9. Symposium on fusion technology.
Garmich-Partenkirchen, F.R. Germany, 14-18 June 1976
CEA-CONF--3580

FR7602990

TECHNOLOGICAL ASPECTS OF THE WEGA STELLARATOR

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WEGA, an ohmically heated STELLARATOR at GRENOBLE for the study of R.F. heating at high power, was designed and is operated by the MPIPP GARCHING and the C.E.N/GRENOBLE, with participation by ERM BRUXELLES. On the vacuum vessel (major radius 72 cm, inverse aspect ratio 3.8) are mounted helical windings with periods $l = 2$, $m = 5$, designed to produce a rotational transform of 0.3 at a main field of 2.5 T. Calculations to simulate the effect of the stray flux of the transformer yokes show that a vertical field variation of the same periodicity as the helical windings (five-fold symmetry) does not affect the magnetic surfaces, whereas a different periodicity (six-fold symmetry) distorts the magnetic surfaces for minor radii larger than 4 cm. Accordingly five transformer yokes are used. To assemble internal R.F. structures, it was required that the two halves of the device be separable, therefore electrically and mechanically distinct. The 14 helical conductors of the 4 windings of each of the device are placed in series by means of end connections. To compensate magnetically each connection by another carrying opposite current, the end connections are arranged along the intersections of seven planes parallel to the insulating gaps and four concentric cylindrical surfaces at right angles ("theta-bridges"). The magnetic surfaces were recalculated up to a radius of 7.5 cm from the magnetic axis including the effect of the resulting magnetic dipoles, all of whose moments are in the direction of the main field. No change was discernible. To facilitate further the separability of the two halves, one of them, weighing 5 tons (vacuum vessel, toroidal field coils, supporting structures) is supported at three points, and can be displaced horizontally by 3 m using an air cushion system (coefficient of friction 10^{-4}).

WEGA has been operating in a preliminary TOKAMAK version since July 1975, with STELLARATOR operation scheduled to begin in 1976.

WEGA is a present-generation ohmically heated STELLARATOR designed to develop and study R.F. heating methods at high power. The stellarator facility has been built, under the auspices of Euratom, by the two institutes, MAX-PLANCK-INSTITUT FÜR PLASMAPHYSIK Garching and the Commissariat à l'Energie Atomique, Grenoble. The main parameters of WEGA are given in Table I. From the table, two basic characteristics of WEGA emerge. First, WEGA has a high inverse aspect ratio (vacuum vessel 3.8). Secondly, WEGA is operated with an iron core transformer, whose air gaps are adjusted such that the stray field of the transformer produces a large part of the equilibrium vertical field. To simulate the effect of this vertical field and its azimuthal variation due to the discreteness of the transformer yokes and to determine their optimum number, calculations were effected with the Gourdon code [1], replacing the transformer yokes by sets of two coils each at the azimuthal positions of the arms of the transformer. The coils have a triangular shape with one apex on the axis of symmetry of the machine and are located at the vertical positions of the transformer arms. The surfaces were calculated for minor radii up to 7 cm with 40 circuits the long way around for the case of five and six sets of coils. For five coils, the amplitude of the vertical field perturbation was 30 G, while for the case of six arms the amplitude was 18 G, corresponding to the same current in the coils which produced 30 G amplitude with five-fold symmetry. All calculations were made at a main field of 1T and an unperturbed rotational transform of 0.25, since it has been found [2] that surfaces of rational ɫare the most easily perturbed.

The calculations show that a vertical field variation of the same periodicity as the helical windings (five-fold symmetry) produces undistorted surfaces shifted less than a millimeter from the unperturbed case whereas a different periodicity (six-fold symmetry) distorts the magnetic surfaces for minor radii larger than 4 cm (Fig. 1). Accordingly five transformer yokes are used.

The particular requirements of the R.F. heating experiments, with a high-level energy transmission and insertion of structures, demand that the number and size of the ports be maximized and that the machine be easily separable. These principles have been incorporated in the design of WEGA. The choice of the number of main field coils as 40 and the winding of the helix along lines of $d\theta/d\phi$ = const. then permit optimal port arrangement and size while retaining good magnetic surfaces.

