DESIGN OF SUPERCONDUCTING DIPOLE FOR HERA

H. Kaiser
Deutsches Elektronen-Synchrotron DESY
2000 Hamburg 52, West Germany

Introduction

The present design of the HERA p-dipole evolved firstly from the cold iron magnet (CIM) developed with BBC (Fig. 1) which had the coil directly clamped by the cold yoke. Secondly it evolved from the warm iron magnet (WIM) (Fig. 2) developed at DESY[1] which makes use of many characteristics of the FNAL-dipole [2].

The present HERA dipole (Fig. 3) uses a DESY-fabricated Al-collared coil of the WIM centered in a cold yoke[3] and a cryostat built by BBC. In this sense it has also been referred to as the "Hybrid"-magnet. The CIM yoke has been altered into a vertically split one. The 2 ph. He tubes are now embedded in the laminated yoke affording a 2 ph. He-line parallel to the magnet axis through adjacent dipoles with gently curved slight offsets in the quadrupoles.

Retained from the CIM were the vacuum tank from ferritic iron (suppresses the stray field by a factor of about 100 and saves cold iron) and design elements of the suspension. The Hybrid is about 9 m long as compared to about 6 m for the CIM and the WIM. Thus, only 2 instead of the former 3 dipoles are required between quadrupoles saving expensive dipole ends and improving the dipole filling factor in the arcs somewhat.

To date 3 CIM, 9 WIM, several 1 m WIM-coils for various tests and 4 Hybrid magnets have been built and in part tested. Currently the design modifications for preseries of 10 dipoles each to be built in Italy and Germany are being made.

Description of the Magnet

The HERA dipole consists of the cold part containing mainly the beam tube and the coil yoke assembly. The cold part is suspended inside the vacuum tank whose heat radiation is intercepted by a shield tube at 60 K.

Cold Part of Magnet

The cold part of the magnet which operates at 4.6 K consists of the 1 ph. He vessel and the magnet within. The He-tank is composed of an outer tube closed off with flat head plates being penetrated by the beam tube and the 2 ph. tubes. The beam tube holds 6 m long quadrupole- and sextupole correction coils[4] offset towards the nearest main quadrupole . The magnet is composed of the coil, the collar for clamping the coil and the yoke. All members of the cold part are fabricated straight and are curved to follow the p-beam only when welding the He-tank tube around the yoke. 1 ph. He-flow passes through 3 parallely connected 4 mm wide annular slits around beam- and 2 ph. He tubes. Upon pressure reduction in a JT valve after one octant of the ring, the He in 2 ph. state and in counter direction passes through the upper 2 ph. He-tube making heat exchange with the 1 ph. He through it wall. The constituents of the cold part and their interaction will now be described in detail from the axis on outwards. Details concerning the magnet as part of the magnet system are covered in a separate paper[5], this conference, and will largely be omitted here.

The Beam Tube The beam tube[6] is made from stainless steel of 2.5 mm thickness to withstand the maximum design pressure for all He-channels of 20 bar, plus the pressure from correction coil presstress and the pressure rise within the He in the surrounding slit due to a quench at the highest possible coil current.

The tube has a Cu-plating on its inner wall and a sleeve with spring contacts to minimize RF losses and slots for pumping at the joint to the tube of the neighbouring magnet. The beam tube is centered within the main coil with local fiberglass spacers. It is rigidly fixed to the He-tank head plates without provision for longitudinal expansion. Radial inhomogeneity of temperature during cool-down or warm-up of the magnet produces tolerable longitudinal and bending stresses in tube and head plates respectively. Magnet Nr. 3 is equiped with suitable temperature sensors on beam tube and He-tank tube to further study this effect.

Dipole Coil, Collar and Yoke The main coil has two layers with one Cu-spacer per quadrant in each to approximate a "cosΦ"-current distribution.

The cable is of the Rutherford-type, keystoned and insulated with kapton and prepreg-glass tape[1].

Coil Geometry The cross sectional geometry of the coil had to be slightly modified with respect to the WIM due to the nearer iron.

Fig. 6 shows the ideal coil geometry and the associated field errors[7]. All multipole coefficients (at $r = 25$ mm, $b_1 = 1$) are $\leq 1 \times 10^{-4}$. It is the function of the collar to accurately define this coil geometry as well as to accept the forces from coil prestress and magnetic force on the conductors without excessive deformation.

