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Abstract

The magnetic field distribution of corrugated theta pinch coils is measured in an analogue experiment (exp. error o.o5 %), in order to determine the perturbation of the rotational symmetry induced by the current feed slot.

The maximum deviations from rotational symmetry are found near the coil surface around the current feed slot. They have a value of a few per cent and are proportional to the width of the current feed slot. The perturbations decrease towards the coil axis to a few tenths per cent only.

The distribution of a locally varying inductance of the current transmission line is computed and applied by moulding inductive lenses into the transmission line plates. The influence of the inductive lenses is measured. Within a radial region of about 1/2 of the coil radius the perturbations are found to be reduced to the level of the experimental error. The residual perturbations outside this region are mainly attributed to the limited space available for the application of the inductive lenses in the transmission line system.

Indroduction

The stability of a theta pinch in corrugated fields was studied by several experiments [1,2,3,4]. The axial variation of the plasma cross section (single or periodic) was achieved either by electrically programming the discharge current [2, 4], or by having the magnetic field diffuse into an additional coil [3] . In the present experiment the magnetic field corrugation is produced by shaping the surface of the theta pinch coil so that the coil radius is varied sinusoidally. A highly rotational symmetric magnetic field is desired for the implosion phase of the plasma and for investigation of its stability behaviour.

This rotational symmetric field is disturbed by the current feed slot. At the maximum coil cross section ("bulge") field lines are pulled out of the feed slot, this causing an increase of the field strength owing to the additional magnetic flux. At the minimum coil cross section ("neck"), on the other hand, field lines are pulled into the current feed slot, which leads to a reduction of the magnetic field strength. This disturbed magnetic field pattern is being investigated in the analogue experiment described.

Numerical computations of these perturbations have proved to be difficult. A computation has been made, however, which yields the distribution of the local inductance inside the transmission line near the theta pinch coil (inductive lenses) necessary for achieving the desired rotational symmetry. These inductive lenses are moulded in the transmission line near the regions of the "necks" and "bulges", and their efficiency is experimentally investigated.

For the magnetic fields investigated the diamagnetic currents of the plasma are not taken into account, although the magnetic field distribution inside and around a corrugated plasma column will be influenced by the plasma currents themselves. It is believed that the deviations from rotational symmetry of the field, which are determined by the current distribution on the coil surface mainly around the current feed slot, can be measured satisfactorily by neglecting the diamagnetic plasma currents.

Calculation of the additional inductances

(inductive lenses)

Deviations from rotational symmetry of the vacuum magnetic field in theta pinch coils are produced if the current lines from the transmission line do not enter the inside coil surface perpendicularly [5] .
This effect usually occurs

1) near the ends of a coil, e.g. due to collector plates or any conducting material the position of which is not rotational symmetric with respect to the coil axis
2) if the coil is not cylindrical in shape, but varies in cross section along the axis, e.g. due to corrugations of the coil surface.

This report does not consider the ends of the coil, but only deals with the influence of the corrugation on the magnetic field pattern. The terms "coil" and "transmission line" refer to the current carrying surfaces of these devices.

The magnetic field strength of a corrugated coil, denoted by R(z), has its maximum value at the "neck", i.e. at an axial position z where R(z) has a minimum value. The minimum magnetic field strength occurs at the "bulge", where R(z) has its maximum value. Consequently, the coil current density increases monotonically from the bulge to the neck; for the case of plane transmission line surfaces, Fig. 1a shows a qualitative plot of the resulting current lines, from which it can be seen that these current lines do not flow perpendicularly towards the coil surface. In order to avoid this, the current lines have to be forced to make a detour around the transmission line regions near the bulge, as is shown qualitatively in Fig. 1b. In principle, this can be done by means of an "inductive lens" in that region, i.e. by locally increasing the distance between the two transmission line plates. This is schematically shown on Fig. 2, and the region of the transmission line, where the inductive lenses are located, is denoted there as "adapter". The mathematical problem is as follows: how is the distance S between the two transmission line plates to be adjusted as a function of z and y in order to have the current lines streaming perpendicularly towards R(z). This problem is infinitely ambiguous. The equation of a current line is given by

$$z = Z(y). \tag{1}$$

As indicated on Fig. 3,
we then have to set up conditions for Z and for the first and second derivatives of Z at two points, whereas the further qualities of Z are arbitrary within a wide range.

In order to simplify the calculation it is assumed that:
For $y = y_a$ the magnetic field is uniform and the distance S between the transmission line plates is constant, i.e.

$$\text{Distance} \quad S(z, y \quad) = S_o \tag{2}$$

$$\text{Magnetic field} \quad \begin{cases} B_z(z, y = y_a) = a \\ B_y(z, y = y_a) = 0 \end{cases}$$

For $y < y_a$ we are looking for S (z,y).

Strictly speaking this assumption is not correct. If for $y \leq y_a$ one has a varying distance S (i.e. there are inductive lenses), then these lenses will be "sensed" by the current lines at $y > y_a$ as well; consequently, the magnetic field $\vec{B}$ at $y = y_a$ will be not homogeneous. However, the error stemming from the above assumption will be the smaller the more the value of y_a exceeds the period length L (as shown, for example, by GREEN et al. [6]).

Using assumption (2), we get the condition for a current line, which within the region $y \geq y_a$ is described as follows:

$$Z(y) = z_a \tag{3}$$

$$\frac{dZ}{dy}(y_a) = 0 \quad \text{(the magnetic field has to be continuous at } y_a) \tag{4}$$

$$\frac{d^2Z}{dy^2}(y_a) = 0 \quad \text{(the transmission line distance has to be continuous at } y_a) \tag{5}$$

The current lines represent lines with constant magnetic scalar potential U . It follows from eq. (2) that the scalar potential along the current line (eq. (3)) has the value:

$$U = a z_a$$

Therefore, the same scalar potential also exists at the point z_1, y_1, where this current line coming from the transmission line joins the coil:

$$U(z_1, y_1) = a\, z_a, \tag{6}$$

where

$$y_1 = R(z_1). \tag{7}$$

Introducing for U in eq. (6) the scalar potential inside the coil, we then get from eqs. (6) and (7) the coordinates of the point z_1, y_1. The function Z has to obey the following equations:

$$Z(y_1) = z_1 \; ; \tag{8}$$

$$\frac{dZ}{dy}(y_1) = -\frac{dR(z_1)}{dz} \quad \text{(current line perpendicular to coil).} \tag{9}$$

When only the conditions formulated thus far are taken into account, the maximum value of S is located immediately on the coil surface and is very large, i.e. the current feed slot is widest at the coil surface. A wide feed slot, however, causes a relatively large magnetic field perturbation since the latter is caused by the components of the additional magnetic flux perpendicular to R(z), which is proportional to the width of the feed slot. Therefore, we are looking for an additional condition which transfers the maximum value of S away from the coil surface (feed slot) towards the more remote regions inside the transmission line. One such condition is:

$$\frac{d^2Z}{dy^2}(y_1) = 0. \tag{1o}$$

In order to determine Z(y) we use a polynomial:

$$Z(y) = z_a + c_1(y - y_a)^3 (y^2 + c_2 y + c_3) + + c_4(y - y_a)^3 (y - y_1)^3 \quad (11)$$

and determine the coefficients c_1, c_2, c_3 from eqs.(8) - (1o); the eqs. (3) - (5) are then automatically satisfied. The term with c_4 is such that even for arbitrary values of c_4 the conditions (3) - (1o) remain unperturbed. This term makes it possible to influence the shape of the inductive lenses, one of which is located near the bulge and the other opposite the neck (Fig.2). The calculation of Z(y) for various values of z_a yields the whole current line pattern. The magnetic field lines $\vec{B}$, which are orthogonal to the current lines, are thus determined as well.

