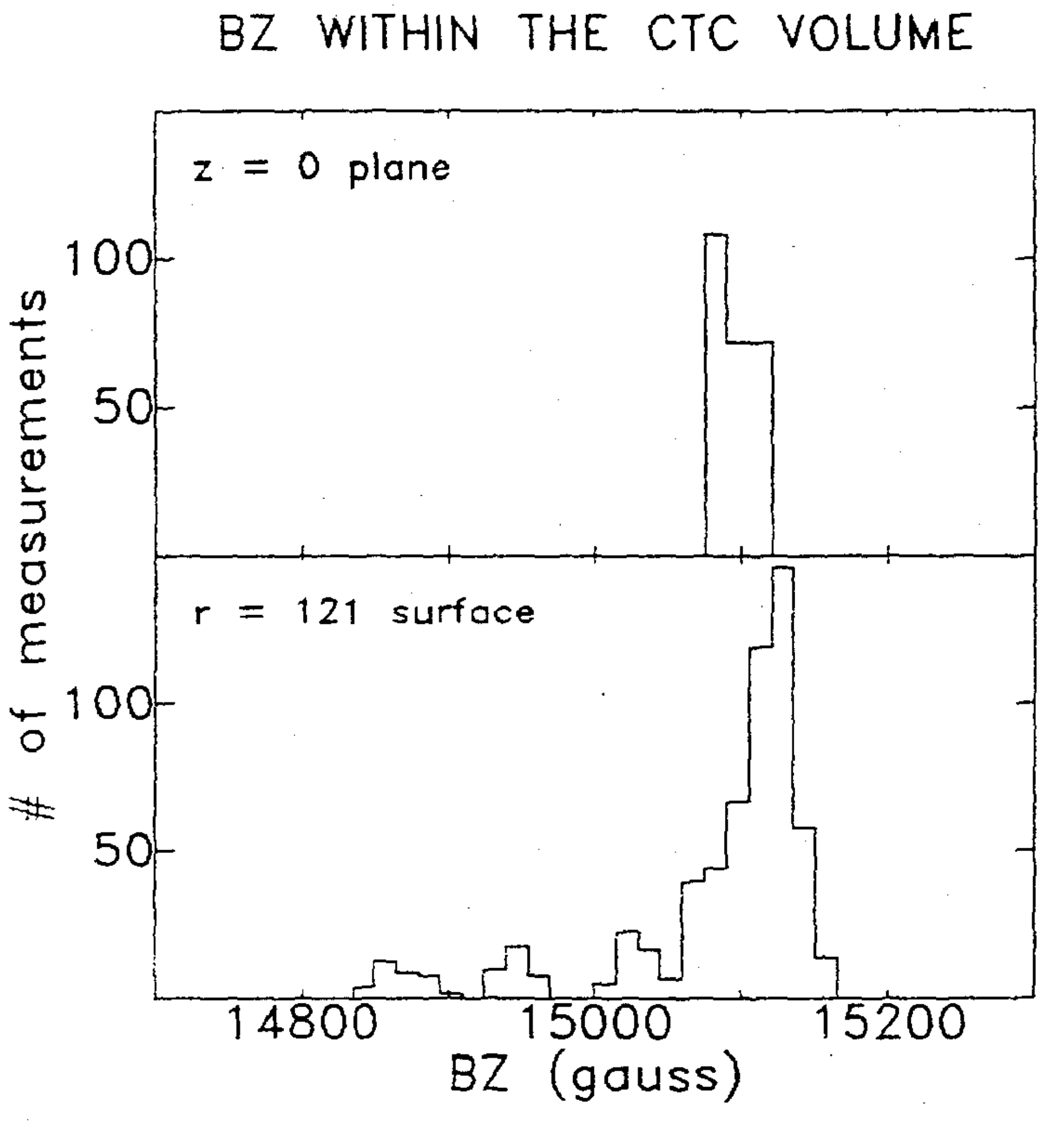

BZ WITHIN THE CTC VOLUME
z = 0 plane
r = 121 surface
100
50
100
50
# of measurements
14800
15000
15200
BZ (gauss)

