THE 1.4m/2.2T SUPERCONDUCTING DETECTOR MAGNET PLUTO FOR THE ELECTRON-POSITRON STORAGE RING AT DESY

C.P. Parsch, E. Bartosch, F. Böhm
Siemens AG., Erlangen/Nürnberg, Germany

G. Horlitz, G. Knust, S. Wolff
DESY, Hamburg, Germany

A. Stephan
Linde AG., Munich, Germany

D. Hauck
Vacuumschmelze GmbH, Hanau, Germany

Abstract

This paper describes the design and the operating condition of a superconducting magnet system, consisting of the following components: superconducting coil with cryostat, iron yoke, refrigerator, power supply, safety system, measuring-, alarm- and interlocksystem.

1. Introduction

The PLUTO superconducting magnet has been designed as a universally employable detector magnet for pulse analysis of high-energy elementary particles for use in a crossing point of the DORIS electron-positron storage system of DESY electron synchrotron in Hamburg. With its cylindrical volume and the fact that the axis of symmetry and the field are parallel with the primary particles, this magnet meets the requirements of experimental work on storage systems with respect to a large space angle while avoiding undesirable path deviations of the primary particles. To eliminate such deviations completely, the magnetic field in the surroundings of the axis can be compensated to zero by an additional shielding coil[1]

Although flux densities of the order of 2 T can without difficulty be produced by means of conventional coils, a superconducting arrangement has been selected for economical reasons. The higher investment costs can be amortized within a comparatively short time, since operating times of several thousand hours can be expected.

The superconducting magnet is integrated into a system consisting of a superconducting coil with a cryostat, an iron yoke surrounding the coil, a refrigeration unit to produce the liquid helium, a highly accurate current supply, and a measuring, control and safety system.

The magnet has a horizontal axis, a magnetic induction of 2.2 T in the centre and a useful volume in the form of a cylinder having a free diameter of 140 cm and a length of 115 cm. The magnet is surrounded by a hexagonal iron yoke with two parallel end plates. The longitudinal sides of the yoke are provided with air gaps running parallel to the direction of the magnetic flux which enables detector devices to be installed. Consequently, the iron can be used simultaneously as an adsorber for reaction products having a weak interaction effect. The refrigerating installation, designed to provide a sufficient reserve and excess capacity, provides a refrigerating power of 97 W at 4.4 K. The installation is designed for continuous operating (> 5000 h) and to tide over interruptions caused by servicing a 500 litre storage tank for liquid helium is included in the cooling cycle which in that event automatically takes over the refrigeration. A highly accurate current supply (1200 A $\pm$ 1 A) is employed to energize and operate the magnet, the system as a whole is protected against incorrect operation by an extensive interlocking system and operation is to a large extent automated.

The specifications for the system were prepared by DESY to satisfy the requirements of the experiments envisaged.[2] Siemens AG was responsible for the planning, design, manufacture and commissioning of the whole system, and the installation was carried out in close co-operation with DESY, Vacuumschmelze GmbH (superconductor), Linde AG (refrigeration installation) and Fried. Krupp Hüttenwerke AG (iron yoke). The construction took 18 months, and the installation was put into operation for the first time on 23.5.1971. Fig. 1 shows a view of the overall system assembled in an experimental hall at DESY.

2. Magnet

2.1 Coil

2.11 Superconductor

The superconductor is a Cu-NbTi multicore conductor (Fig. 2 shows a cross section) VACRYFLUX® 5001, made by Vacuumschmelze GmbH. Specific details will be found in Table 1.

Figure1 View of the PLUTO magnet system

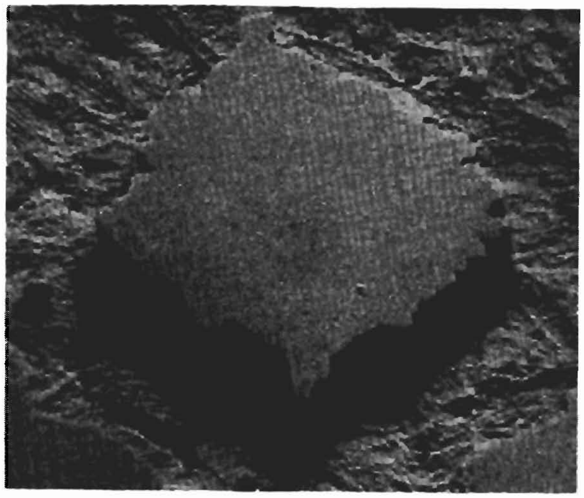


Figure2 Cross-section through the superconductor; photograph of an NbTi filament (taken by means of an electron microscope at the Institut für Kernenergieversorgung, Geesthacht)