From

$$\text{div } \vec{B} = 0$$

one gets approximately the following differential equation for the transmission line distance S:

$$\frac{\partial}{\partial z}(SB_z) + \frac{\partial}{\partial y}(SB_y) = 0 . \quad (12)$$

The following equation is a sufficient condition to make eq. (12) represent a good approximation:

$$|\text{grad } S| \ll 1 . \quad (13)$$

Condition (13) is not necessary, since there exist cases where ∇S might be large and eq.(12) is nevertheless fulfilled, e.g. if $B_y = 0$, B_z = const., and S only depends on y. In order to solve eq.(12) nummerically, we use (see also eq.2)

$$S(z, y_a) = S_o$$

as a boundary condition for $y = y_a$. However, instead of looking for another boundary condition, we want

$$\min S(z,y)_{y=\text{const}} = S_o \quad (14)$$

i.e. the transmission line distance S has to be nowhere smaller than S_o and has to be equal to S_o at one point at least along each straight line y = const.. The numerical computation was made for a periodically corrugated coil with a period length L = 10 cm, y_a = 16.3 cm, R_{min} = 5.3 cm, R_{max} = 5.8 cm, and S_o = 3.4 mm. On the assumption that the z-component of the magnetic field depends sinusoidally on z [5] , one obtains approximately for the coil radius:

$$R(z) = R_{min} + \frac{1}{2}\Delta R(1 + \cos 2\pi z/L), \quad \Delta R = R_{max} - R_{min}.$$

Analogue experiment for measuring the magnetic field perturbations

The model coil for producing the magnetic field to be investigated is made of aluminium. The dimensions of this model coil were determined by the dimensions of the coil used in the Isar I bank. The current is fed into this coil along a transmission line 250 cm in length and of the same width as the length of the coil. The last part of the transmission line joining the coil consists of exchangeable plates and is refered to as "adapter". The current for the magnetic field in the model coil is supplied by a generator with a constant frequency of 714 kHz. The magnetic field to be investigated is measured with a small pickup coil by balancing its signal with a reference voltage taken from the transmission line. The pickup probe has a space resolution of about o.7 mm and is thus considerably smaller than the width of the feed slot, which governs the magnitudes of the field perturbations. With this device, which has been described in detail elsewhere [7] , local variations of the magnetic field strength of o.o5 % can be measured reproducibly. Figure 4 shows the principle of the measurement applied to a corrugated theta pinch coil.

The field perturbation caused by the current feed slot was measured for two different field coils:

1) a cylindrical coil with only one sinusoidally shaped bulge of length L = 3o cm and total amplitude ΔR = 3 cm. The width of the current feed slot was 2 mm.
2) a cylindrical coil with 5 sinusoidally shaped corrugations of period length L = 1o cm, total amplitude ΔR = o.5 cm. The width of the current feed slot was 1, 2, and 3.4 mm. This

periodically corrugated coil was used to investigate the influence of the computed inductive lenses, the width of the current feed slot in this case being 3.4 mm.

Perturbations of the field of a coil with a single bulge of length $L = 30$ cm and amplitude $\Delta R = 3$ cm

The field coil has a total length of 100 cm and a bore of 10.6 cm outside the bulge. Around the midplane of the coil a bulge of length $L = 30$ cm is shaped by increasing the coil radius sinusoidally from $R_{min} = 5.3$ cm to $R_{max} = 8.3$ cm. The width of the current feed slot is 2 mm. Figure 5 shows a schematic diagram around the shaped region of this coil.

The z-component B_z of the magnetic field was measured as a function of z for various radii r ($r = 0$ is coil axis) and for the azimuthal angle $\theta = 0^o$. A plot of these values is shown in Fig. 6. The angle θ is defined by the location of the collector feed slot $\theta = 180^o$. At the cross section of the maximum bulge amplitude ($z = 0$) the magnetic field strength is reduced to between 42 % and 46 % of its value inside the cylindrical part of the coil ($|z| > 15$cm), where the field is nearly homogeneous. The field distribution was measured for values $r \leq 4.9$ cm; for $r > 4.9$ cm the field strength would decrease below 42 %.

From flux conservation it follows that the relative value of the magnetic field is 41 %, on the assumption that the field strength is constant across the bulge. At the end of the bulge and in the neighbourhood of the coil surface (large values of r) the magnetic field strength even exceeds its value in the unshaped region. This effect can be ascribed to flux conservation associated with the decrease of the field strength on the axis.

The field perturbation caused by the current feed slot is determined by an azimuthal measurement. The relative variation of the magnetic field, $\Delta B_z(\theta) = B_z(\theta) - B_{zo}$ ($B_{zo} = B_z(\theta = 0)$), is normalized to the value B_{zo}. Figure 7 shows $\Delta B_z(\theta)$ at $z = 0$ (bulge) and $z = 15$ cm (neck) for various values of radius r.

This quantity is a good measure of the relative perturbation of the current feed slot as long as the perturbation itself is confined to a small azimuthal region around the feed slot. The graphs show, however, that, particulary around the neck, there is hardly any azimuthal region where the magnetic field remains unperturbed by the feed slot. In that case normalization to the field strength B_{zo}, as defined above, is more or less arbitrary. At the bulge cross section (z = 0) the measured field perturbation has its maximum value of + 2.1 % at r = 4.9 cm. Near the inner surface of the vessel (r = 4.4 cm) the perturbation has still a value of + 1.7 %, but near the coil axis (r = o.65 cm) its value has dropped to + o.2 %. At the neck cross section (z = 15 cm) the perturbation has a value of - 1.o % on the inner wall (r = 4.4 cm), which drops to - o.16 % near the axis (r = o.65 cm).

Perturbation of the field of a periodically corrugated coil with period length L = 1o cm and amplitude R = o.5 cm

The following measurements were made using a field coil with five sinusoidally shaped corrugations of a period length L = 1o cm and a total corrugation amplitude R = o.5 cm. The computations of the inductive lenses as presented in this paper are valid for periodically corrugated coils and were made specially for the above coil dimensions. The coil with a total length of 1oo cm was fitted with five corrugation periods symmetric to its mid-plane; between both ends and the corrugated regions there are cylindrical coil sections each 25 cm in length and 5.3 cm in radius (i.e. the same radius as at the necks of the corrugations). In a first measurement the field perturbations occurring without magnetic lenses were determined. Figure 8 shows the azimuthal variation of this perturbation for various radii r. As can be seen, the rotational symmetry of the magnetic field remains nearly unperturbed over an azimuthal angular range of about $18o^{o}$ ($-9o^{o} < \Theta < +9o^{o}$). As a matter of fact, therefore, the plotted curves can be interpreted as the relative deviation from an elsewhere rotational symmetric field distribution. These perturbations decrease strongly with decreasing radius. Correspondingly, the half-width of these curves increases with decreasing radius from 25^{o} at r = 4.9 cm to about 18o° at r = o.9 cm.