Fig. 6

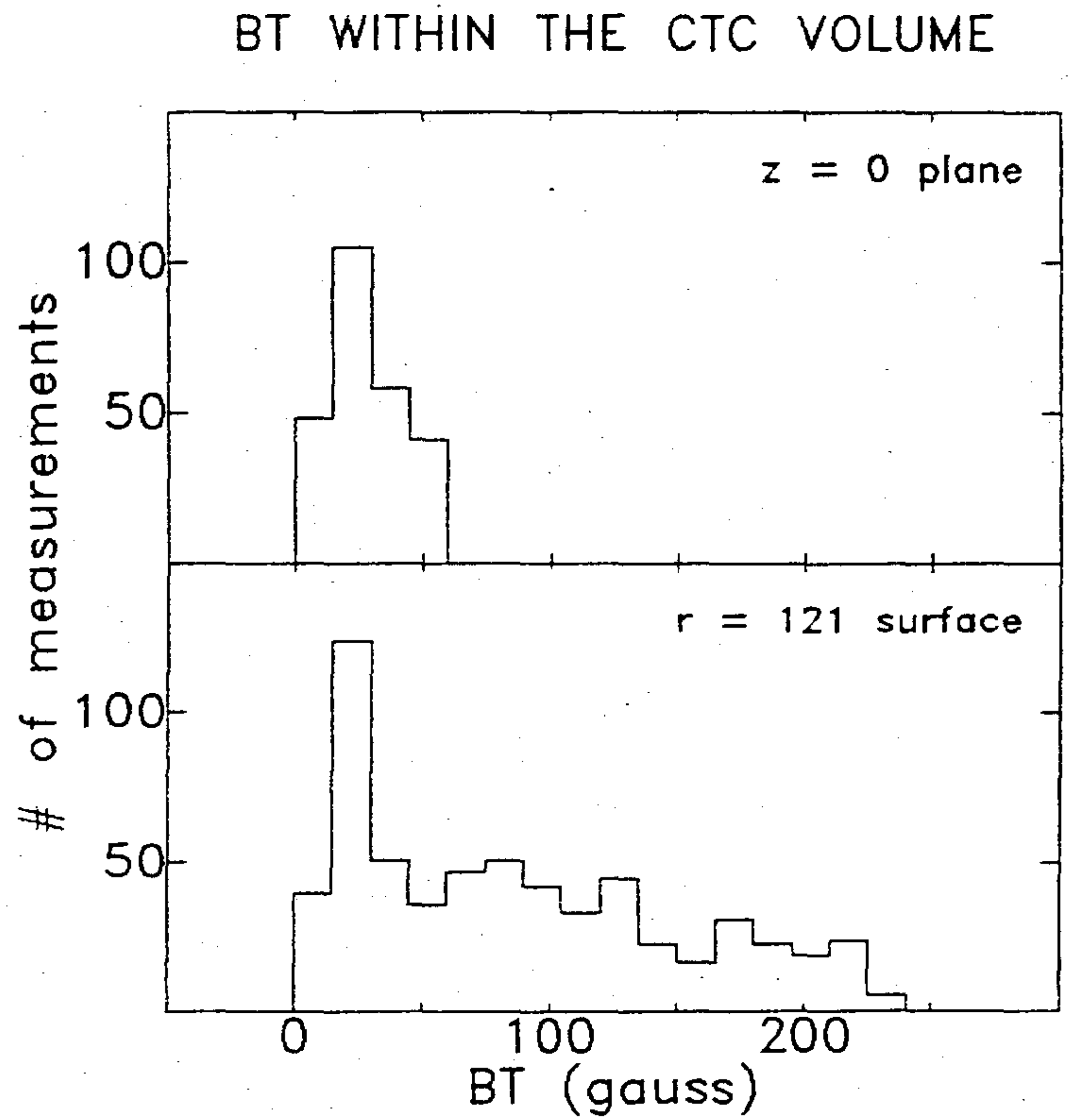

BT WITHIN THE CTC VOLUME
z = 0 plane
r = 121 surface
# of measurements
100
50
100
50
0
100
200
BT (gauss)