Table 1

Cross sectional area	3.5 mm x 7.6 mm
Diameter of filament	0.1 mm
Number of filaments	210
Surface ratio Cu/NbTi	14.5
Twist pitch	30 mm
Critical current at 3 T, 4.2 K	≥ 1600 A
Resistance ratio	150
0.1 % yield strength at 4.2 K	≥ 150 N/mm^2

According to Stekly's[3] stabilization criterion, the conductor is fully stable.

For the stabilization current I_s we get

$$I_s \leq \left[\frac{h \Delta T A U B}{\rho}\right]^{1/2} = 1700 \text{ A}$$

Superconducting equalizing currents which cause excitation instability and field disturbances which vary with time can be avoided by means of twisting the superconductor. According to Wilson,[4] a maximum $\dot{B}$ is given when

$$\dot{B} = 1/l_c^2 (4\pi^2 j_c d \rho)(z d^2/D^2)^{1/2}(w/w+d) = 0,3 \text{ T/min}$$

The dependence of the critical current I_c on the temperature T was investigated by Hampshire[5] for NbTi. With the working current for the magnet of I_b = 1270 A it is possible to operate the system at up to 4.8 K.

Measurement of the critical current I_c is carried out on specimens bent into a U-shape, the magnetic field being perpendicular to the flat side of the conductor. That current I, which causes to a voltage drop of 1 µV/cm on the specimen, is defined as the critical current I_c. Fig. 3 shows the I_c-B-curve and the statistical range of deviation of all of the specimens.

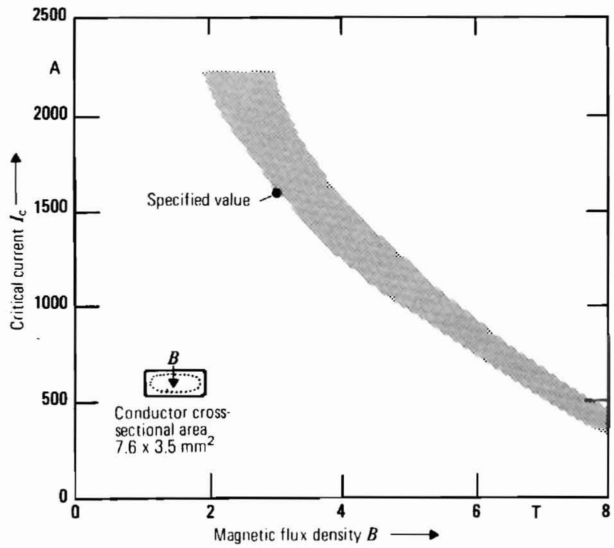


Figure3 Critical current I_c as a function of magnetic flux density B.

Measurement of the stabilizing current I_s is by means with the aid of the heat pulse method.[6] Here the superconductor current is commutated into the copper through a suitable heat pulse and at a constant magnetic field. After the heat source has been switched off, the current at $I = I_s$ flows back into the superconductor. For all of the specimens, $I_s > 1600$ A at 3 T 4.2 K.

The resistance ratio $r = \rho_{300K}/\rho_{4.2K}$ and the 0.1 % yield strength $\sigma_{0.1}$ are inversely dependent upon each other,[6] i.e. a high resistance ratio means low mechanical strength and vice versa. Both of the parameters r and $\sigma_{0.1}$ may be varied through a suitable annealing treatment followed by cold working (Fig. 4). The optimum range for the conductor described is shown in Fig. 4.