Similar measurements were made with collector feed slots 2 mm and 1 mm in width. The perturbation near the feed slot is proportional to the width of the slot, as expected. In Figure 9 the maximum relative field perturbations are plotted as function of the radius r for the three different values of the feed slot width.

Th perturbation at the neck cross section and at the bulge cross section are of the same order. For the radius r = 4.9 cm these perturbations have a value of 1 % - 3 % for a slot width from 1 - 3.4 mm. The value of the perturbation for r = 1 cm, at about which a compressed plasma column would be located, is in every case smaller than o.1 %.

<u>Efficiency of the inductive lenses for restoring rotational symmetry of the magnetic field distribution</u>

Inductive lenses have been calculated (as described above) for a distance of the transmission line plates of S_o = 3.4 mm. The chosen parameters were: $R_{min} = R_{neck}$ = 5.3 cm; $R_{max} = R_{bulge}$ = 5.8 cm, y_a = 16.3 cm (related to the length of the adapter plates in Isar I). The inductive lenses consist of cavities machined in the upper and lower adapter plates. Figure 1o shows these lenses at the bulge and the neck in contour line representation. Since the computation of the lenses did not account for the junctions between the corrugated and cylindrical sections of the coil (the rather shallow lenses for the necks have been omitted there), the measurements were made around the midplane of the coil. The azimuthal variation of B_z was again measured for various radial positions r. The result of this measurement is shown in Figure 11 for the cross sections at the bulge and neck. Comparison with Figure 8 clearly shows the improvement of the rotational symmetry induced by the inductive lenses. At the bulge cross section there is no perturbation at all that exceeds a value of o.4 % and at radii $r < 3.9$ cm this perturbation is only of the order of the experimental error.

For large r, i.e. in the neighbourhood of the coil surface, the measured perturbation at first increases when approaching the current feed slot ($\Theta \rightarrow 18o^{o}$) but eventually drops again. This behaviour might be due to the two slots o.2 mm in width which are located between the adapter plates and the field coils (see Figure 4) and which so far have not been mentioned. This effect was also found at the neck cross section for radii $r > 4.4$ cm. The plotted curves are qualitatively similar to those without inductive lenses (Fig.8), apart from the fact that the absolute amplitudes are considerably reduced. The largest perturbation now found is - 1.7 % at r = 4.9 cm.

The influence of the inductive lenses investigated is seen best in Fig. 12, were the maximum field perturbations with (continuous line) and without (dashed line) inductive lenses are plotted versus the radius r for the bulge and neck cross sections. While at the bulge cross section the application of these lenses was found to be very effective for any value of r, a comparable reduction of the original perturbation at the neck cross section only occurred for values of $r < 3.5$ cm, which, however, is still sufficiently larger than the plasma radius.

Discussion of the results with magnetic lenses

The calculation of magnetic lenses for restoring rotational symmetry of the magnetic field distribution is based on assuptions which are not sufficiently fulfilled in the present analogue experiment.

1) The coil shape investigated consisted of five corrugation periods and of cylindrical sections at the ends whereas the calculations assume an infinite, corrugated coil. However, it was found by measurements at various cross sections that this discrepancy in the boundary conditions does not influence the field distribution in the three periods around the coil midplane.

2) The length of the adapter, in which the inductive lenses are moulded, is assumed to be large compared with the period length of the bulge. By contrast, the adapter length of 11 cm used experimentally (governed by the arrangement of the Isar I current feed system) is about equal to the period length of the corrugations, thus violating the condition (2). This is believed to be the main reason for the residual field perturbations.

3) The influence of the plasma on the magnetic field and field perturbation was not considered. The diamagnetic currents in a plasma can cause appreciable changes in the magnetic field strength. In the compressed state these currents flow near the coil axis, where the field perturbation due to the slot have considerably declined. It can therefore be assumed that the perturbation of the rotational symmetry of a vacuum field is not changed much by the diamagnetic currents in a compressed plasma.

Conclusion

Inductive lenses moulded into the transmission line system of a theta pinch coil reduce the deviations from rotational symmetry caused by the current feed slot. Within a radial region of 1/2 of the coil radius the residual perturbations are less than 2o % of the perturbations without inductive lenses; they are approaching the level of the experimental error of the measurements. These small residual perturbations are mainly attributed to the limited space available for applying inductive lenses in the transmission line system.

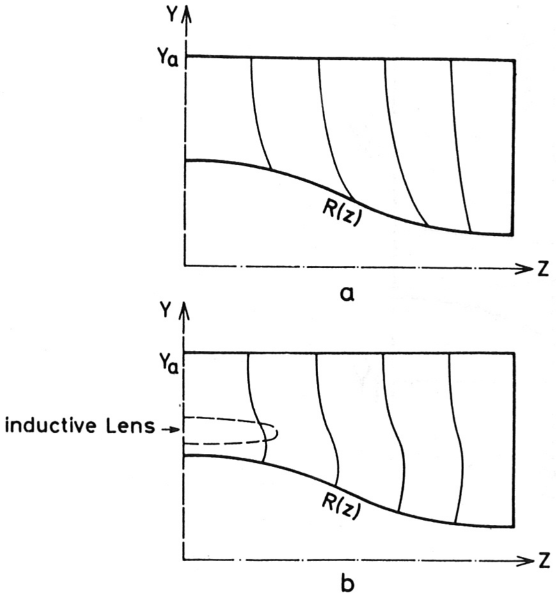

Fig. 1

a) Current lines not perpendicular to a periodically corrugated coil. This is the case for plane and parallel transmission line plates.

b) Current lines forced to stream perpendicularly towards a periodically corrugated coil by means of variable distance S between the transmission line plates (inductive lenses).

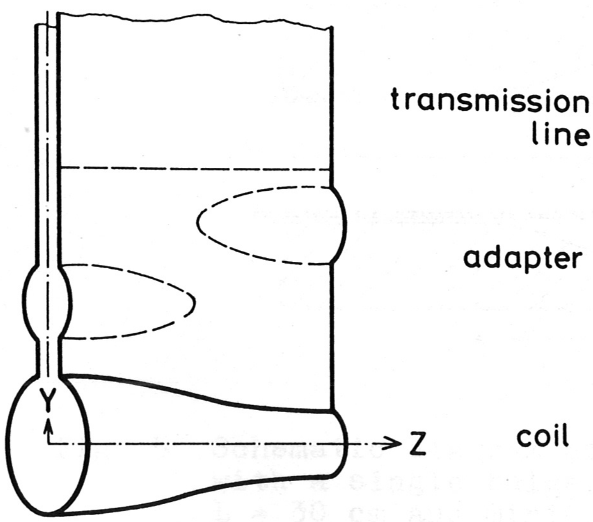

Fig. 2

Schematic arrangement of the inductive lenses at the neck and bulge of a periodically corrugated coil.

