A SUPERCONDUCTING FIELD COMPENSATION COIL FOR THE 1.4 m /2.2 TESLA SUPERCONDUCTING DETECTOR MAGNET " PLUTO " AT DESY

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Abstract

A superconducting coil has been constructed in order to compensate the magnetic field along the axis of the superconducting 1.4 m/2.2 Tesla magnet "Pluto" which will be used as a detector magnet at the intersection point of the storage ring at DESY.

Within a region of $r < 4$ cm around the magnet axis the magnetic induction is reduced to the following limits:

$$B_z < \pm 5 \cdot 10^{-3}\ \mathrm{T},\ B_R < \pm 2 \cdot 10^{-3}\ \mathrm{T}$$

and

$$\int B_R(z)\,dz < 10^{-3}\ \mathrm{T \cdot m}$$

Because of the shape of the "Pluto" field at the ends of its axis a solenoid consisting of several sections with different currents was necessary.

The coil material and the walls as well as the total thickness of the cryostat were reduced to a minimum in order to increase the accuracy of the momentum measurement for the particles to be detected. A maximum of 0.6 radiation lengths or 0.11 collision lengths will not be exceeded for particles traversing the coil at 90° with respect to the magnet axis.

The mean current density in the coil will be $3.2 \cdot 10^4$ A/cm^2. The design of the coil and the cryostat is described in detail; the computed final shape of the field along the magnet axis is given.

I. Introduction

Field compensation or screening is often necessary where beams of charged particles have to cross a magnetic field in order to enter an analysing apparatus without distortion or deflection. There are different possibilities for the performance of the compensation depending on the geometry and the surrounding conditions of the problem. A special case which is discussed here is the compensation of the field of the superconducting magnet "Pluto"[1] which is intended to be used as a detector magnet in the DESY storage ring[2].

II. Outline of Problems

Purpose of Apparatus

The 3 GeV electron-positron storage ring at DESY consists of two ring tubes placed on top of each other in which two beams of charged particles are forced to circle around. Generally the beams are independent of each other and have opposite directions. At two points in the ring the beams cross, thus forming two reaction regions where particles hit each other, leave their original trajectory or produce secondary particles. The reaction products will be analyzed in the manner used in high energy physics, and therefore it is planned to use magnetic detectors at each crossing point. Beside of some very sophisticated detectors which are under construction at DESY there exists already the superconducting magnet "Pluto", which had been designed as a first detector in the storage ring.

A detailed description of "Pluto" is given in a separate paper of this conference[1]. It is a solenoid of 1.4 m free diameter and 1.15 m open lengths which is surrounded by iron. The field is rather homogeneous. The maximum magnetic induction at the center of the magnet is 2.2 Tesla. In the storage ring, "Pluto" is set up in such a way that the particles in the ring would fly roughly along the axis of the field. Because of the intersection of the beams there is a small angle of 12 mrad between the beam particles and the axis.

The presence of the field would disturb the performance of the storage ring. One way to get out of trouble is to compensate the field along the axis of "Pluto" in such a way that the particles of the beam always see zero field (see Fig. 1). Although it is hard to get exactly zero it is possible to achieve a sufficient field reduction with a tolerable effort. The disadvantage is that the material of the compensation coil will decrease the accuracy of the momentum measurement for the secondary particles which traverse this coil. On the other hand, there is no doubt that the storage ring could operate in a satisfactory manner this way.

Another way is to compensate the field inside "Pluto" by magnets at both ends of the "Pluto"