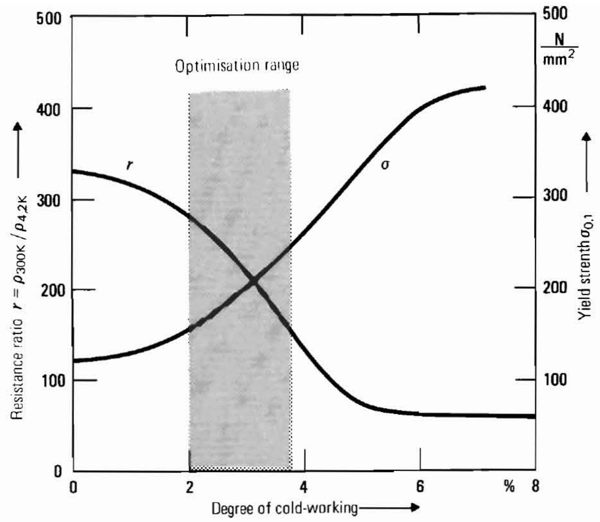


Figure4 Dependence of resistance ratio r and yield strength $\sigma_{0.1}$ as a function of the degree of cold-working

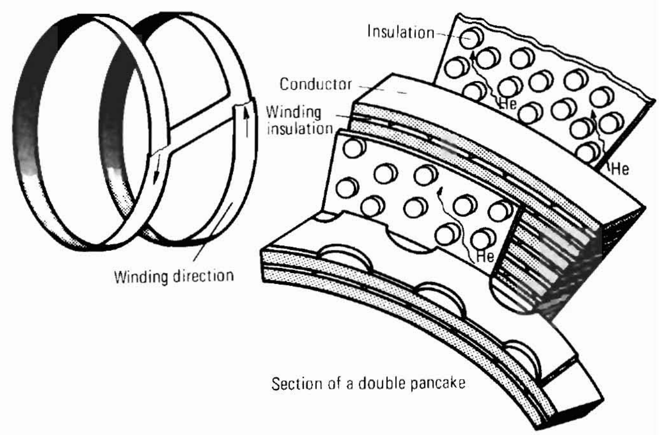


Figure6 Double pancake winding

2.12 Winding

Winding construction. The magnetic field in the working space is produced by a cylindrical coil consisting of 36 double pancake windings. There are 2 double pancake coils on each of the L-shaped spools. The homogeneity required for the magnetic field of $\pm$ 5 % within the space given in Fig. 8 is achieved by the shape of winding as shown in Fig. 7.

Each 9 of the L-shaped spools are located on both sides of the spool centre, 5 of which have a single and 4 a double winding height (sections A and B).

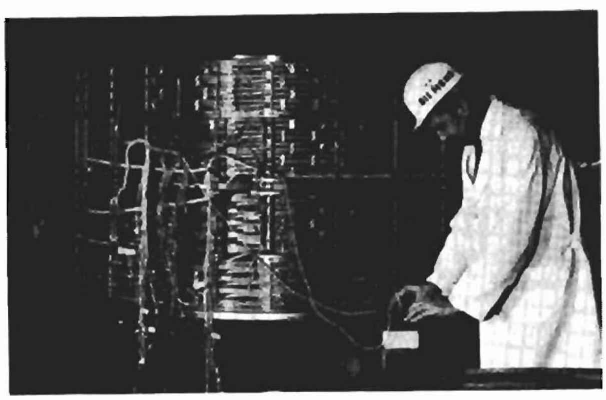


Figure 5 Coil

The construction of a double pancake is shown in Fig. 6. The axial insulation is formed from plates made of fibre-glass-reinforced polyester assembled in segments and provided on both sides with nubs. The last layer of each coil is secured by clamping elements. These elements transfer a part of the resulting magnetic forces onto the L-shaped coil spools and at the same time they relieve the soldered connections between the double pancakes. Any difference in the radial thermal contraction between the winding and the spool is compensated by cup springs in the clamping elements. Both halves of the spools in each set of 18 double pancakes are bolted to a ring welded onto the helium inner cylinder. The differing axial thermal contraction between the winding, insulation and spool on the one hand and the bolts on the other hand is compensated by suitably pre-stressing the bolts. The winding is cooled at the small sides of the conductor (edge-cooling). The surface wetted by the helium comprises 80 % of the total surface of the small side. The HOSTAPHAN tape (7.6 mm x 0.5 mm) wound together with the radial insulation of the conductor is circularly notched and increases the wetted surface by 30 %. The complete coil is shown in Fig. 5.