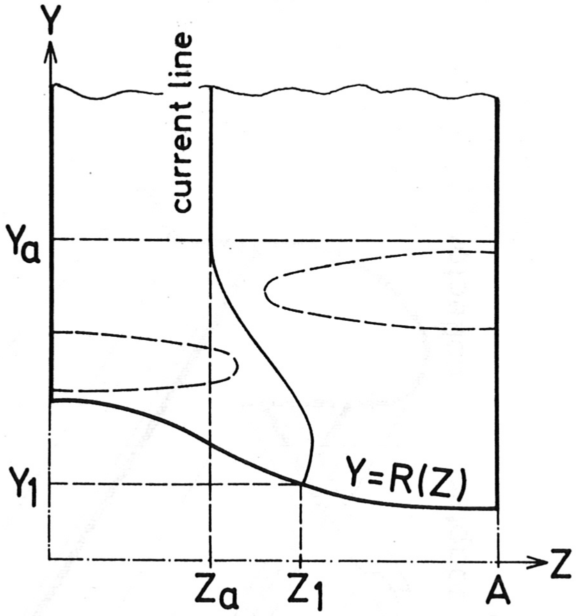

Fig. 3 Path of a single current line in the z - y plane influenced by inductive lenses at the neck and bulge of a periodically corrugated coil.

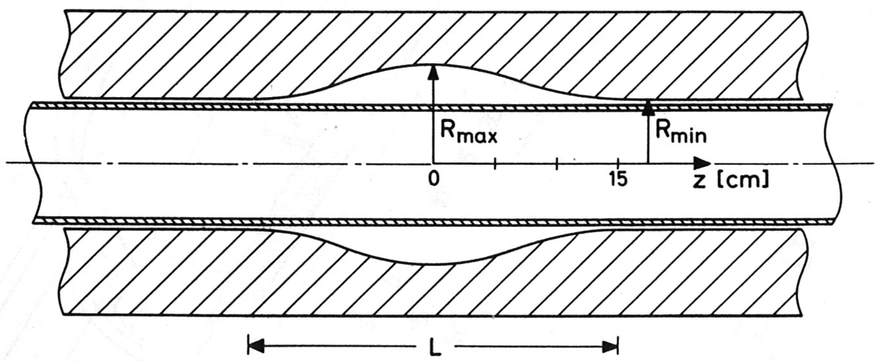

Fig. 5 Schematic diagram of discharge tube and coil with a single bulge. The bulge is of length L = 30 cm and minimum radius R_{min} = 5.3 cm; its total amplitude is $\Delta R = R_{max} - R_{min}$ = 3cm.

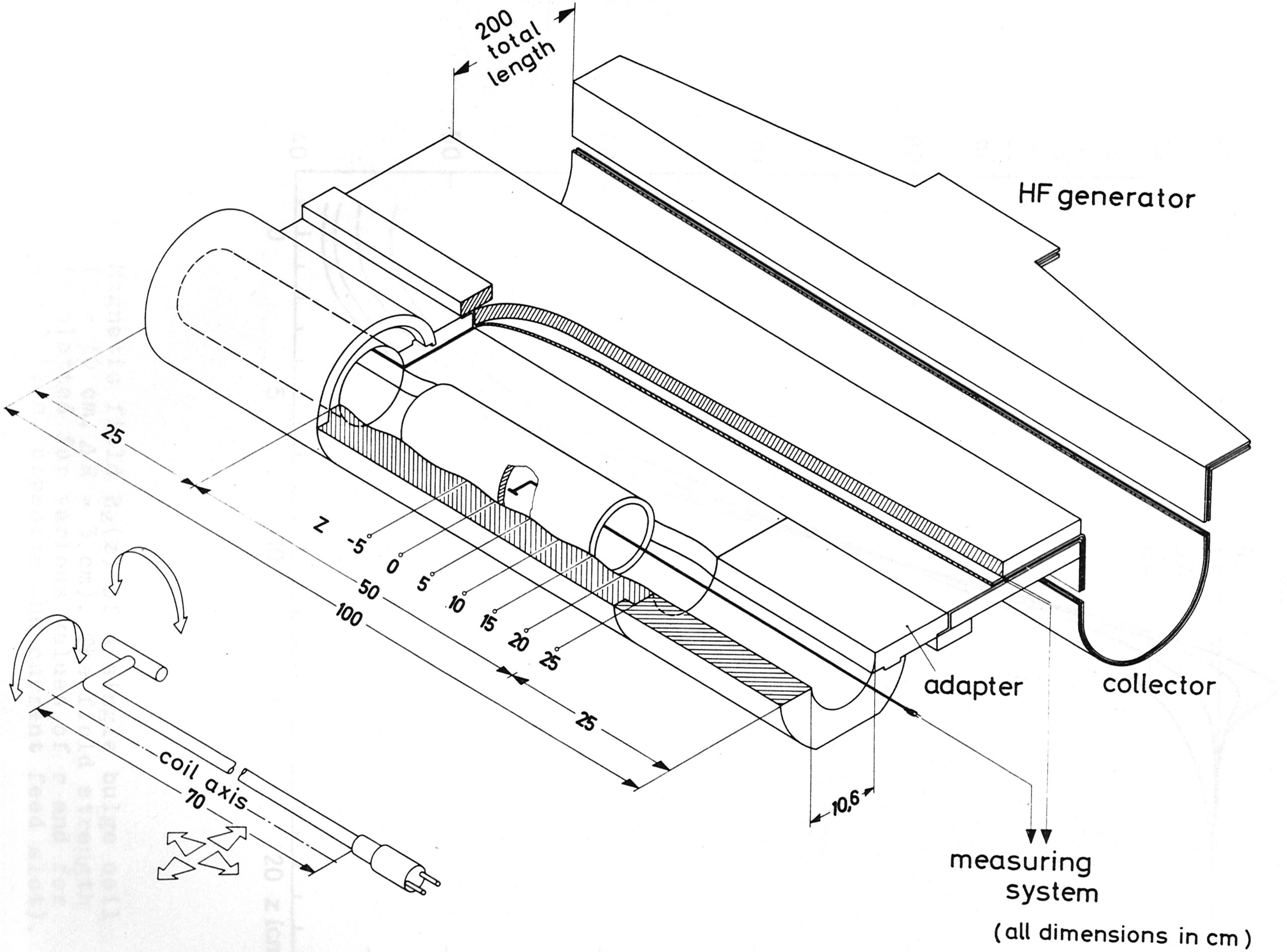

Fig. 4 Schematic diagram of magnetic field measurement by balanced pickup probe with field coil, transmission line and adapter. Various plastic tubes, the inner surfaces of which are used to move the pickup probe on concentric circles, are inserted in the field coil.