To achieve easy separation of the two halves of the torus, the concept of "theta-bridges", which allows the two halves of the helix to be mechanically and electrically distinct, was developed. The 14 helical conductors of the 4 windings of each half of the device are placed in series by means of end connections. To compensate magnetically each connection by another carrying opposite current, the end connections are arranged along the intersections of seven planes parallel to the insulating gaps and four concentric cylindrical surfaces at right angles. These theta-bridges (version 2) are shown schematically in Fig. 2. In a preliminary concept, the end connections were arranged along the intersections of 14 planes parallel to the insulating gaps on only one cylindrical surface at right angles (Fig. 3 theta-bridges version 1).

To determine the better theta-bridge version, the magnetic surfaces were calculated for both cases up to a radius of 7.5 cm from the magnetic axis including the effect of the remaining uncompensated magnetic dipoles. The two theta-bridge versions differ in that in version 1, all of these moments are oriented in the r-direction, whereas in version 2 all the dipole moments are oriented in the direction of the main field. The calculations then show that the dipole moments (each dipole carries one-half of the helical winding current) oriented in the main field direction do not affect the magnetic surfaces whereas the moments in the r-direction distort the surfaces appreciably (Fig. 4). Therefore the theta-bridges version 2 have been chosen.

These end connections are subjected to appreciable radial magnetic forces, as they run in the Θ-direction, i.e. perpendicular to the main magnetic field, and carry up to 16 ka current each. The inward forces resulting from the one current direction must be sustained by the intermediate cylindrical piece of the vacuum vessel, whereas those directed outward (the other current polarity) are held by an outer cylinder covering the whole area of the theta-bridges. To these forces, resulting only from the end connections, are added the forces exerted on the helical conductors by the main field, which act on every portion of the torus. The deformation of the torus (3cm thick) resulting from the helix forces alone due to a main field of 1.5 T at a helical conductor current of 16 ka has been calculated, using the correction factors for helicity and torus effect [3] , to be ± 0.15 mm. The largest forces obviously exist on the intermediate piece where the helix forces add to the inward forces on the end connections, which act on two quadrants of the cylinder (Fig. 5). A calculation assuming an infinitely long cylinder gives a net force of 60 kN at the intersection of two of the helix packets, and their theta-bridges, which results, in the most unfavorable case, in a radial deformation of the cylinder by ± 0.35 mm. This, however, will be reduced in practice because a part of the deformation will be taken up by the torus.

To facilitate the separability of the two halves of the device, one of them, weighing 5 tons including vacuum vessel, toroidal field coils and supporting structures can be displaced horizontally by means of an air cushion system. Each half of the device is supported at three points, which, on the movable half, are connected with the individual air cushion units. For proper operation of such units, it is necessary to allow them to float freely at their proper height, that is, to preserve the vertical degree of freedom for the whole movable half. Nevertheless, in the assembled state, the coil framework must form a solid structure, capable of transmitting the torsional and shearing stresses induced by the magnetic forces on the main field. To satisfy these opposing requirements, the movable part is only loosely guided (horizontal clearance 0.2 mm, vertical clearance 5 mm) until the minimum distance for "docking" is reached (20 mm), where the clearance in both directions becomes negligible and the two halves are pulled together with bolts and then wedged in place. The air cushion (thickness of air film 35 μm) is produced by the laboratory installation of compressed air at 7 atm. The system allows a horizontal separation of 3 m, and a lateral displacement of 20 mm. The force required is less than 20 N (coefficient of friction ~ 10^{-4}).

In summary, the following special design requirements of WEGA have been treated : First, it has been shown that a vertical field of the same periodicity as the helical windings (five-fold symmetry) does not disturb the magnetic surfaces, permitting the use of the stray field of the five transformer yokes to produce the main equilibrium vertical field. Secondly, a system of helix end connections has been developed, which permits the two halves of the device to be electrically and mechanically distinct while not disturbing the magnetic surfaces, and holding mechanical deformations of the vacuum vessel to tolerable levels. Thirdly, the easy separability of the device is further enhanced by the use of an air cushion system, permitting horizontal displacement of one half of the device.