Fig. 7

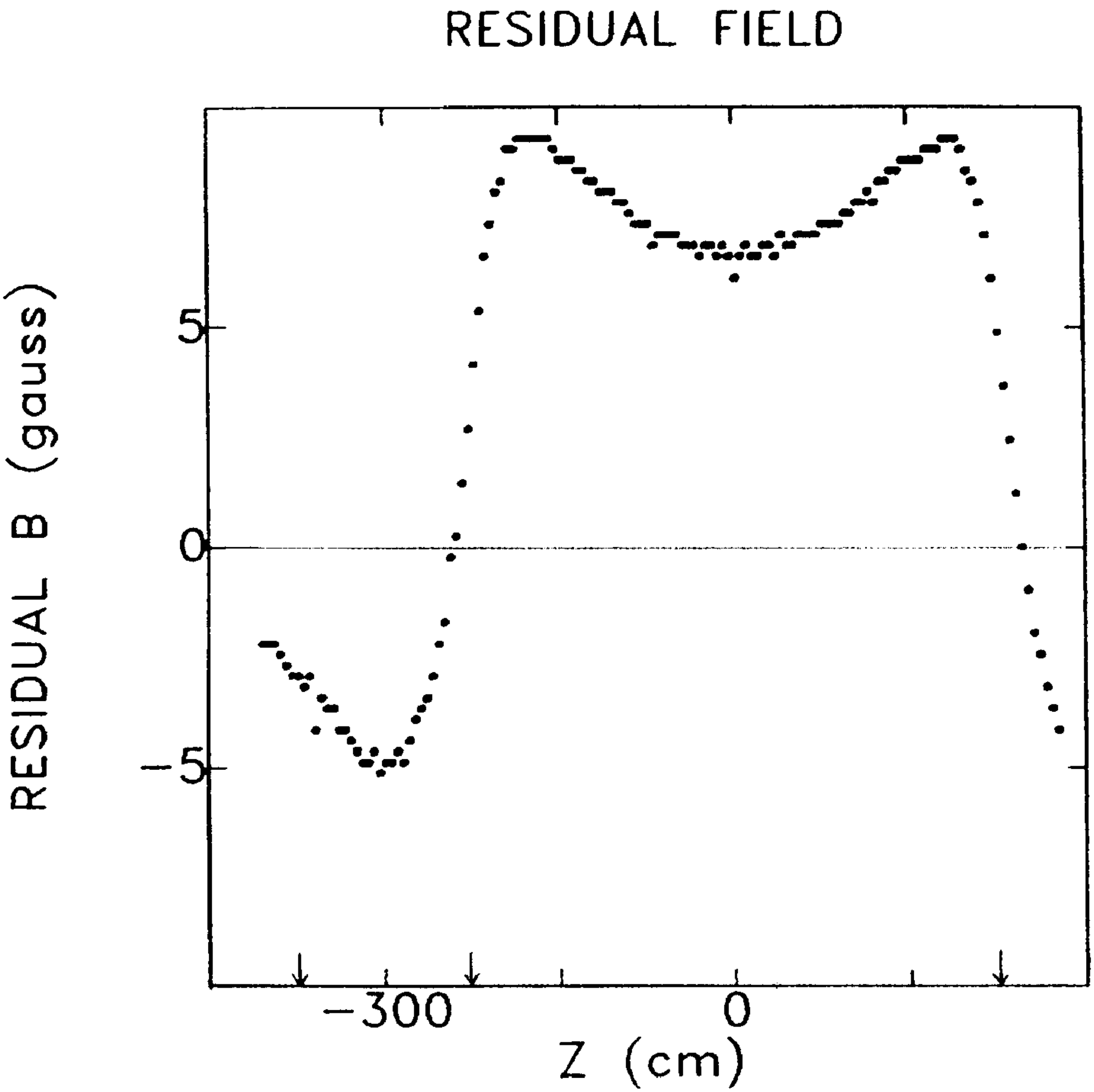