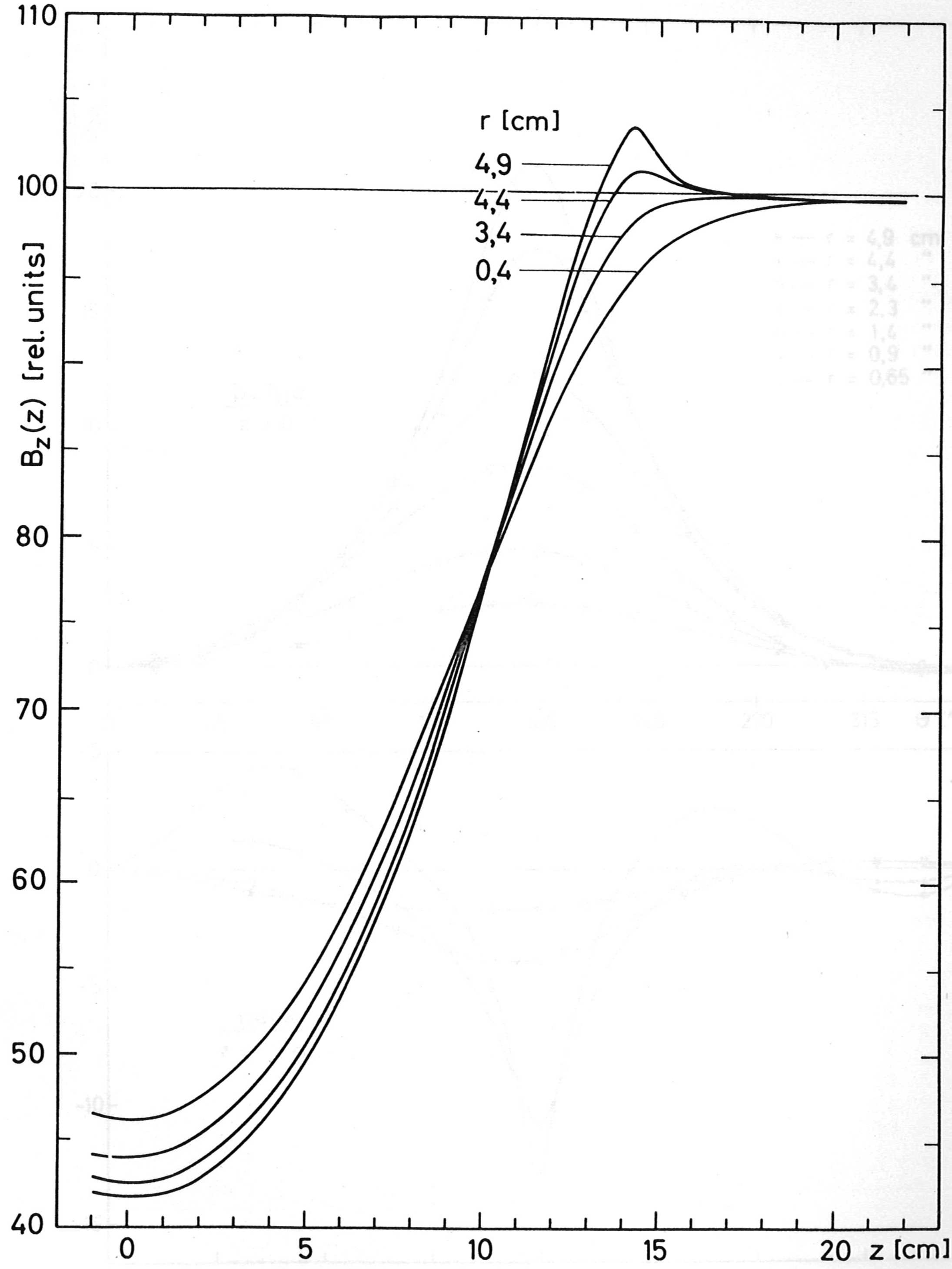

Fig. 6 Magnetic field $B_z(z)$ of a single bulge coil ($L = 30$ cm, $\Delta R = 3$ cm). The field strength is plotted for various values of r and for $\theta = 0$ (i.e. opposite the current feed slot).