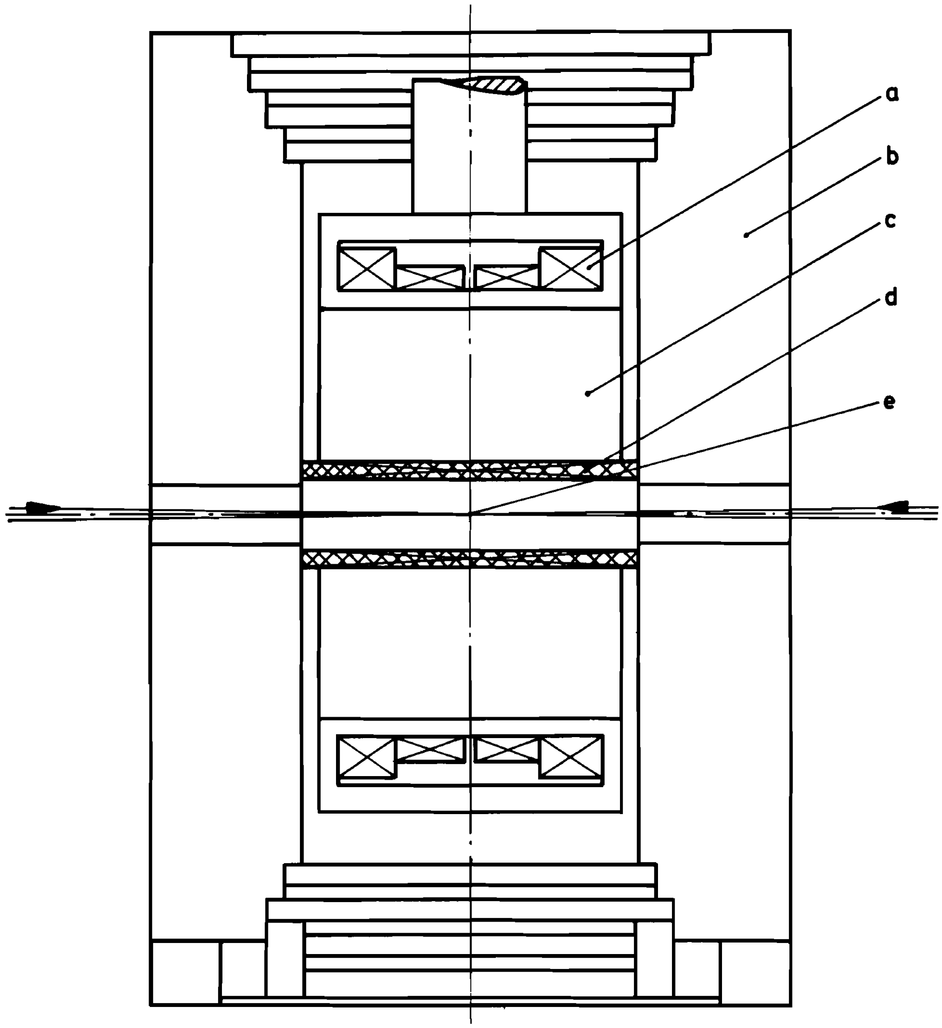

Fig. 1. "Pluto" with compensation (schematic). Legend: a = magnet coil of "Pluto"; b = iron yoke; c = useful field volume; d = compensation coil; e = intersection point

axis which produce fields of inverse directions. Here not the field itself but only its integral along the field axis is zero. With the aid of quadrupoles in the beam line it should be possible to keep the storage ring operating.

Although everyone is sure that this method would work there was a strong demand for an apparatus which would produce the least disturbance of the performance of the storage ring. Therefore the first of these two methods was chosen as a first step, although the second method would leave the detector region in the "Pluto" unchanged and would not produce distortions in the tracks of secondary reaction particles.

Requirements to be fulfilled

The degree of compensation of the "Pluto" field along its axis is determined by the maximum distortions of the beam which can be corrected by the normal means of storage ring control. Thus it was required that the axial component B_z and the radial component B_R of the induction should be limited as follows:

$$(1)\quad B_z < \pm 5 \quad 10^{-3}\ \mathrm{T}$$

$$(2)\quad B_R < \pm 2 \quad 10^{-3}\ \mathrm{T}$$

and

$$(3)\quad \int B_R(z)\,dz < 10^{-3}\ \mathrm{T \cdot m}$$

The space near the axis which should be free of any material components was required to have a diameter of 25 cm, 10 cm of which are for the beam tube of the storage ring; the remaining 15 cm are for counters, so that the experimenters can have a look at the secondary particles before they enter the material of the compensation device. All these requirements can be fulfilled by a shielding coil (Fig. 1). An absolute compensation of the field along the axis, e.g. by superconducting cylinders, would be very difficult within these dimensions, and is not necessary in this case.