REFERENCES.

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[2] - S. REHKER, H. WOBIG, The effects of perturbations on the magnetic field of the W7 Stellarator, Max-Planck-Institut für Plasmaphysik Internal Report IPP 2/218, January 1974.

[3] - B. STREIBL, Calculations on toroidal supporting structures, IPP-Garching, internal communication.

TABLE I

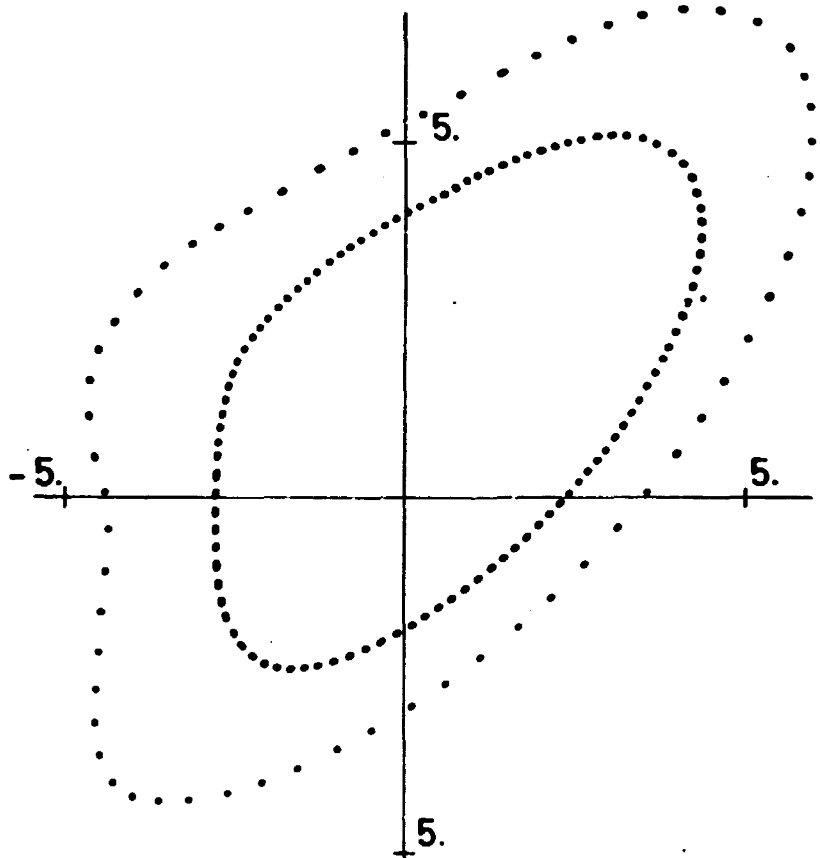
WEGA
MAIN PARAMETERS

Torus major radius		R = 72 cm
Torus (inner) minor radius		b = 19 cm
Thickness of the vacuum vessel		t = 3 cm
Toroidal fieldcoils :	number	40
	winding inner radius	28.5 cm
	winding outer radius	39.5 cm
Helical windings :	poloidal periodicity	l = 2 (4 packets of conductors.)
	toroidal periodicity	m = 5 ($d\theta/d\phi$ = 2.5)
	number of conductors	14 (per packet)
	conductor dimensions	1.3 x 3 cm
Toroidal magnetic field		B = 2.5 T (at 17 kA/coil)
Rotational transform		ι_0 = 0.3 (at 2.5 T and 30 kA/helical conductor.)