The cross section of the collar placed around the coil is shown in Fig. 4. It is stacked from fine stamped aluminium laminations shaped like a "U" with legs of unequal lengths. There is only one type of lamination (Fig. 5). Two laminations assembled as in Fig. 3 form a ring. The collar is a stack of such rings with the shown ring orientation alternating with that obtained by rotating the ring by 180° about its vertical axis. The longer legs then overlap in the horizontal midplane.

The collar is made up of an upper and a lower half collar which are prefabricated in 150 mm long stacks, held together by stainless steel rods A. To assemble the collar, half collars are placed around the coil over its entire length, then pressed together in a large press over the entire coil length by ca. 0.08 mm beyond the ideal geometry. The 9 m long rods are then slipped in.

To facilitate insertion of rods A and B the holes in the collar are noncircular with a shape such that there is surface contact between rod and wall of hole where force is transmitted between the two and clearance everywhere else (Fig. 5). This avoids plastic deformation of the lamination as would occur with a circular oversized hole and gives better transverse positioning of the rod relative to the lamination.

When the force of the press is released rods A and B together with the laminations and the force resulting from the coil prestress will completely define the shape of the collar and therefore of the coil. If the various rods all have uniform diameter (this can be accomplished by selecting them) and the laminations are all uniform in shape (very nearly the case as their complete contour - holes included - is produced in only on punching operation), then the 4 symmetric positions of the lamination occuring in the collar described above assure symmetry of the coil confinement about the horizontal and vertical midplanes. From this follows that the collar itself cannot produce skew multipoles or normal multipoles of even order (quadrupole, octupole etc.). The accuracy of the coil confinement is determined by the punching accuracy (about .02 mm) and the rod diameters. The uniformity of shape of punchings is much better than their absolute accuracy of shape.

The described collar design completely avoids welding operations on the laminations as used in FNAL dipoles and earlier WIM with associated shape errors prior to welding, weld distortion and stress concentrations.

The forces acting on coil and collar have been calculated for aluminium and stainless steel collars for the warm, cold and excited magnet[8]. The prestress in the coil is so adjusted that inner and outer layers each exert a force of 2 kN per cm magnet length when magnetic forces are at 1.5 times those at nominal field. For such a stress to exist in the cold coil it was computed for the warm magnet that as a result of different thermal shrinkage of aluminium and stainless steel (being greater and smaller than that of the coil respectively) the necessary stress in the steel collared coil is 5.6 kN/cm^2 as compared to only 3.5 kN/cm^2 in the Al-collar. The steel collar is therefore more likely to produce coil stress relaxation due to plastic deformation of the insulation than the Al-collar. The Al-collar also costs much less than the steel collar.

The yoke iron being nearer to the coil than in the WIM produces some 22 % of the field. Its particular cross-sectional geometry as well as its magnetic properties will therefore affect the field at the beam. As the details of the yoke cross section were more and more fixed during the design of the magnet their effect on current dependence of the most sensitive allowed multipoles (sextupole, decapole) and the linearity of the field were examinated with field calculation programs[9]. In this way, the outer yoke diameter, the large cutouts for the 2 ph. He-tubes and less important details were defined. The final yoke-produced dipole and sextupole current dependences are shown in Fig. 7. One can see that up to 1.5 I/I. linearity of field and sextupole are still satisfactory.

The collar needs to be centrally and azimuthally locked inside the yoke despite differential shrinkage between the two. The spline-like engagement of teeth on the collar in grooves in the yoke serves this purpose. As the magnet is cooled down the teeth slide radially in the groove while concentricity and azimuthal relation is maintained between collar and yoke. To reduce friction and possibly wear a hard bronze channel is inserted between the teeth and the grooves. An excentricity of 0.1 mm would produce only about 1×10^{-4} of quadrupole at a radius of 25 mm and would be tolerable. From the fact that teeth and grooves are stamped together with the remainder of collar and yoke laminations and the way they are arranged in symmetric positions in the stacks, it is seen that except for some looseness of the "spline joint" no systematic asymmetry can occur in the collar yoke unit with respect to vertical and horizontal midplanes of the magnet. Consequently skew and even numbered normal field harmonics are also not to be expected from the collar-yoke joint.