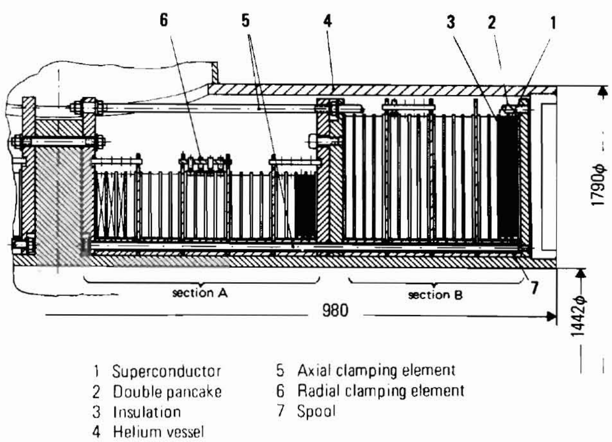


Figure 7 Winding construction

Forces. During operation, the conductor material and insulation in the winding package are subjected to the following forces:

- Forces through pre-stressing arising from the winding tension and the clamping elements.
- Forces arising from the differing thermal contraction of the materials used in the winding package.
- Axial and radial magnetic forces.
- Asymmetrical forces caused by the yoke.

The spool is wound with a winding tension of 500 N corresponding to an initial stressing of approx. 20 N/mm^2. Pre-stressing through the clamping elements may be disregarded. On cooling from room temperature to 4.2 K, the stabilizing copper of the conductor is loaded with a tangential tensile stress of about 15 N/mm^2 due to its greater coefficient of contraction as compared with NbTi and steel.

The sum of the axial components of the magnetic forces is so directed that all of the double pancakes and consequently the conductors are under pressure in the direction of the centre of the coil. The maximum axial force is 1.2 MN and - taking into account a 20 % contact surface through the nubbed discs - a maximum surface pressure of the conductor of 12 N/mm^2 is obtained. The nub spacing on the insulating segments is restricted by the maximum permissible tangential stress in the conductor caused by the bending strain between the nubs. At a permissible stress in the outer fibre of the conductor of 20 N/mm^2, a nub spacing of about 25 mm is obtained. Radial magnetic forces are absorbed by tangential stresses in the conductor. Assuming a homogeneous winding package the maximum tangential stress is 40 N/mm^2.

With a symmetrical arrangement of the coil in the iron yoke no further forces appear. When there is axial asymmetry, a force of 20 kN per mm of deflection occurs, and with radial asymmetry a force of 5 kN per mm of deflection. The asymmetrical forces increase approximately linearly with the deflection. Winding data are given in Table 2. Apart from the forces through winding tension, all of the forces were determined mathematically.

Table 2 Winding data

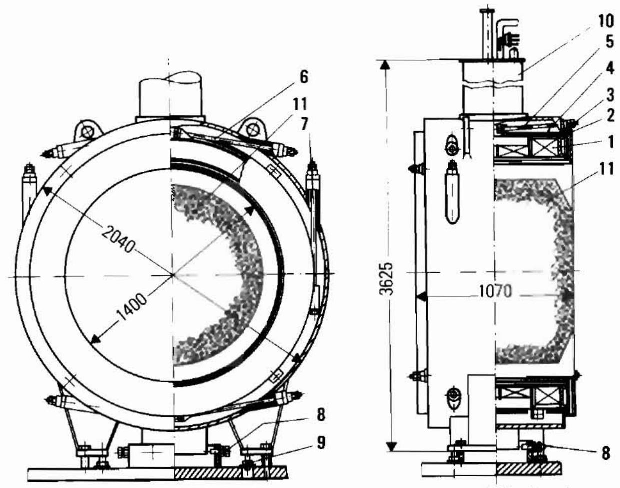
Radial winding dimensions		
Inside diameter		1494 mm
Outside diameter	A	1614 mm
	B	1734 mm
Superconductor		3.5 mm
Insulation (cooling)		0.5 mm
Height of winding	A	60 mm
	B	120 mm
Number of layers	A	15
	B	30
Windings/double pancake	A	30
	B	60
Length of conductor/double pancake	A	146 m
	B	304 m
Total number of windings		1560
Total length of conductor		7800 m
Axial winding dimensions		
Superconductor		7.6 mm
Insulation (cooling)		2.0 mm
Spool flange		3.0 mm
Length of spool incl. 2 double pancakes		43.4 mm
Number of spools	A	2 x 5
	B	2 x 4
Number of double pancakes	A	2 x 10
	B	2 x 8
Winding width:		
Free central part		2 x 36 mm
Part A		2 x 217 mm
Free part between A-B		2 x 20 mm
Part B		2 x 174 mm
Weights:		
Superconductor		1800 kg
Spools		1100 kg
Forces:		
Max. axial force		1.2 MN
Max. axial pressure on conductor/insulation		12 N/mm^2
Max. tangential stress in the conductor caused by:		
Winding tension		20 N/mm^2
Thermal contraction		15 N/mm^2
Axial deflection		20 N/mm^2
Radial Lorentz force		40 N/mm^2
Asymmetrical force per mm of deflection:		
Axial		20 kN/mm
Radial		5 kN/mm