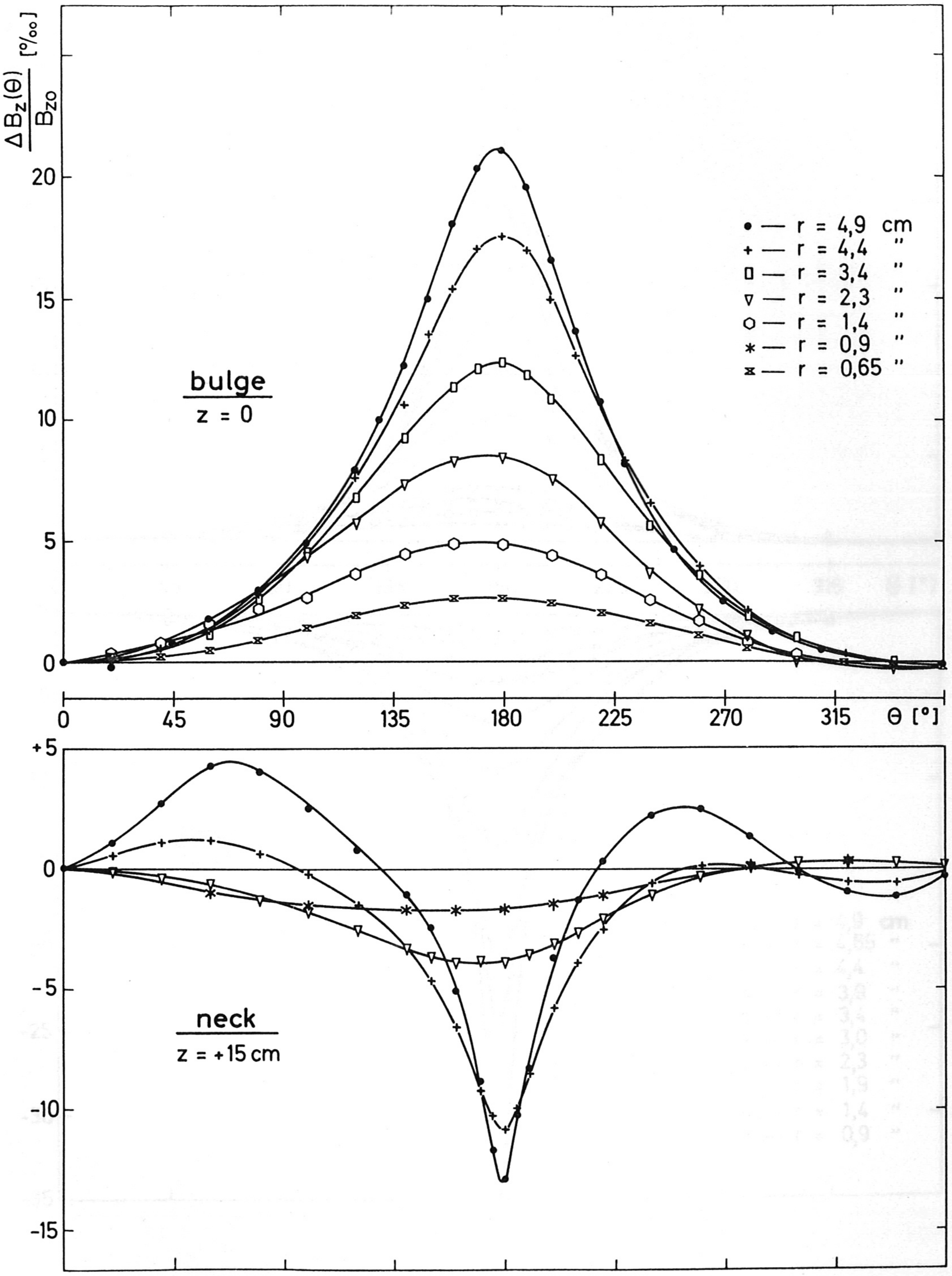

Fig. 7 Relative variation, $\Delta B_z(\Theta)/B_{zo}$ of the magnetic field in a single bulge coil (L = 30 cm, ΔR = 3 cm). $B_z(\Theta)$ is normalized to the value B_{zo} at the azimuthal angle $\Theta = 0$ opposite the current feed slot. The measured values are plotted for various radii, r, at the axial positions z = 0 (bulge) and z = 15 cm (neck).

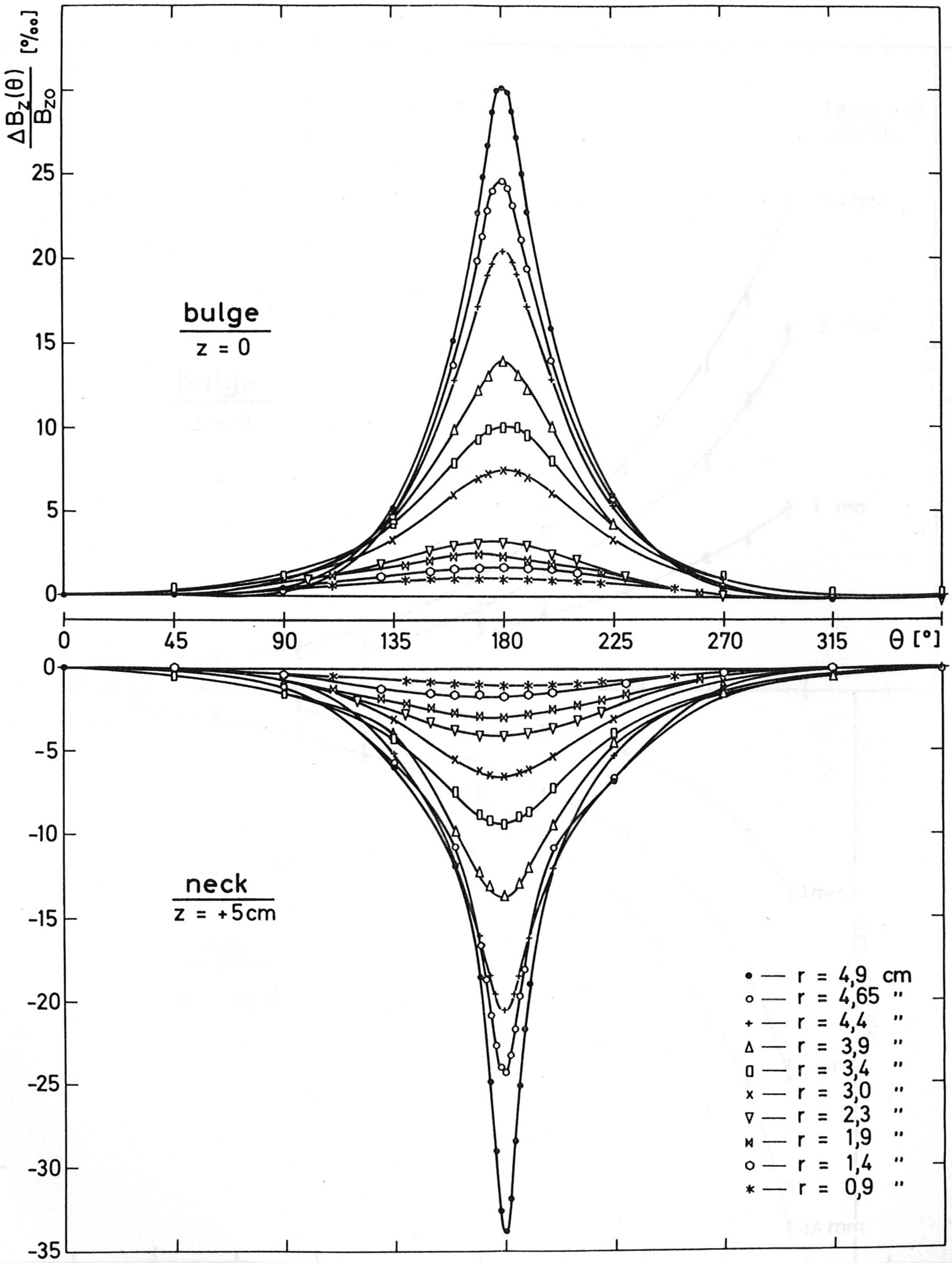

Fig. 8 Periodically corrugated coil (L = 10 cm, ΔR = 0.5 cm) <u>without</u> inductive lenses. The azimuthal variation of the relative field perturbation $B_Z(\Theta/B_{ZO}$ for various radii, r, is plotted for the cross sections at z = 0 (bulge) and z = 5 cm (neck). The width of the current feed slot is <u>3.4 mm.</u>