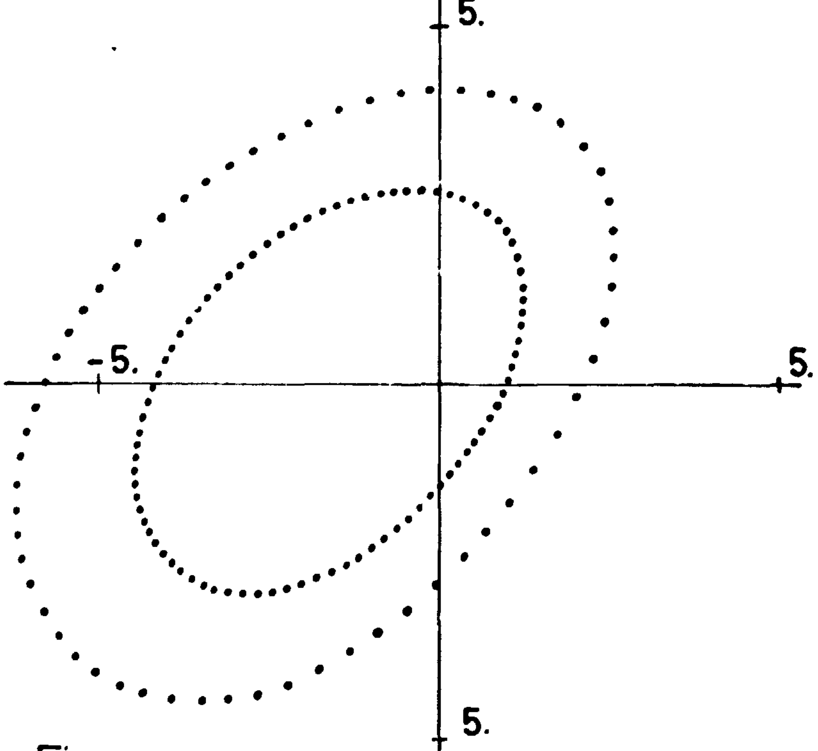
Maximal flux variation in the 5 yokes ohmic-heating iron transformer
Ø ~ 0.4 Wb (without biasing).