2.13 Current leads

For current transfer between points at room temperature and 4.2 K, use is made of a 3-pole current lead assembly which is cooled by helium gas. While the plus and minus poles are connected to the ends of the coil, the third pole is the centre-tapping and is at earth potential. The individual poles are made of copper laminae. These laminae are kept apart by steel netting which also forms the duct for the helium cooling gas. The copper cross-section of the two current-conducting poles is 0.72 cm^2 in each case, that of the central-tapping, which carries no current under normal operating conditions is 0.12 cm^2. The warm end of each pole is kept constantly at 300 K by a thermostat-controlled heater. Control of the helium-gas is carried out jointly for all of the poles; a regulating valve keeps the temperature of the laminae constant, measured at a point at 1/4 of the total length from the warm end.

2.2 Cryostat

Fig. 8 shows a cross-section and a longitudinal section of the cryostat.



1 Coil 2 Helium vessel 3 Radiation shield 4 Vacuum chamber 5 Axial tension rod 6 Radial tension rod 7 Vertical tension rod 8 Horizontal adjusting device 9 Vertical adjusting device 10 Service column 11 Space occupied by homogeneous field

Figure8 Cryostat

The helium vessel consists of 2 concentric cylinders which are welded to 2 covers at the ends. In the geometrical centre a ring is welded onto which the spool is attached on both sides and mechanically locked to the helium vessel (see also Fig. 7). The weight of the spool, the helium vessel and the radiation shield of 4500 kg is transferred via 4 tension rods onto the outer jacket of the vacuum vessel. In the axial direction, the helium vessel is braced on both sides, in each case with 4 tension rods, to the vacuum vessel covers and in the radial direction with 8 tension rods to the outer jacket of the vacuum vessel. These tension rods transfer any axial or radial asymmetrical forces which may be present.

The points of attachment of the tension rods take the form of a spherical joint with compensating spring. The glands in the vacuum jacket are sealed with flexible bellows, so that the position of the helium vessel or of the coil can be adjusted in relation to the vacuum vessel. The spring seating avoids mechanical prestressing of the tension rods resulting from thermal contraction during cooling. To reduce the introduction of heat into the helium vessel, the tension rods are firmly coupled to the radiation shield at a suitable point.

The service column accommodates the following connections to the helium chamber:

- three-pole current -lead assembly
- helium transfer pipe (supply and return pipe)
- nitrogen transfer pipe for the radiation shield
- 180 measuring leads
- vapor-pressure thermometer and pressure measuring pipe
- cooling line
- safety opening with bursting disc (3bar)

The working pressure in the helium vessel is 1.2 bar, the maximum pressure permitted 5 bar.

A radiation shield made of copper surrounds the helium vessel. The two horizontal cylinders and the cover are made of several sections, and they are electrically insulated from one another so that, in the event of rapid de-energizing or quenching of the coil, eddy currents and the resulting forces are avoided. The cooling agent is liquid nitrogen and this is fed through a meandering tube welded onto the outer jacket and the covers of the shield. For the electrical insulation of the individual segments, the tube is replaced at the gaps by ceramic elements. The radiation shield and the helium vessel are wrapped with super-insulation.