Fig. 8

Fig. 9a

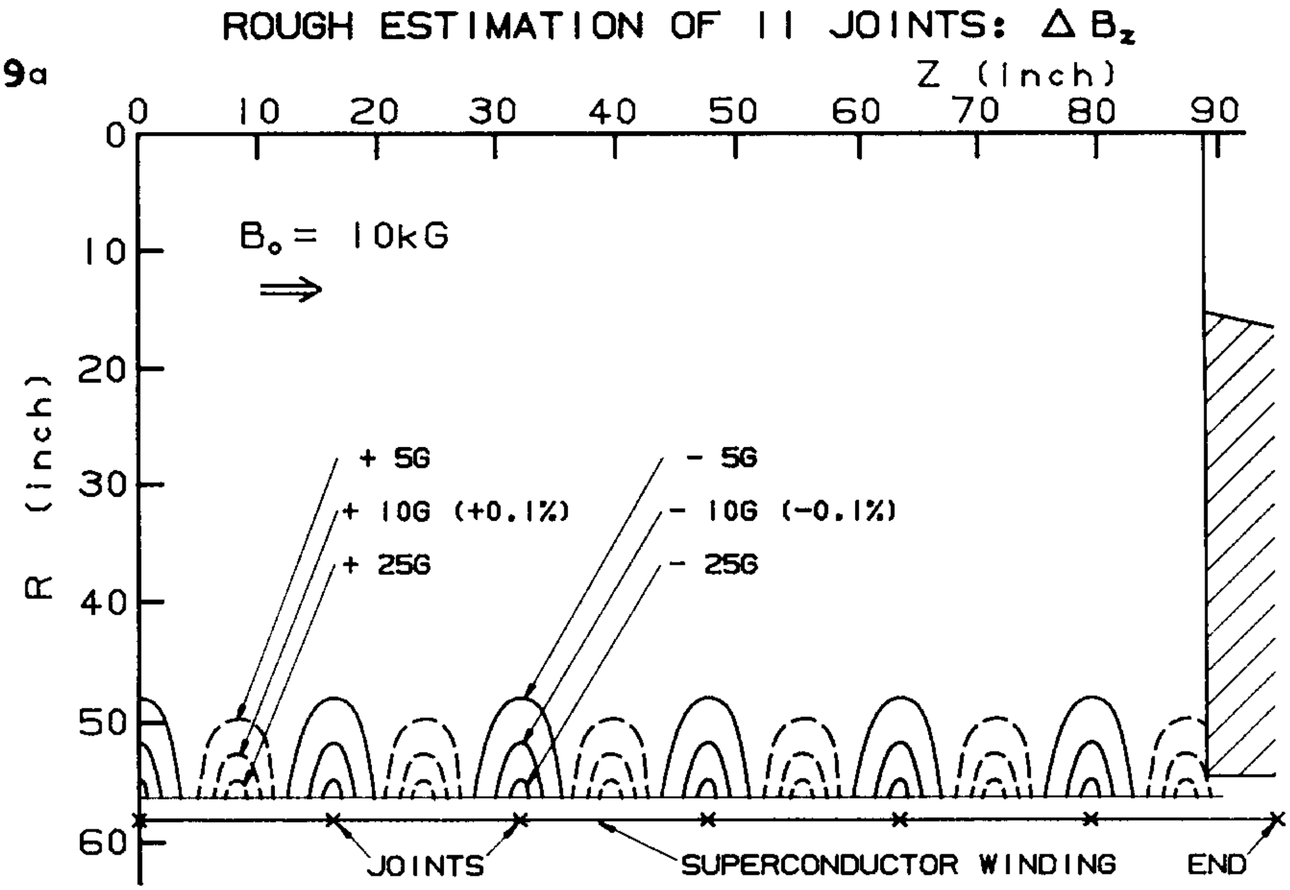