The thickness of the material of the coil affects the momenta and trajectories of the secondary particles, thus impairing the accuracy of measurement. Therefore the high-energy physicists entreated us to make the material of the coil as thin as possible. The total material through which particles from the reaction point have to pass to reach the detection region was not to exceed one radiation length. This requirement clearly needs a solution where the coil is superconductive. Evidently the space necessary for the compensation apparatus should be as small as possible because otherwise it diminishes the detector volume leading to a loss of accuracy in momentum measurement. So what we need is a superconducting coil in a cryostat, both of these having nearly no mass and no space.

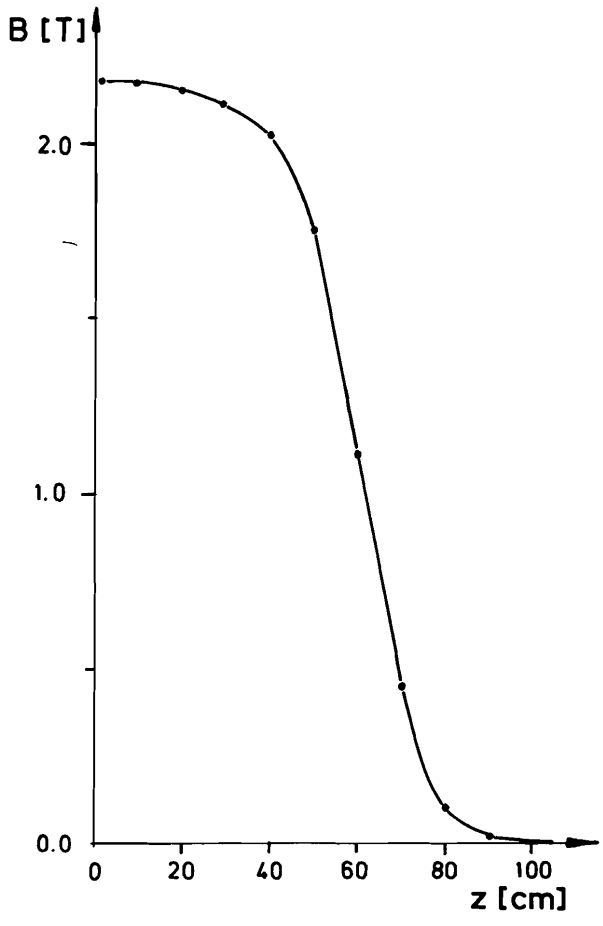

Fig. 2. Flux density of "Pluto" along the axis without compensation as a function of the distance z from the magnet center.