EFFECT OF PERIODIC VERTICAL FIELD

B_ϕ = 10 KG ; ι = 0,25

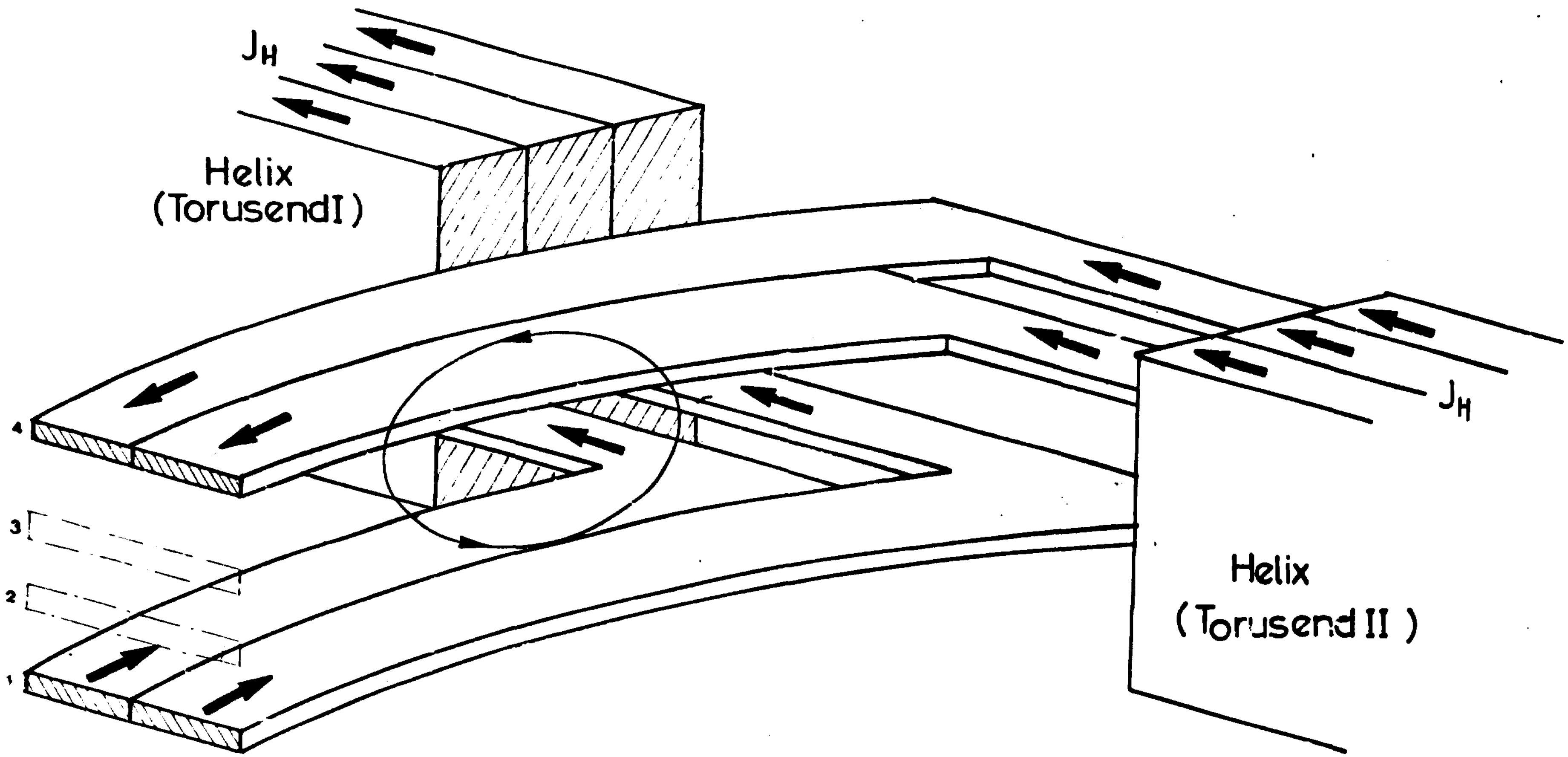


Perturbation with six fold periodicity B_z = 18 G amplitude.



Perturbation with five fold periodicity B_z = 30 G amplitude.