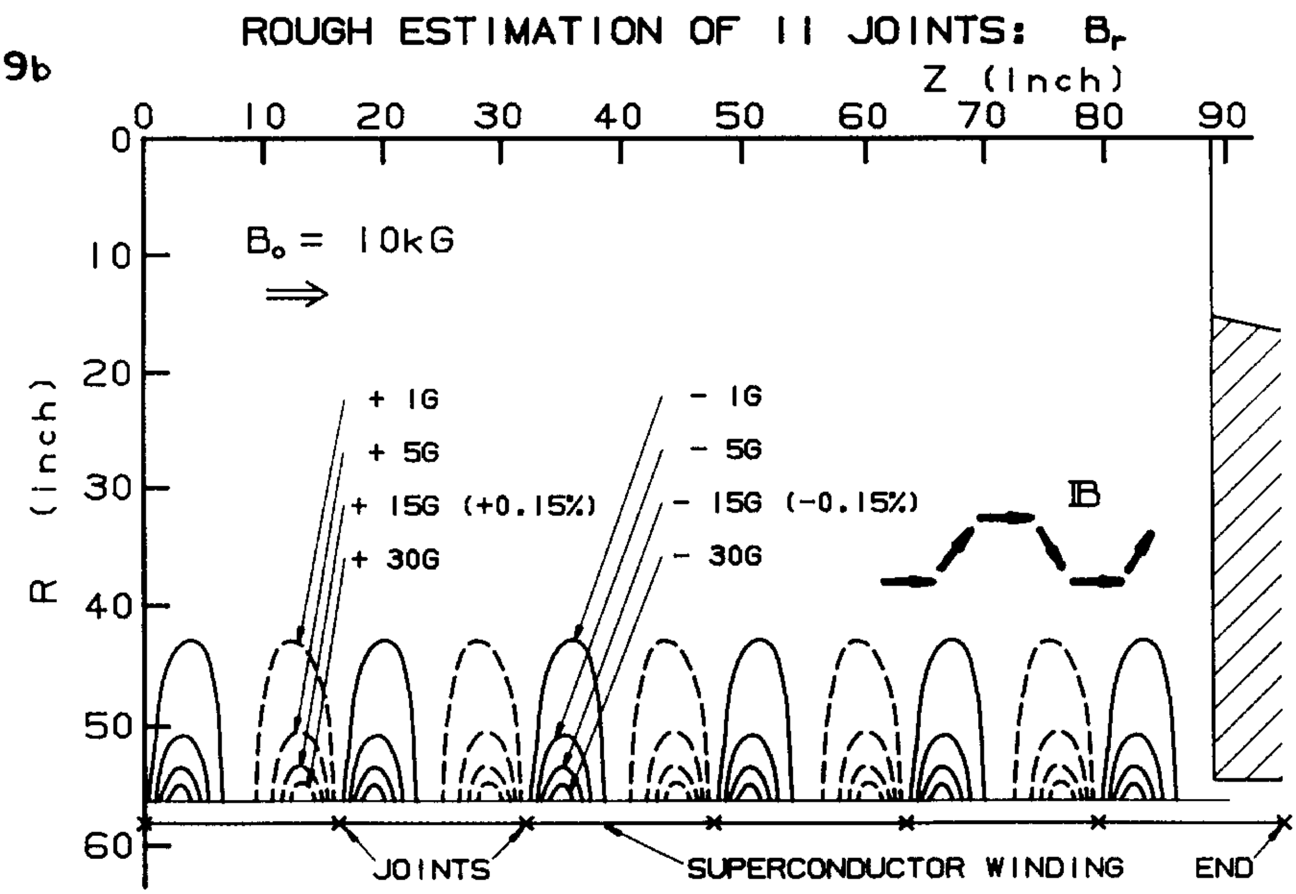