The vertical split between half yokes allows the insertion of 2 ph. tubes complete with flanges and expansion bellows and pretested for leaks into the half yoke. The half yokes are joined by welding. Then the halfshells, manufactured straight, of the 1 ph. He-vessel are tightly placed around the yoke in a special fixture which also introduces a curvature corresponding to that of the beam. They are then welded together, thus "freezing in" the curved form. The tube is azimuthally prestressed from weld shrinkage.

The spaces between horizontal collar teeth and yoke groove bottoms are filled with shim strips. Cooldown will produce clearance in these places again (cf. left hand picture in Fig. 8 where the field is still zero in the cold magnet). Increasing the current will deform the collar (coil forces) until at ca. 6 T the horizontal teeth will touch the groove bottoms again. The max. stress in the collar (bending in horizontal midplane) is still safe as has been verified with fatigue-tests with several hundred cycles at 6900 A in a 1 m long test coil. Further increase of field cannot deform the collar any more, hence the stress (being largely bending) will also not rise any more. Should the yoke weld break, then the collar force would not overcome tube pretension until more than (totally unrealistic) 9.5 T were reached. The stresses in the collar-yoke joint are thus seen not to limit the maximum field.

The He-tank tube has at the required thickness for 20 bar internal pressure appropriate bending- and torsional stiffness such that with the 3 place suspension of the cold part one can change the axis-sagitta vertically or horizontally by ± 2 mm and the twist between magnet ends by 2 mrad respectively. This is a valuable means of correction of statistical fabrication errors of magnet form.

At the magnet ends there is some space left for a cold protective diode-pair, expansion loops for the current leads and a thermometer for the 1 ph. He temperature (Fig. 9 and Fig. 10).

With commercially available diodes one can operate solely with passive quench protection up to 6500 A[10]. All superconduction main coil connecting leads are stabilized with sufficient copper cross section for carrying the magnet current during a shut off with time constant of 18 s.

Since the cable in the coil will reach short sample current of at least 6500 A, it follows from the above discussion that one A can expect safe and reliable operation with good field quality at up to 6000 A corresponding to ca. 5.6 T which is well above the design field of 4.65 T.

<u>Vacuum Tank, Suspension and Shield</u>

Fig. 3 shows a cross section through the suspension of magnets Nr. 1 to Nr. 3. Vertical and horizontal fiberglass bands[11] with unidirectional fibers and rods, penetrating the shield through relatively large holes suspend the magnet in the tank. The heat flow to the cold part was ca. 30 W for Nr. 1 and 2 and 11 W for Nr. 3 where with great difficulty the openings in the shield were reduced somewhat. Fig. 11 shows a re-design for magnets Nr. 4 and Nr. 1* (rebuilt from Nr. 1 after its electrical failure). With more space between parts at different temperature and better shielding of radiation to further reduce heat losses.

Between the suspension rods and -bands and a short pieces of rectangular Al-tube around them are installed truncated sheet-metal pyramids as shown, which block radiation from vacuum tank to cold part, yet allow sufficient motion of shield, cold part, and suspension members relative to each other and the vacuum tank. The holes in the vacuum tank are enlarged to make room for installation of a cap over the hole in the shield at the point of attachment of the suspension band. Magnet 4 is finished and will be tested shortly.

<u>Design Changes for Preseries of Magnet</u>

What was learned from the experimental HERA-p dipoles is being applied, to sparingly redesign some parts of the magnet. The aim is to produce preseries magnets good enough to be used in the ring. Some of the more important changes will be described. The coil insulation will have besides local fortification near the leads Cu-braid stabilization reaching into the coil body as far as possible. Where the half-collars overlap M_0S_2 will be applied to prevent seizure during collar assembly.

The already described improvements of the suspension-shield-vacuum tank complex will be retained.

The twist of the magnets was too large with a maximum of 7 mrad in Nr. 3[5]. It has been observed that both, the clamping of the half tubes of the He-vessel to the yoke and the welding of the seams contribute to the twist. At BBC and Zanon, Italy, alternate methods of fabrication of the tube are being tested.

All cold bellows will be from 316 LN stainless steel. The access to the cold diode is being improved. There are also improvements in the main-conductor expansion loop and the connection of the various superconductors between magnets.

The Al-shield tube will be assembled largely with tiveting rather than welding, to keep its distortion under control.

Galvanizing of the vacuum tank will be abandoned, as it produced distortion of the tank.