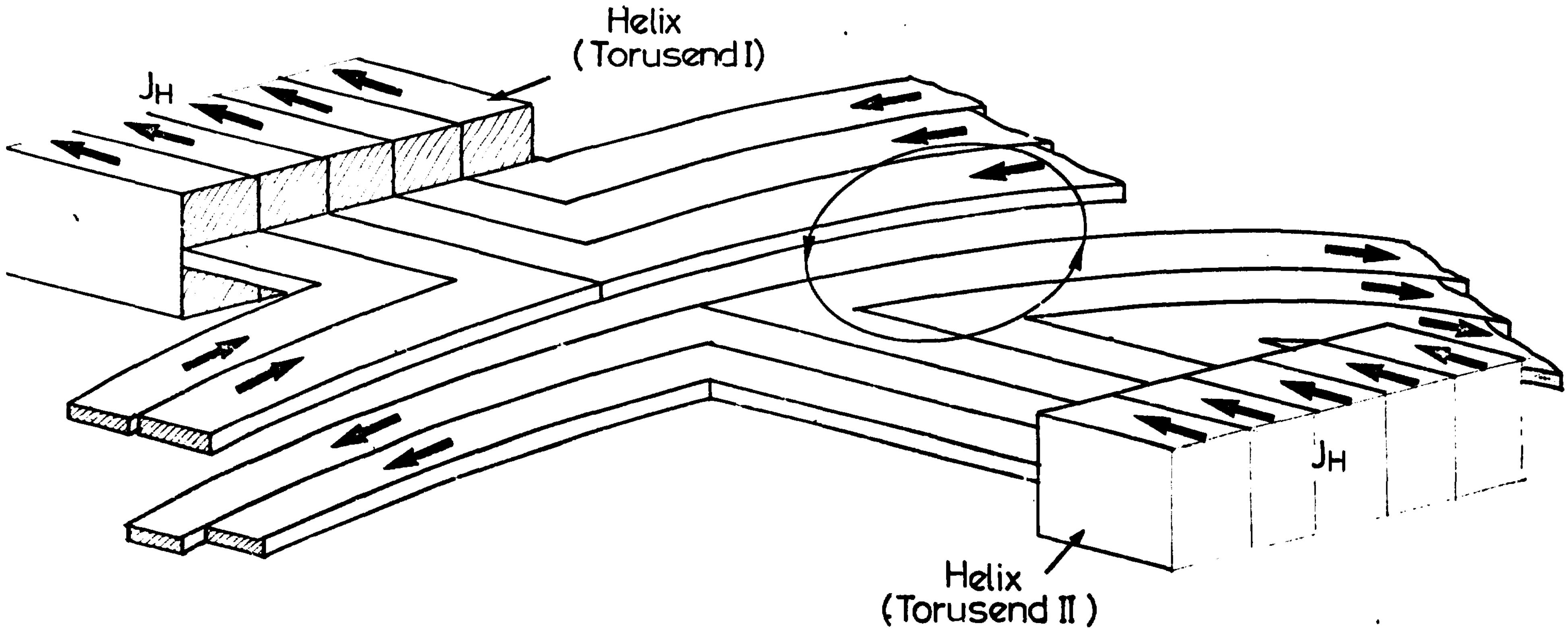
.Fig 1_



"Θ _ Bridges"

_Fig 2.