The individual parts of the vacuum vessel, inner cylinder, outer cylinder, the two covers and the service column are sealed by screw connections with O-rings. At the bottom of the outer cylinder there is a support construction which is fixed to the iron yoke. It is arranged in such a manner that the vacuum vessel is adjustable in 3 directions. At the upper end, the column of the vacuum vessel is fitted with bellows which compensates for the change in length during cooling between the column of the vacuum vessel and the helium vessel, the weight of the coil and the helium vessel being supported only by the tension rods. At the column there are the following connections to the vacuum vessel:

- vacuum pump stub - 60 measuring leads
- pressure measuring stub - safety opening with bursting disc (1 bar).

Evacuation of the cryostat is done via a pump connection about 10 m in length with a pump set consisting of a rough pump, Rootspump and diffusion pump. The inlet volume of the diffusion pump is 6000 l/s at a pressure of 10^{-7} bar.

Table 3 shows the principal data of the cryostat.

Table 3 Cryostat

Helium vessel:	
Material	Steel 1.4550
Inner cylinder diameter	1442 mm
wall thickness	15 mm
Outer cylinder diameter	1770 mm
wall thickness	10 mm
Lenght	960 mm
Weight	1100 kg
Radiation shield:	
Material	Copper
Inner cylinder diameter	1424 mm
wall thickness	3 mm
Outer cylinder diameter	1814 mm
wall thickness	2 mm

Length	970 mm
Cross sectional area of tube	10 ø x 1 mm
Weight	430 kg
Vacuum vessel:	
Material	Steel 1.4550/1.4301
Inner cylinder diameter	1400 mm
wall thickness	5 mm
Outer cylinder diameter	1970 mm
wall thickness	35 mm
Length	1050 mm
Weight	1800 kg
Mass (incl. coil) to be cooled to 4.2 K	4000 kg
Total weight of cryostat	6230 kg
Total height of cryostat (incl. column)	3625 mm

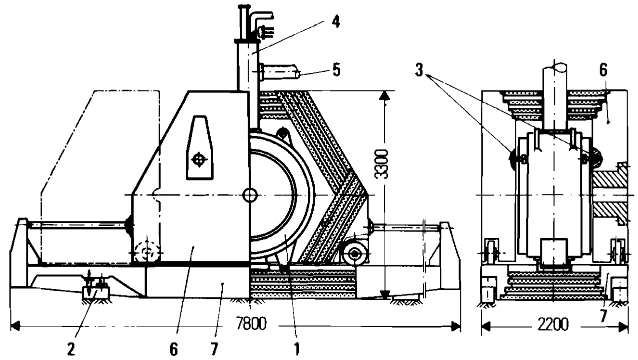
2.3 Iron yoke

The yoke essentially consists of iron plates which surround the cryostat in a hexagonal arrangement. The purpose of the yoke is both to guide the magnetic flux and also to transfer the forces of 3.5 MN occurring between the front plates of the yoke when the magnets are energized. The cross-sections of the iron plates are so dimensioned that a field strength of 80A/cm is not exceeded on the outer surfaces of the yoke. The end plates consist of cast steel GS - minimum RA, the supporting beams of GS - 45 and the plates of the hexagonal configuration of soft magnetic iron with a saturation induction of 2.05 T at a field strength of 300 A/cm. The cast-iron components and laminations were manufactured and assembled by Fried. Krupp Hüttenwerke AG.

By means of a hydraulic lifting device consisting of 6 jacks, the yoke can be raised by 100 mm, and arrested at any desired height by means of spindles with a supporting nut. Inclination and distortion of the yoke during lifting beyond a permitted extent is prevented by lock-nuts on the spindle. The yoke is split along the axis of the magnet. An electro-mechanical drive allows movement of the halves of the yoke - even independently of one another - and consequently provides unrestricted access between the cryostat and yoke. The air gap between the movable yoke and the base plate is ≦ 0.5 mm. At each of the inner sides of the front plate there are 2 adjustable supporting bolts for the cryostat which prevent it tipping or distorting on strong asymmetrical forces. Fig. 9 shows the construction of the yoke. The main dimensions and tolerances will be found in Table 4.