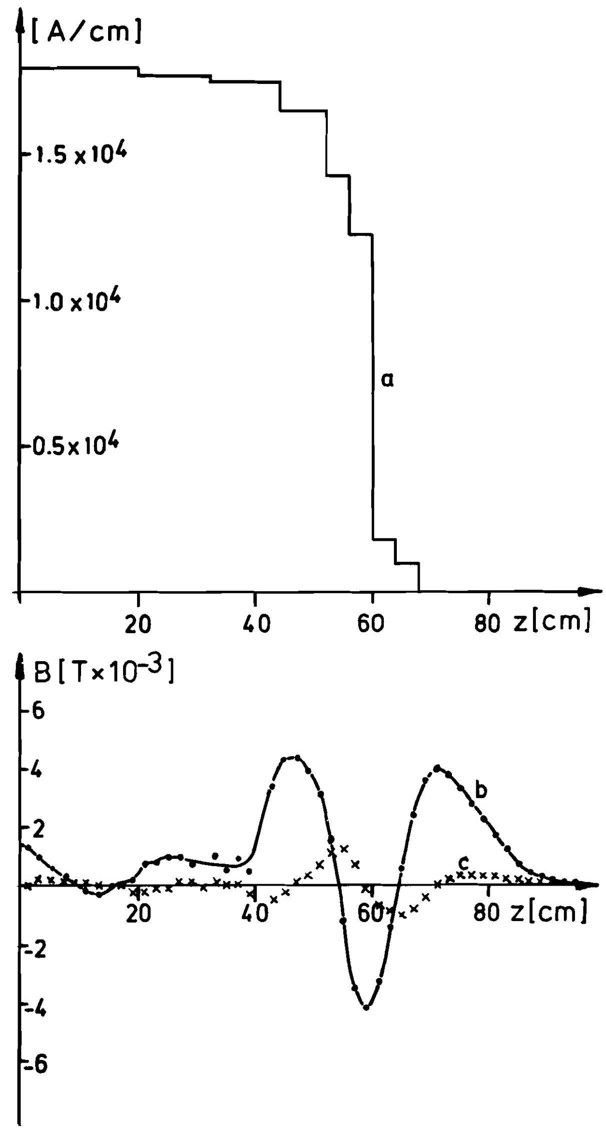

Fig. 3. Results of field computations. Legend: a = linear current density in the compensation coil; b = axial component of the compensated magnetic induction at a distance of 1 cm from the axis; c = radial component of the compensated magnetic induction at a distance of 3 cm from the axis.

Fundamentals of the Project

A homogeneous magnetic field is very easy to compensate, but the "Pluto" field is homogeneous only in the language of high-energy physicists. The field shape along the axis has been measured and calculated (Fig. 2). It shows a slight decrease from its maximum in the center of the magnet to the iron end plates. Near the iron there is a strong decrease of the field due to the holes in the iron which have been reserved for the beam tubes. With the aid of the magnet program "Nutcracker"[3] field maps for several arrangements of compensation coils have been computed. As it is not possible to build the coil in close contact to the "Pluto" iron - some space for thermal insulation and vacuum has to be left - another difficulty for the compensation is introduced. Such spaces cause disturbances of the ideal compensation. The compensation coil had to be extended into the holes in the end plates while the distances between coil and iron were kept to a minimum. At the same time the coil was subdivided into several units of different current density to get a better compensation. The optimum compensation obtained theoretically is shown in Fig. 3. The curves for the magnetic induction show that it is possible to fulfil the require ments given in the foregoing chapter. The field integral can be kept to zero easily but there are some maxima and minima in the components B_z and B_R which appear near the iron end plates of "Pluto". As field calculations with iron are very time-consuming, the optimization of our problem could be done in only a few steps. So we are sure that in practice when we are able to tune the coil by a slight change in the currents the maxima and minima will be reduced.

The requirements for the field compensation have consequences for the stability of the power supplies which are necessary to operate the coil. The critical point for the people who have to run the storage ring is the field integral of B_R along the magnet axis. As the radial component of the induction in this cylinder-symmetric case is smaller than the axial component by the order of a magnitude an overall stability of $\pm 10^{-4}$ for the currents would be sufficient. This also seems to be the limit with respect to the cost of these power supplies. A stronger demand for stability would increase the cost disproportionately.

Another difficulty arises from the fact that the "Pluto" current itself shows a time variation around the design current in the order of $\pm 10^{-3}$ which gives a variance in the magnetic induction of $\pm 2.2 \cdot 10^{-3}$ T. A fluctuation of this order may disturb the operation of the storage ring. Therefore a coupling of the compensation currents to the "Pluto" current will be necessary.

The field of 22 kOersted to be compensated demands a current of $1.75 \cdot 10^6$ A/m. It is clearly possible to buy an intrinsically stabilised superconductor with a short sample current density at 2.5 Tesla of $1 \cdot 10^5$ A/cm^2. Applying a safety factor of about 0.6 for not reaching the short sample values in a large coil one ends up with a winding thickness of below 4 mm.

If we consider the whole conductor to be pure copper the coil thickness is equivalent to 0.3 radiation length which is already a considerable part of the allowed value. All other parts which are necessary to operate the coil like e.g., the cryostat should be made of a material of low atomic number which is favorable with respect to radiation lengths.

The thin windings of the coil are mechanically very weak so that they must be put on a coil former capable of standing the magnetic pressure of about 20 atmospheres acting on the coil from the outside. Since the coil is cooled by liquid helium from the outside only there will be an additional pressure of about 5 atmospheres in the case of a quench.