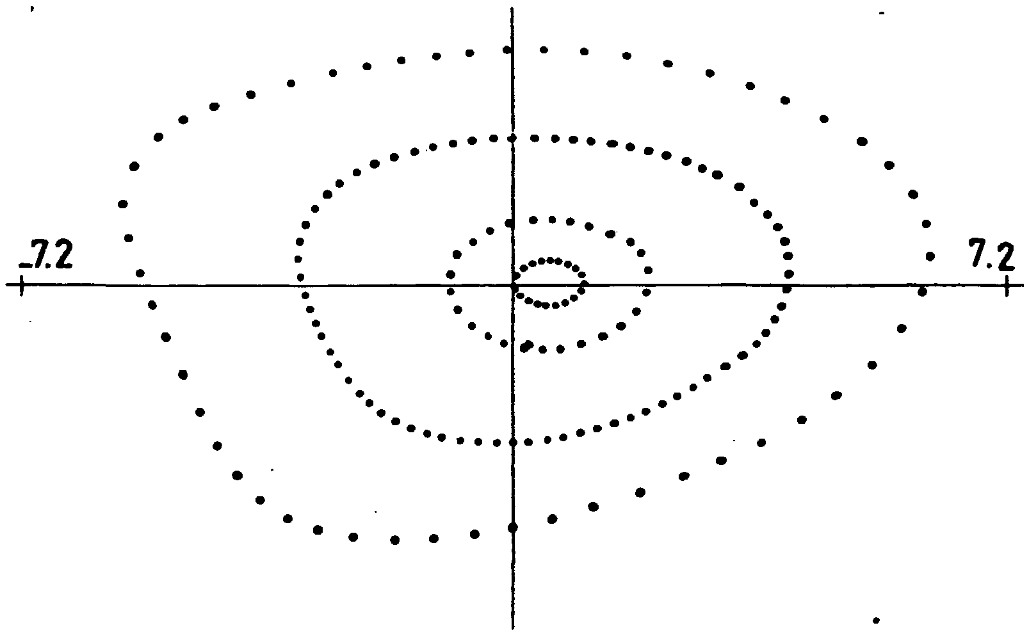
Version II



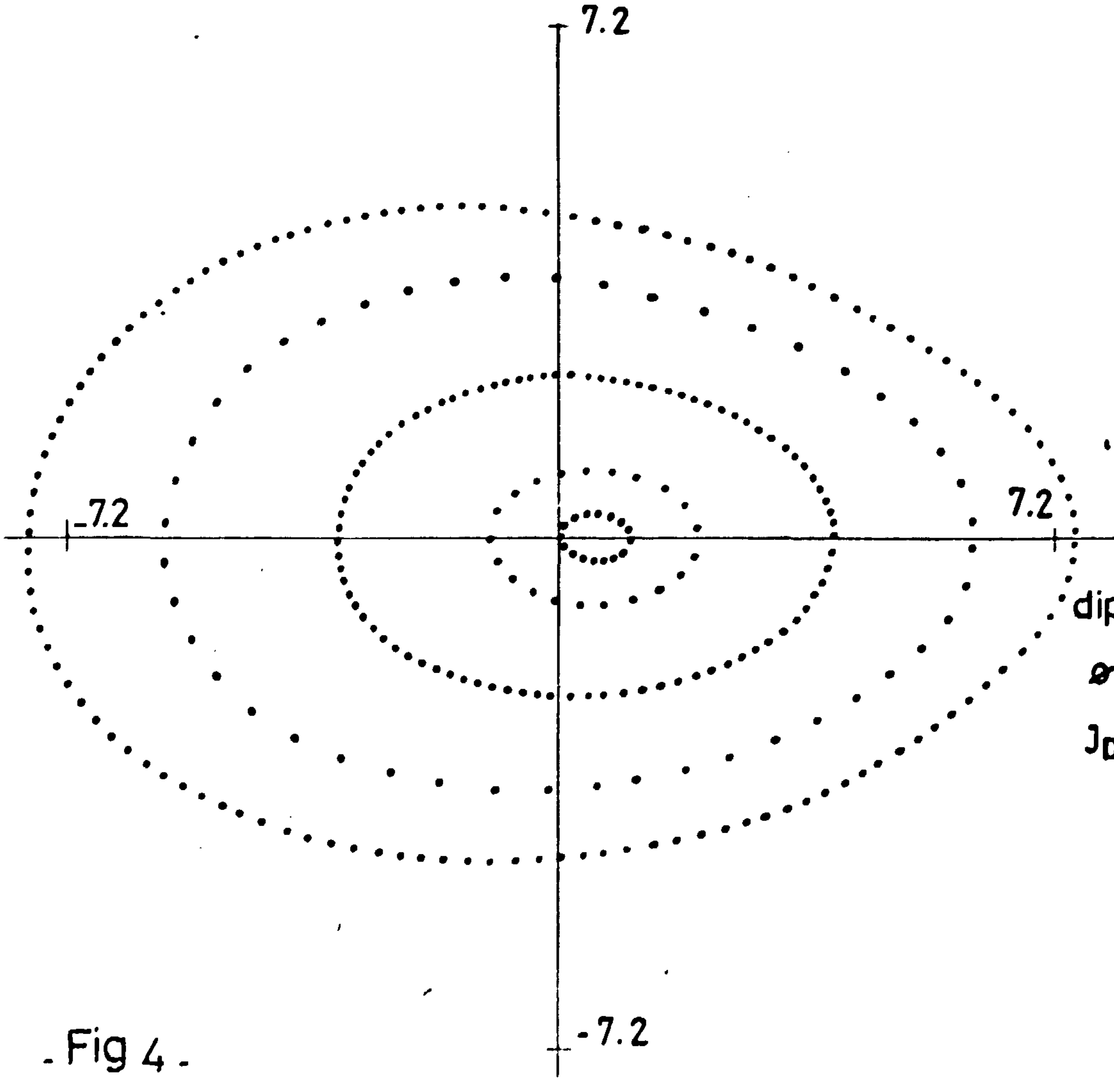
- Fig 3 - " θ Bridges "
Version: I

SIMULATION OF THE EFFECT OF " θ - BRIDGES " ON MAGNETIC SURFACES

$B_\phi = 10\,KG$; $\iota = 0,25$

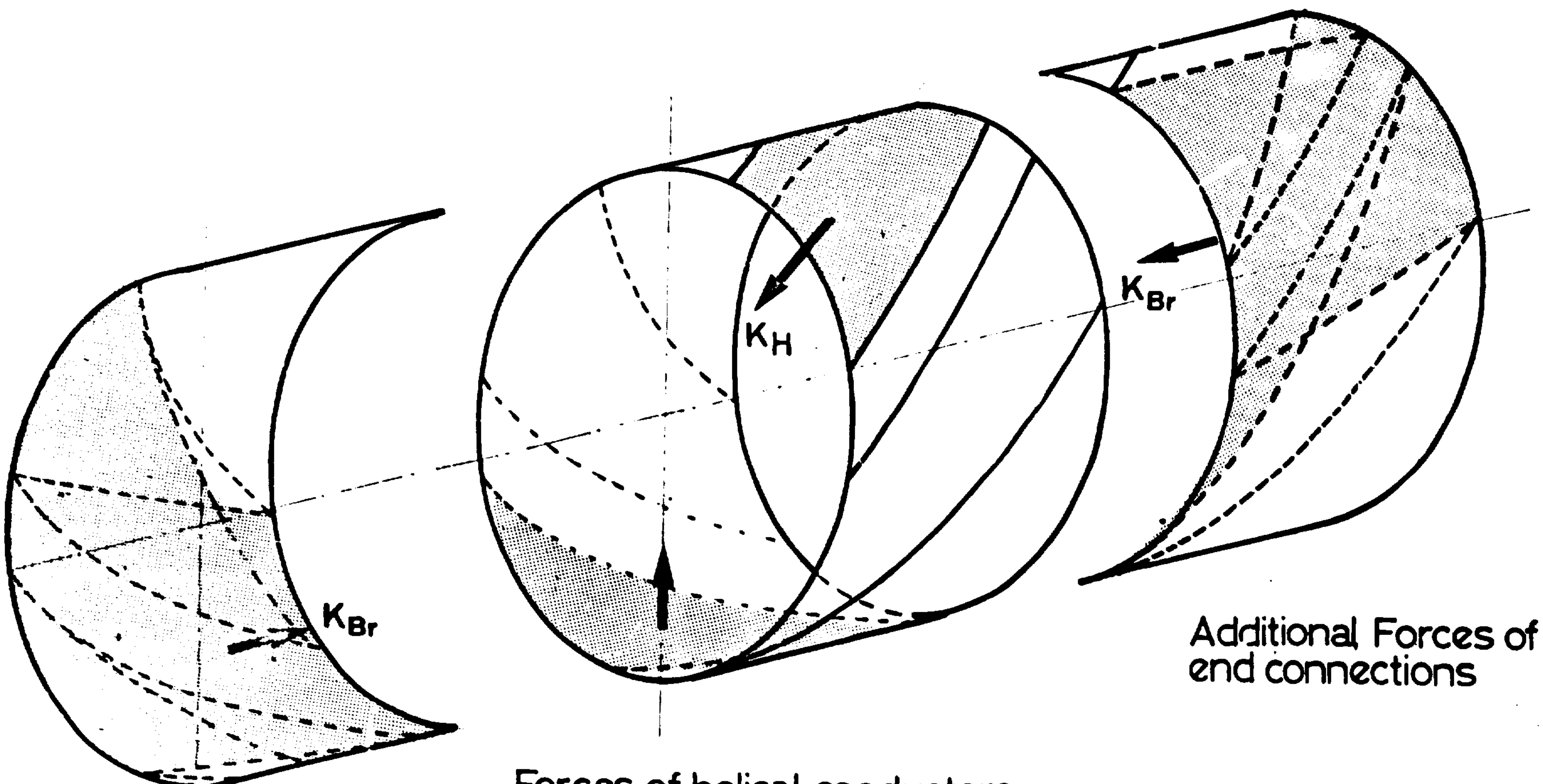


" θ - Bridges "
Version I
dipole moment
r - direction
$J_{DIP} = 75$ KA



" θ - Bridges "
Version II
dipole moment in
ø - direction
$J_{DIP} = 75$ KA

- Fig 4 -



Additional Forces of end connections

- Fig 5 - Forces of helical conductors (at the intermediate cylindrical piece)