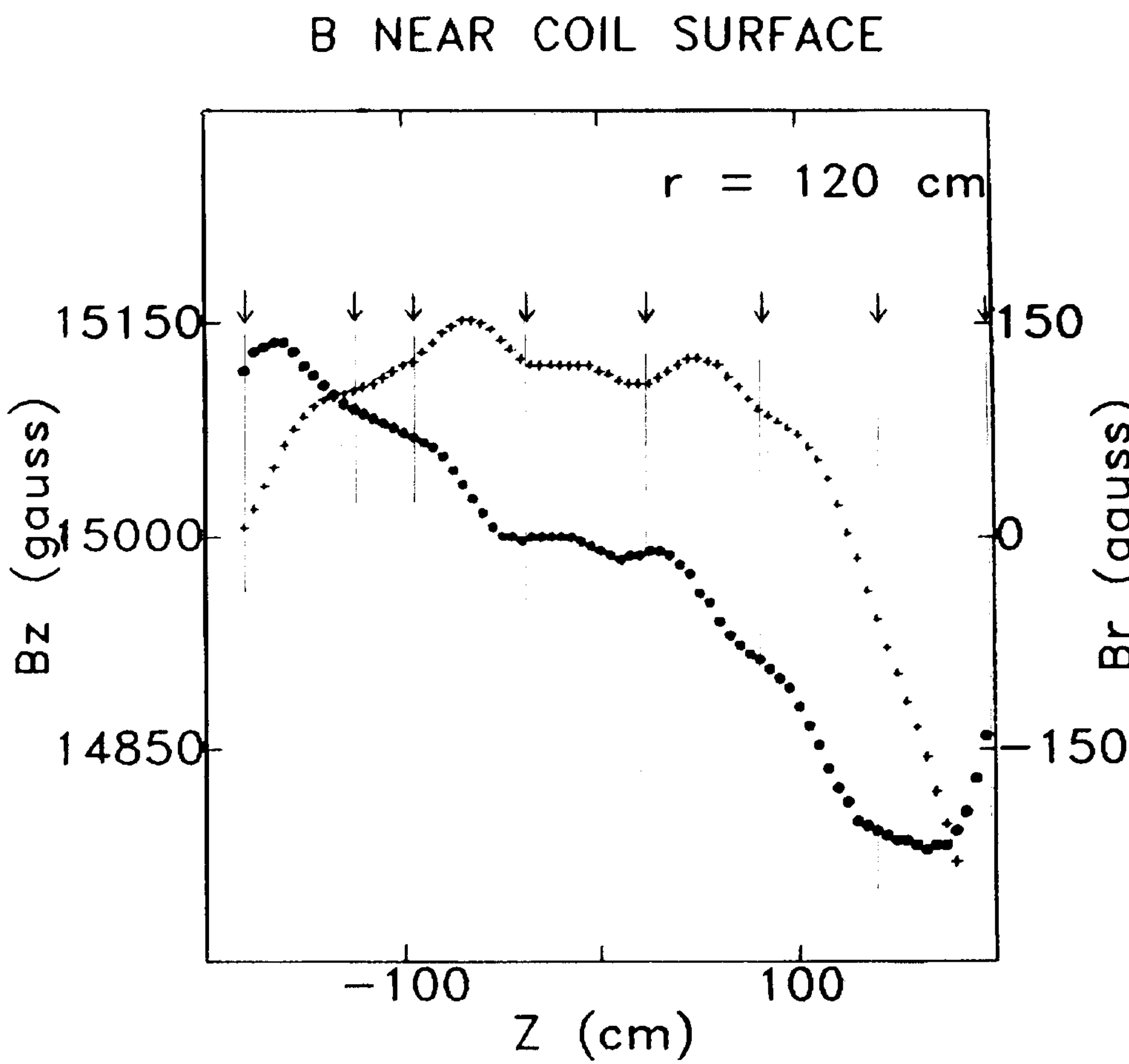