III. Details of Construction

Coil

The calculation of the influence of a compensation coil on the field map of the magnet "Pluto" shows that a sufficient compensation near the axis is possible with eight different current steps in the coil (Fig. 3). The steps differ in length in the z direction due to the different field gradient of "Pluto" along the axis. At the center there is a step of 40 cm length while the length of the steps at the ends of the coil is only 4 cm. Therefore we took 4 cm as the smallest unity into which the coil could be subdivided. The coil consists of 32 such units. At either side of the coil an end unit is attached which will be discussed below.

The conductor for the coil was chosen to be of rectangular cross section. The reason for this was a better filling factor, an easier winding procedure and a better definition of the conductor location in the coil. The conductor will be furnished by Vacuumschmelze, Hanau, Germany. It is made of about 164 NbTi wires of 36 micron diameter which are situated in a copper matrix and twisted with a pitch of 2 cm. The copper to superconductor ratio is 1.4. Short sample critical current is 425 A at 2.5 T and a bath temperature of 4.2 K. The insulation is achieved by glass fibre which is woven around the wire. The total thickness of the insulation is less than 0.1 mm. This conductor is wound on a coil former, which is made of a tempered aluminum alloy of high thermal conductivity and very good mechanical properties. For each coil unit a groove is machined on the coil former. The coil units are separated by ribs of aluminum of 2.6 mm width which serve as heat drains and as reinforcements of the coil. In the central part of the coil nine layers of 31 windings of the conductor are wound into each groove (Fig. 4). At each end of the

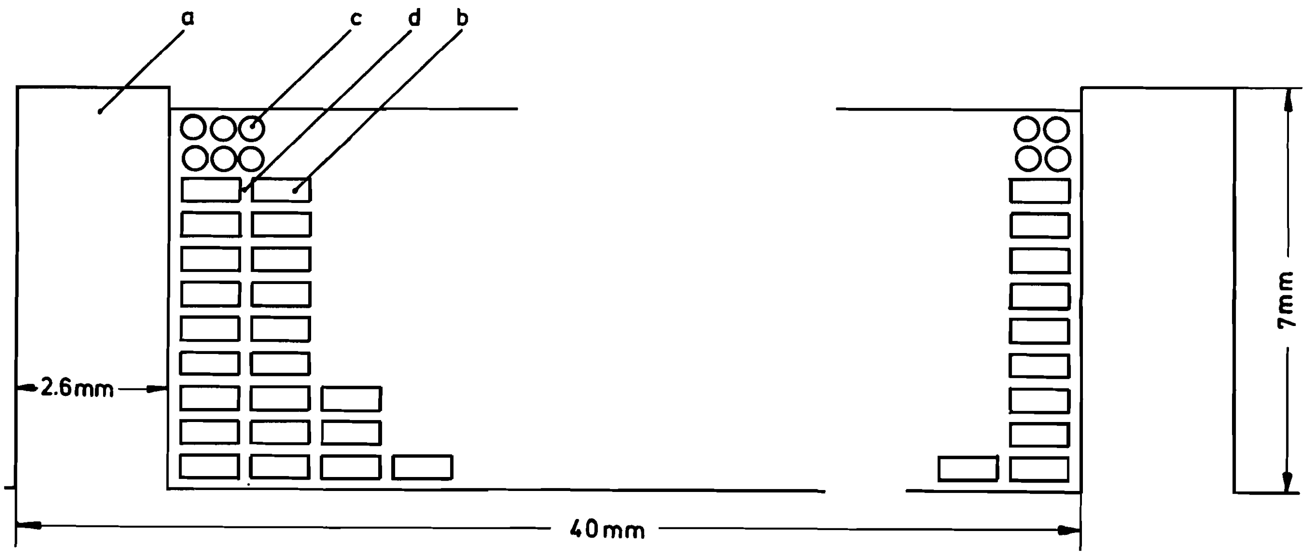

Fig. 4. One section of the compensation coil. Legend: a = aluminum rib; b = main conductor; c = correction windings; d = fibreglass epoxy insulation.