<u>Outlook on Future</u>

Depending on results of tests on a string of 2 quadrupoles and 4 dipoles towards the end of this year, more will be learned about the cooldown[12] and operational characteristics of the magnets. It is hoped that only one 2 ph.-tube for the stationary case will be needed with use of 1 ph. He channels and He-gas return through the safety exhaust tubes on the magnets for cooldown[13].

On the basis of measured temperature distributions one can calculate stresses in various parts of the magnet and check some assumptions earlier made about, for example, rigidly fixing the beam tube and the main coil to the ends of the He-tank.

Other characteristics that can be checked are the electrical and hydraulic connections between magnets, alignment operations on the assembled structure, and the proper functioning of the various safety devices.

Acknowledgements

I wish to thank expecially those colleagues who through discussions or related work have influenced the development of the HERA p-dipol:

J. Carson, Drs. R. Lundy and A. Tollestrup at FNAL.
Drs. Art Greene (BNL) and Perot (Saclay).
Dr. C.H. Dustmann, M. Förster and F. Reizle from BBC.
G. Deppe, K. Balewski, Drs. H. Lierl and G. Horlitz, G. Meyer,
Drs. Meß, P. Schmüser, K. Steffen, D. Trines, B. Wiik and S. Wolff.

References

1. G. Horlitz et al, Superconducting Dipole Coils for HERA, DESY HERA 83/22.
2. F.T. Cole et al, editors, A Report on the Design of the FNAL Superconducting Accelerator, May 1979.
3. This combination first proposed by P. Schmüser.
4. C. Daum and P. Schmüser, DESY HERA 83/01.
5. S. Wolff, Superconducting Magnets for HERA 13th International Conf. on High Energy Accelerators, 1986.
6. D. Trines, The HERA Cold Bore Vacuum System, DESY HERA 85/22.
7. K. Balewski, Untersuchung der Feldqualität Supraleitender Dipole (Diplomarbeit), Universität Hamburg, March 1985.
8. G. Meyer, DESY, private communication.
9. K. Balewski, private communication, see also Ref. 7).
10. K.H. Mess, private communication.
11. Similar bands described in:
    V. Buchanan et al, The Isabelle Magnet Support and Adjustment System, IEEE Transactions on Nuclear Science, Vol. NS-26, No. 3, June 1979.
12. H. Lierl and P. Schmüser, DESY HERA 84/16.
13. G. Horlitz, private communication.

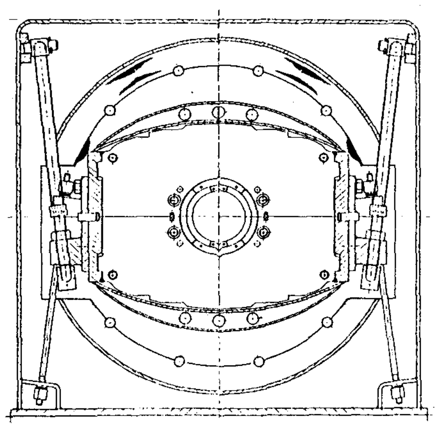

Fig. 1 Cold iron magnet (CIM)

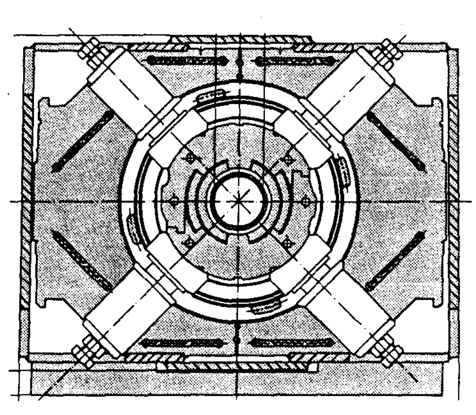

Fig. 2 Warm iron magnet (WIM)

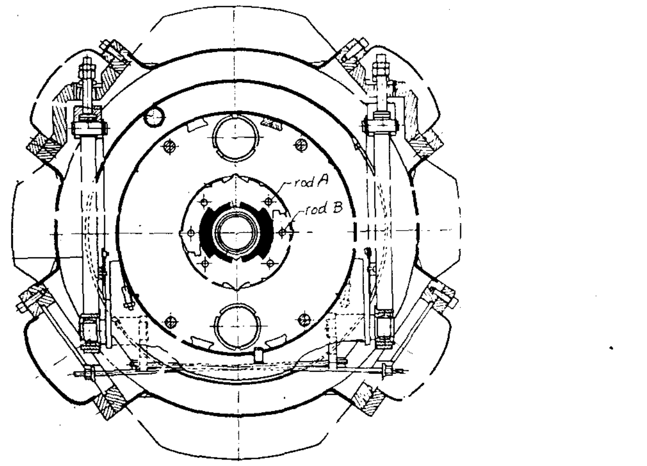

Fig. 3 HERA p-dipol (present design)