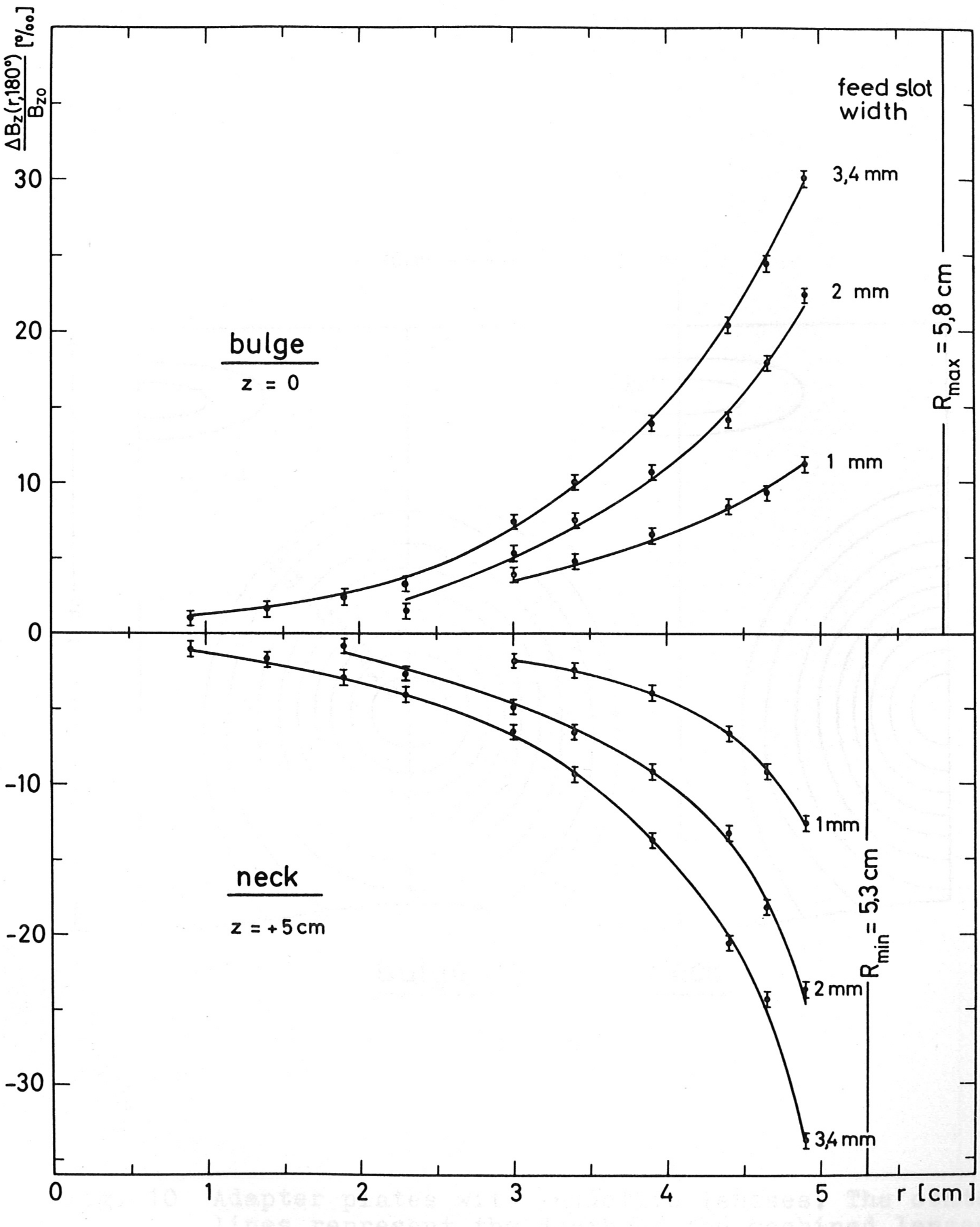

Fig. 9 Periodically corrugated coil (L = 10 cm, ΔR = 0.5 cm) <u>without</u> inductive lenses. The radial variation of the maximum relative perturbation $\Delta B_z(r)/B_{zo}$ occuring at $\Theta = 180^o$ is plotted for the cross sections at z = 0 (bulge) and z = 5 cm (neck) and for the different values of the current slot width.

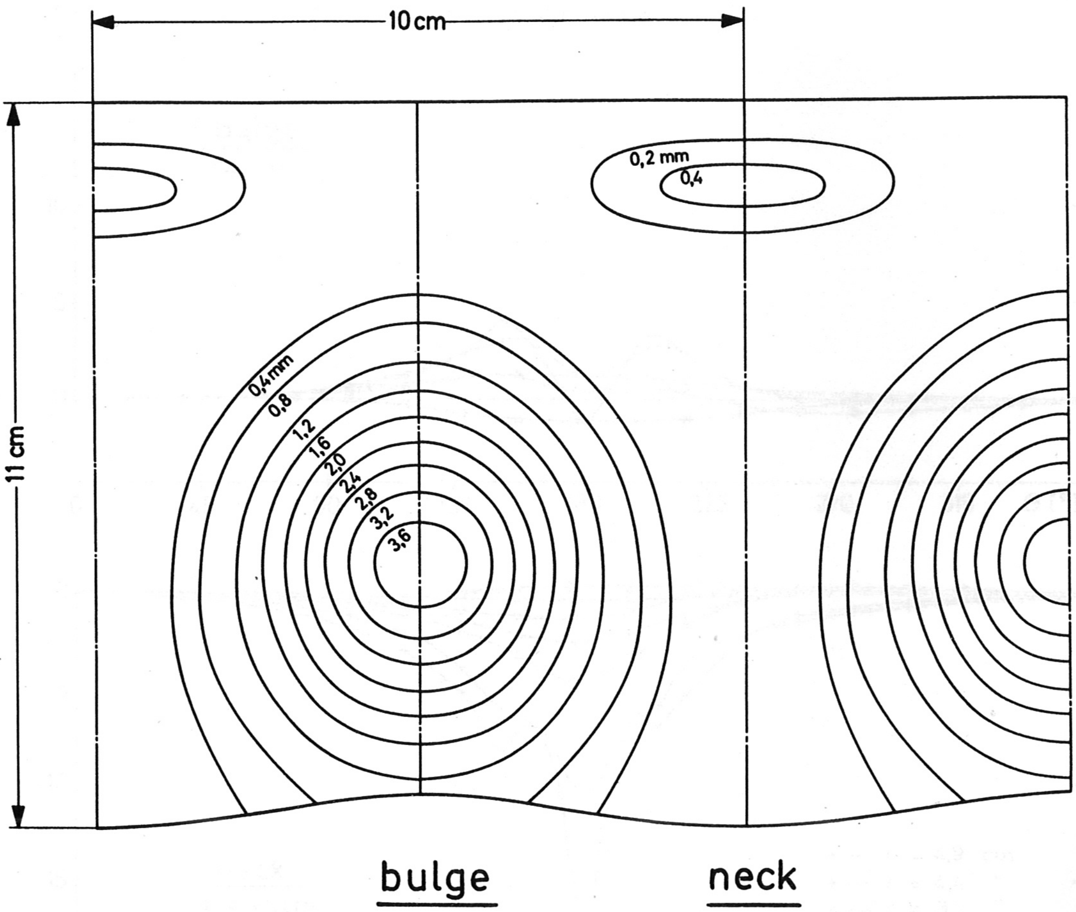

Fig. 10 Adapter plates with inductive leneses. The contour lines represent the depth of the machined lenses.