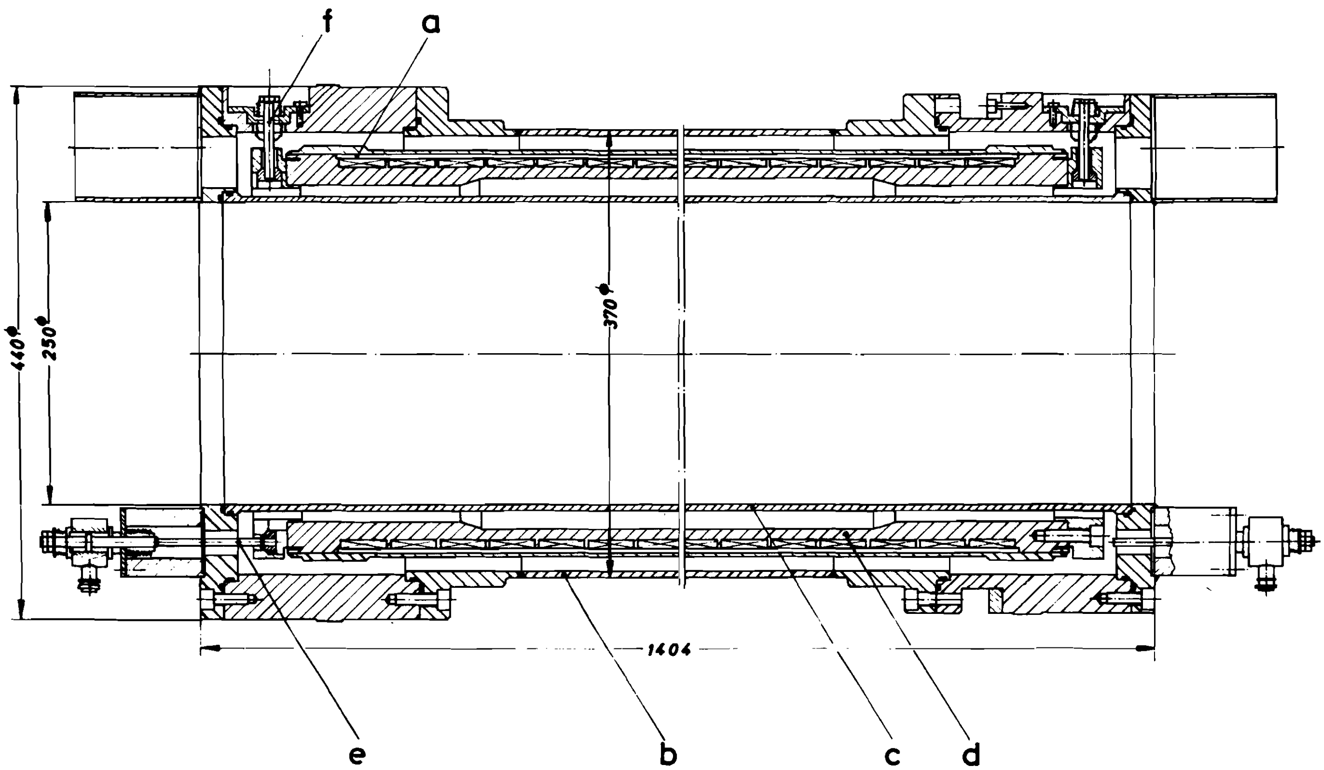

Fig. 5. Compensation coil with cryostat. Legend: a = liquid helium; b, c = outer and inner cylinder of vacuum container; d = coilformer with coil; e = axial rod; f = radial rod.

coil there is one groove with only 8 layers and another with 7. This is to decrease the current density roughly according to the decrease of the "Pluto" field in this region. After the coil is wound with this main conductor two layers of a smaller conductor are wound on several parts of the coil. These serve as correction coils to the main coil. The last groove at each end of the coil is filled with such windings only. The conductor used for this purpose is a varnish insulated standard one from Vacuumschmelze called F 60. It consists of 60 NbTi filaments in a copper matrix. The diameter of the twisted filaments is 35 microns. The copper-to-superconductor ratio is about 1.2. The short sample critical current at 4.2 K and 5 Tesla is 110 A. The field computation shows that we also need correction units of about 4 cm length at each end of the coil. Because of the limited space for flanges and supports it is not possible to put these windings on the coil former directly. Therefore the last necessary correction coils are wound on the cold outer side of the helium vessel. They are cooled only by heat conduction. The possibility of this way of cooling has been tested at DESY[4]. After the conductor is wound on the coil former and the current leads are fixed on the coil the windings are potted with varnish, so that the whole coil together with the coilformer is a compact unit where movements of conductor are impossible.