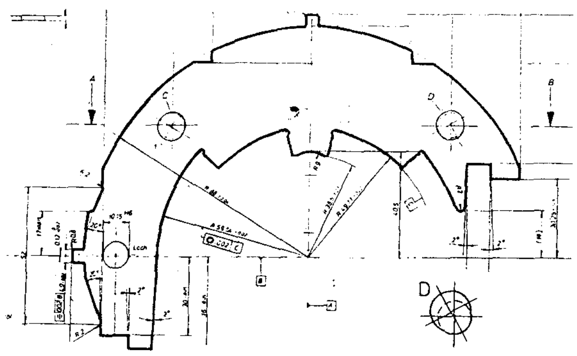

Fig. 5 Lamination for collar

n	$b_n \cdot 10000$
3	-0.2
5	0.9
7	0.3
9	-0.6
11	-0.1

$B_1 = 4.53$ T

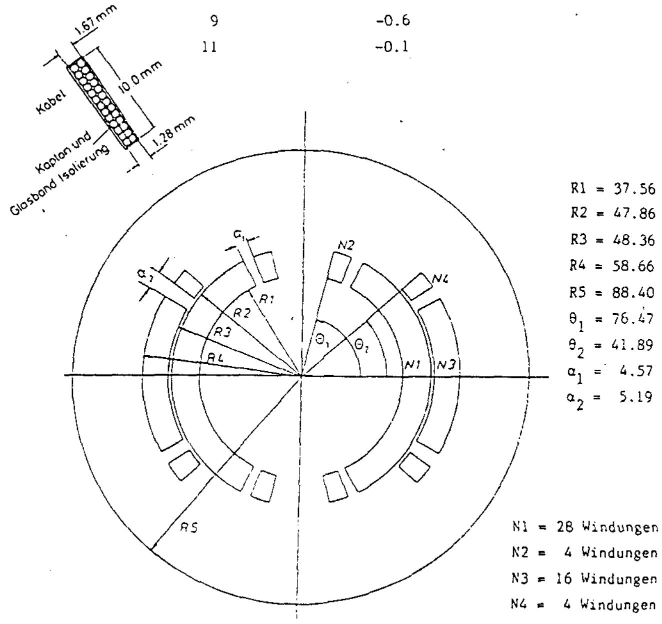

Fig. 6 Ideal coil geometry and multipoles

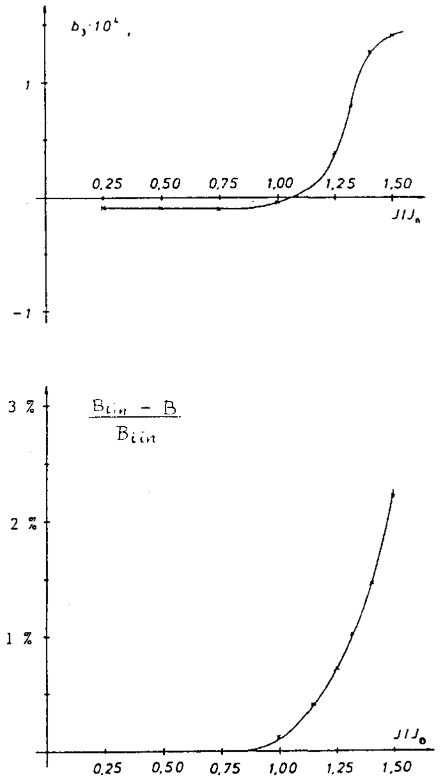

Fig. 7 Current dependencies of sextupole and relative error of field linearity