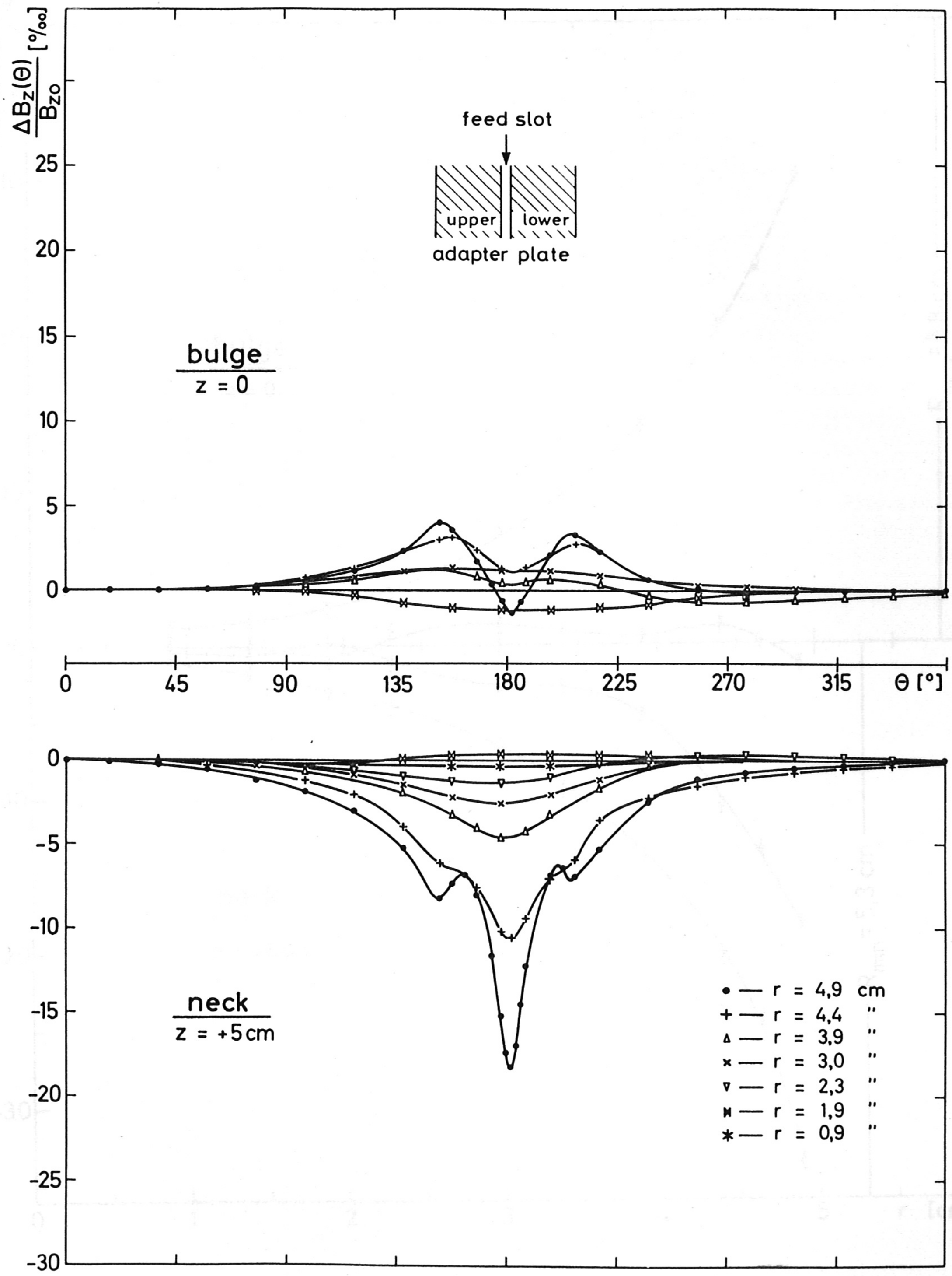

Fig. 11 Periodically corrugated coil (L = 10 cm; ΔR = 0.5 cm) with inductive lenses. The azimuthal dependence of the magnetic field perturbation, $\Delta B_z(\Theta)/B_{zo}$, at the bulge (z = 0) and the neck (z = 5 cm) cross sections is plotted for various radii r . The current feed slot has a width of 3.4 mm.

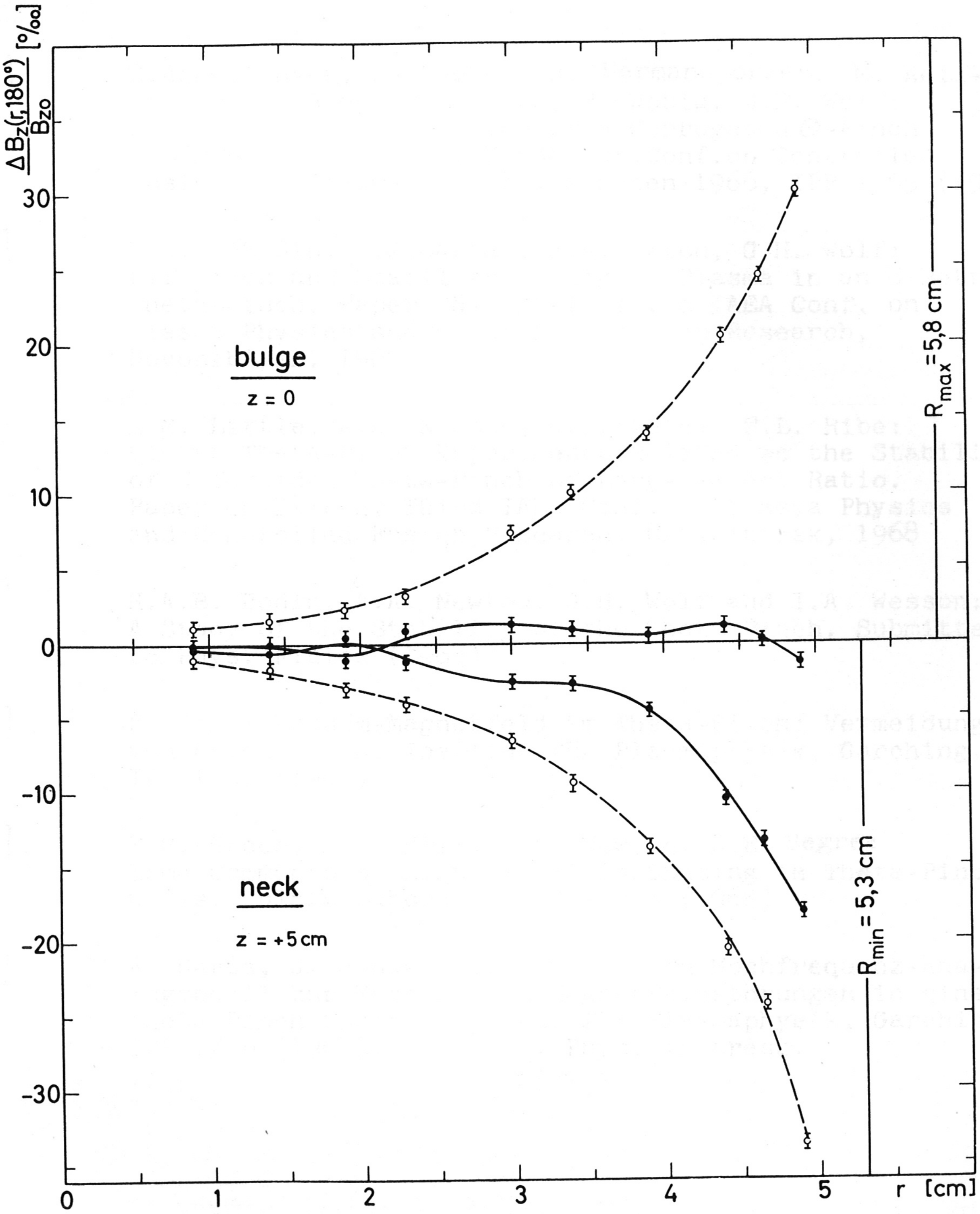

Fig. 12 Periodically corrugated coil (L = 10 cm, ΔR = 0.5 cm) with a current feed slot of 3.4 mm widths. The maximum relative field perturbation is plotted versus the coil radius r . The continuous lines show the values of the perturbation <u>with</u> inductive lenses, while the dashed lines show for comparison those perturbations <u>without</u> inductive lenses.

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