The total thickness of the winding package will not be more than 6.6 mm from which 2.2 mm will be fibre glass and epoxy insulation. The thickness of the coilformer in the physically important region at the center of the coil is 9 mm of aluminum.

The Cryostat

The coilformer with the coil units is put into an aluminum cylinder of 3 mm wall thickness, with their ends welded together to form a helium vessel for the coil (see Fig. 5). The distance between the outer side of the

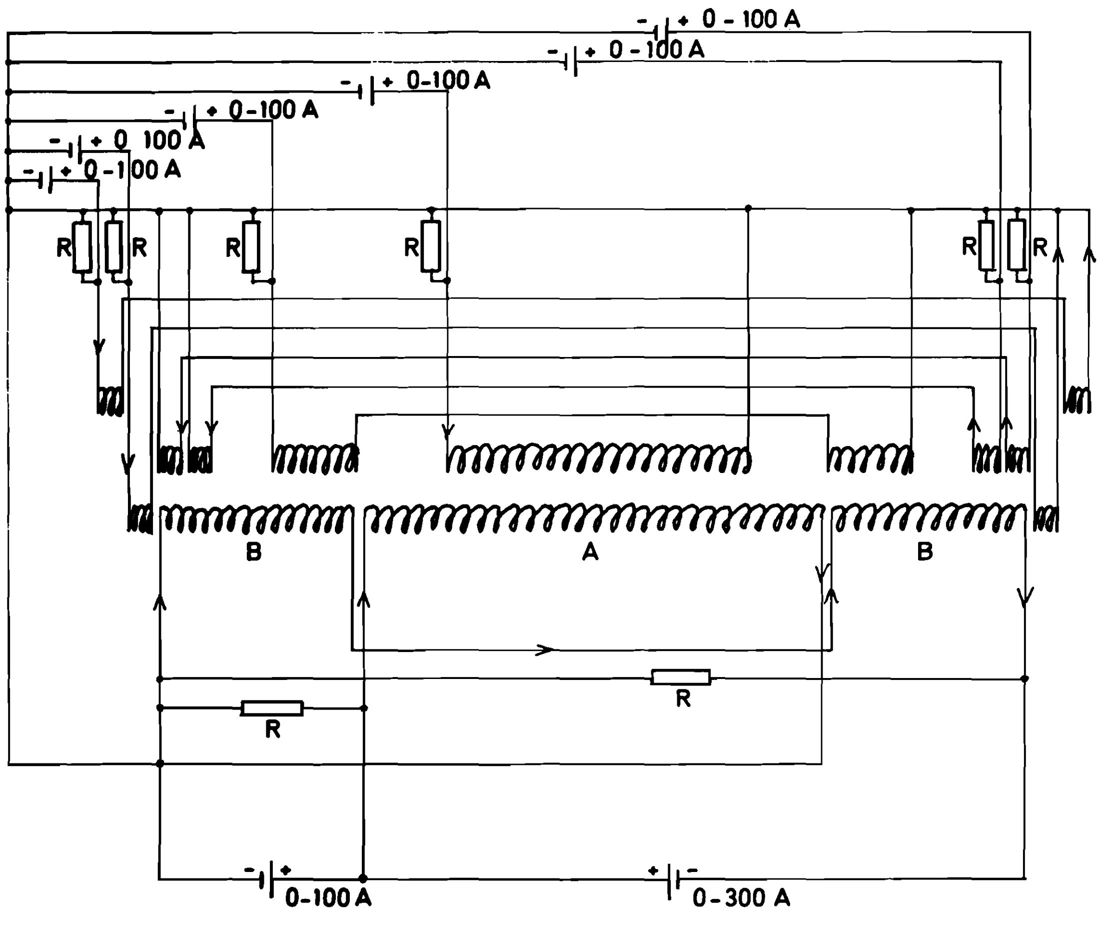

Fig. 6 Current schematic of compensation coil and correction windings.

coil and the outer wall of the vessel is 4 mm, thus leaving enough space for liquid helium to flow around the coil. On the other hand the amount of helium around the coil is small enough to insure a moderate pressurisation in the case of a quench in the coil.