ROUGH ESTIMATION OF 11 JOINTS: ΔB_z
Z (inch)
0 10 20 30 40 50 60 70 80 90
R (inch)
0 10 20 30 40 50 60
B_o = 10kG
+ 5G
+ 10G (+0.1%)
+ 25G
- 5G
- 10G (-0.1%)
- 25G
JOINTS
SUPERCONDUCTOR WINDING
END

Fig. 9b


ROUGH ESTIMATION OF 11 JOINTS: B_r
Z (inch)
0 10 20 30 40 50 60 70 80 90
R (inch)
0 10 20 30 40 50 60
B_o = 10kG
+ 1G
+ 5G
+ 15G (+0.15%)
+ 30G
- 1G
- 5G
- 15G (-0.15%)
- 30G
B
JOINTS
SUPERCONDUCTOR WINDING
END



B NEAR COIL SURFACE
r = 120 cm
15150
15000
14850
150
0
−150
Bz (gauss)
Br (gauss)
−100
100
Z (cm)

Fig. 10

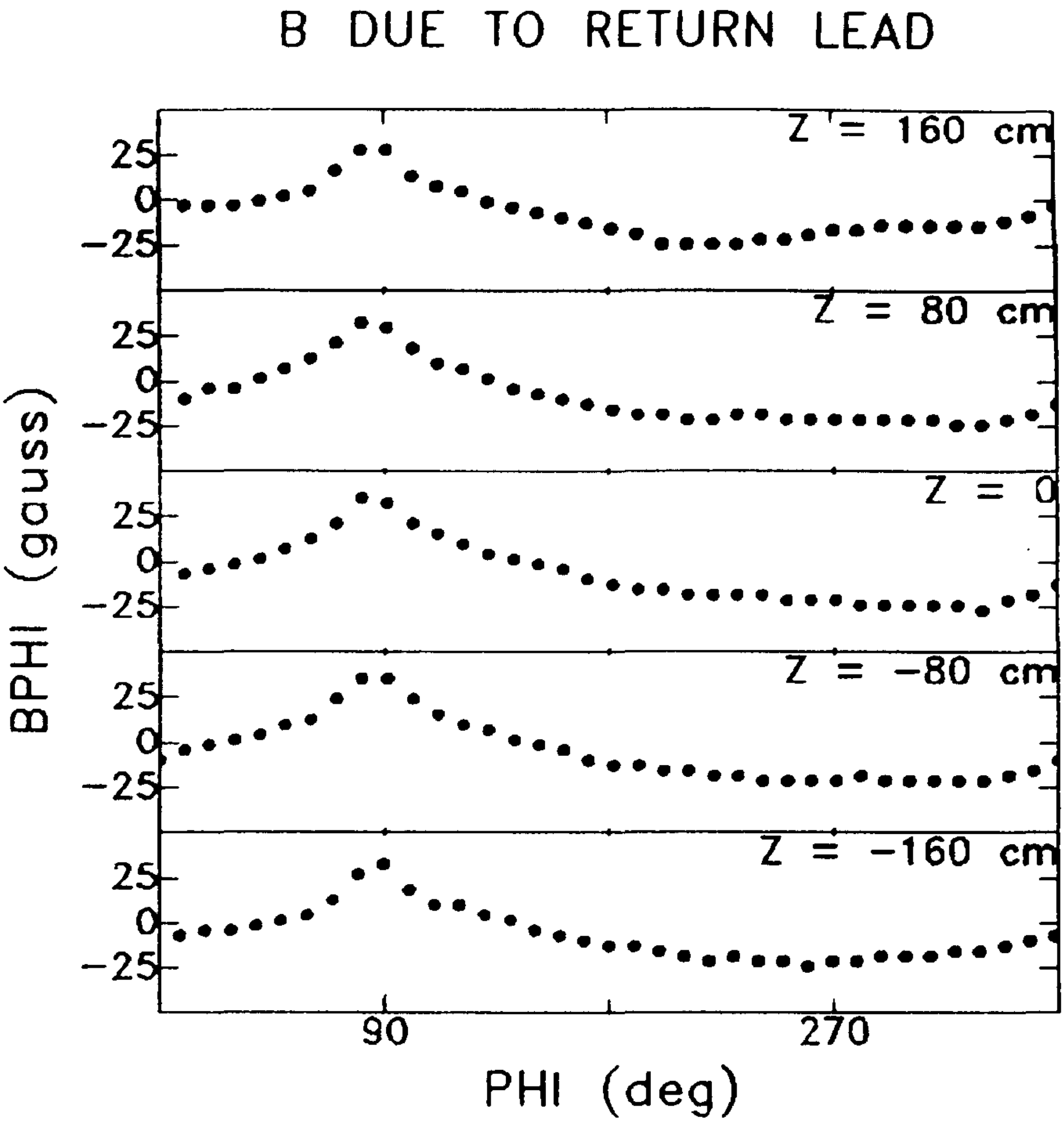

B DUE TO RETURN LEAD
Z = 160 cm
Z = 80 cm
Z = 0
Z = −80 cm
Z = −160 cm
25
0
−25
BPHI (gauss)
90
270
PHI (deg)

Fig. 11