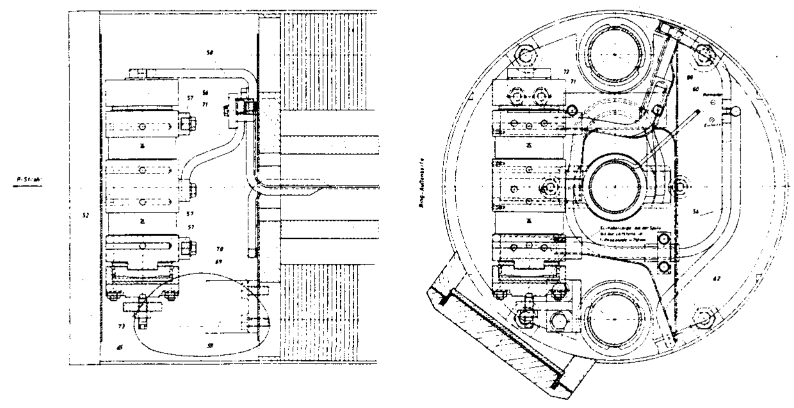

Fig. 9 Diode end of cold part

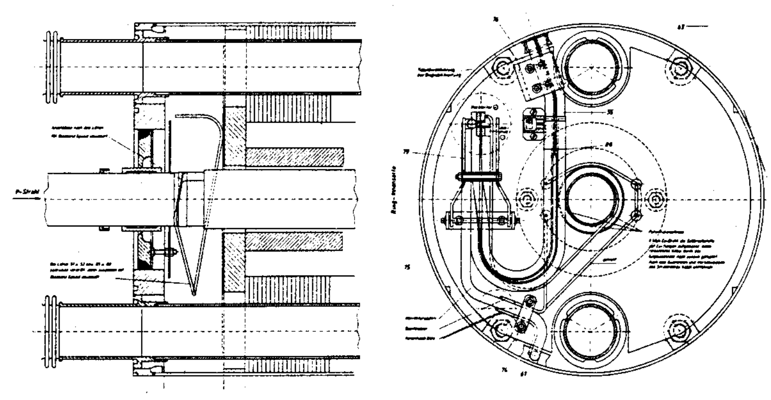

Fig. 10 Non-diode end of cold part

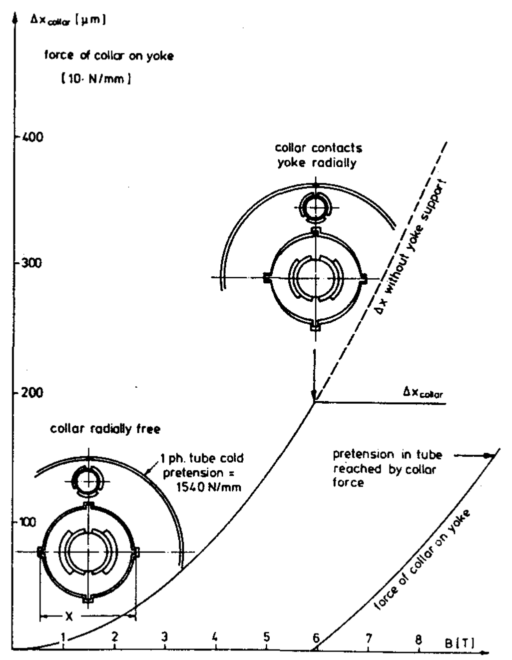

Fig. 8 Calculated deformation of collar and its force on yoke as function of field

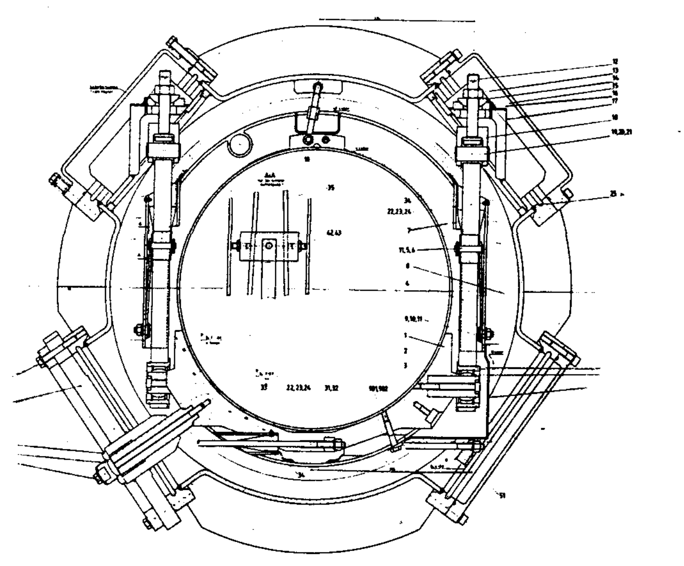

Fig. 11 Redesign of suspension region of magnet