The vacuum tank of the cryostat consists of an inner and an outer cylinder. Both are made of aluminum alloy. The inner cylinder has a wall thickness of 5 mm throughout its length. The outer cylinder is also 5 mm thick in the region where it is necessary from the physicist's point of view. The total thickness of coil and cryostat thus corresponds to about 0.6 radiation lengths or 0.11 collision lengths of material. Towards the ends of the cryostat where the vacuum tank fits into the holes of the iron endplates of "Pluto" two thick iron rings are flanged to the outer cylinder. Both cylinders are then held together by iron flanges at the ends. The iron in the cryostat is necessary to get a better compensation at the ends of the "Pluto" field.

The helium vessel inside the vacuum tank is held in its position by axial and radial rods, three of them at each end of the cryostat for fixing the axial position and three for fixing the radial position. On the helium vessel side they all are fixed to stainless steel rings which are screwed onto the aluminum of the coilformer. As the distances between the cold helium vessel and the room temperature walls of the vacuum tank are very small, the rods are made of titanium having a very low thermal conductivity. The warm ends of the rods are fitted with spring washers which allow for a contraction of the coil and the rods during the cool-down period. A final positioning of the coil inside the cryostat is possible even when the coil is already cooled down. A measure for a possible asymmetric position of the coil are the magnetic forces which act on the coil. Here the forces in axial direction are measured electromechanically.

The thermal irradiation to the helium vessel is reduced by a package of superinsulation inside the vacuum tank. There was no space for a nitrogen- or helium-cooled radiation shield.

The vacuum is pumped through tubes from the sides, which do not narrow the inner free diameter of the cryostat of 25 cm and which do not extend above the outer diameter of the end flanges inside the "Pluto" yoke.

The helium for the coil is supplied through tubes inside the pumping tubes. The helium backflow tube contains nine superconductive current leads which go to a helium filled box outside the "Pluto" yoke. From there the currents flow through normal current leads which are cooled by a regulated helium gas flow.

Power Supply

We have seen that the compensation coil consists of a lot of coil units. The major part of the current is intended to flow in a main conductor. (Fig. 6). This part of the coil is divided into two main coil sections: one section A which covers the central part of the coil and the other section B which consists of two coil regions at the sides which are connected in series. In addition to these main sections there are six correction windings on each half of the coil. The symmetric parts of both coil halves are connected in series because the field to be compensated is symmetric.

All coil sections apart from the main section A have a common current lead which can be grounded. Each coil part is guarded against overvoltage by a small resistor.

The normal use of the coil is to compensate the "Pluto" field. For this purpose the coil sections A and B are connected in such a way that the current is flowing in both of them in the same direction. This main current is delivered by a 0-300 A, 0-10 V power supply. For total compensation, a correction current must flow through coil section A. This current and all the currents in the correction coils are given by 7 power supplies which are capable of 0-100 A and 0-10 V.

If one only energizes coil section B, the "Pluto" field can be overcompensated at the ends of the axis without any compensation in the center. This is a possibility to achieve $\int B_z dz = 0$ without having $B_z = 0$ at a reduced main field. The storage ring will be tested with this configuration.

The power supplies are designed to fulfil the specifications necessary for correct field compensation. Stability will be better than 10^{-4} for the main current and $5 \cdot 10^{-4}$ for the correction currents. The currents can be swept linearly to any desired value within the range of the power supply. This sweep can be made for all power supplies in common or for each one individually. The currents can be coupled to the "Pluto" current. Thus any deviation of the "Pluto" current causes all currents in the compensation coils to change by the same ratio.

IV. Conclusions

The construction of the compensation coil described above together with its cryostat and power supplies will give a satisfying solution to the problem of screening the "Pluto" field along its axis. The requirements necessary to operate the storage ring can be fulfilled as indicated by the results of the field computations. A minimum of material as well as a minimum of space have been used for the coil and the cryostat. The influence of the coil on the particles emerging from the interaction point in the storage ring is thus minimized, ensuring sufficient accuracy of track measurement within the detector.

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