Table 4 Iron yoke, Dimensions and tolerances

Distance between the end plates (length of field space)	1150 mm
Axial distance between cryostat and yoke	50 mm
Radial distance between cryostat and yoke	≧ 200 mm
Outer length of yoke in axial direction	2200 mm
Distance between magnetic and mechanical axis of symmetry in the yoke	≦ 1 mm
Angle between magnetic and mechanical axis of symmetry in the yoke	≦ 1 mrad
Angle between the axis of symmetry and the end faces in the yoke	$\pi/2 \pm 1$ mrad
Field strength in the outer space	≦ 80 A/cm
Air gap between yoke (movable) and baseplate	≦ 0.5 mm



1 Cryostat
2 Jack
3 Supporting bolt
4 Service column
5 Vacuum pump line
6 End plate
7 Supporting beam

Figure 9 Iron yoke

2.4 Electrical system

The electrical system consists of the power supply, the safety and discharging system, and the measuring, alarm and interlocking system. The equipment is installed in a control board about 10 m distant from the magnet and the most important parameters can also be monitored in a control room about 30 m away.

Power supply. The magnet is supplied by an electronically controlled rectifier unit with the following ratings:

Start-up voltage	0 - 10 V
Working current	0 - 2500 A
Accuracy	± 1 A/month

When the magnet is energized, the working current and the start-up voltage are pre-selected. The increase in the coil current as a function of time is then determined through the self-induced emf of the coil which gives the actual value for the pre-selected start-up voltage. When the coil current reaches the pre-selected working current, the power supply unit switches over to constant-current operation. The possibility of exceeding the maximum magnet current of 1300 A is prevented by means of an internal locking mechanism.

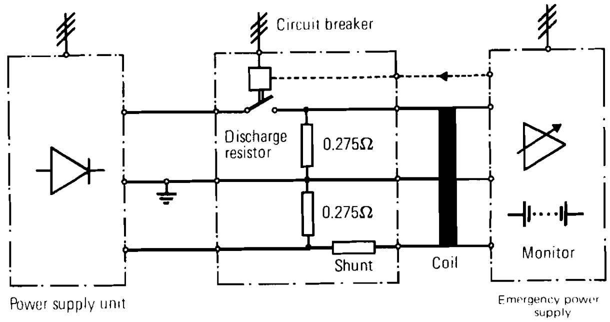


Figure10 Block diagram of power supply and safety system

Safety and discharging system. The safety and discharging system consists of the magnet monitor, the discharge resistor, the emergency power supply and the circuit breaker. Fig. 10 shows the block diagram of the power supply and safety systems. The magnet monitoring system controls the operating condition of the magnet. With this monitor asymmetrical voltages occurring over the two halves of the coil are measured; when adjustable limit values are exceeded - voltage occurring over a preselectable time - the magnet is quickly discharged by opening the circuit breaker. The inductive voltage occurring at the terminals during normal energizing and deenergizing of the magnet is symmetrical with respect to the coil halves and does not result in operation of the magnet monitoring device. The discharge resistance for absorbing the coil energy during rapid de-energization consists of cast-iron resistors of 2 x 0.275 Ohm. The task of the emergency current supply is to maintain the magnet monitoring system in operation for about 1 h during failure of the main supply and to prevent the undervoltage trip of the circuit breaker rapid de-energizing from coming into operation.

Measuring, alarm and interlocking system. All parameters of the magnet system and of the refrigerating installation which are of interest from the physical, operational and safety aspects are measured and, depending upon their importance, indicatet recorded and processed in the alarm and interlocking system. The most important parameters are:

- Pressure: Pressure in the vacuum system at the cryostat, the pump pipe and at the inlet of the individual pumps. Pressure in the helium vessel of the cryostat and in the 500 l storage tank. Pressure at important points in the refrigerating plant.
- Temperature: Coil temperature during cooling down. Temperature of the helium in the cryostats (vapour-pressure thermometer). Temperature at the radiation shield and at the tension rods. Temperature of the current leads and of the cooling gas. Temperature at important locations of the refrigerating system.
- Liquid levels: Helium level in the cryostat, Helium level in the 500 l tank. Nitrogen level in the radiation shield and at the nitrogen cooling traps of the diffusion pump.
- Magnetic field, magnetic flux: Magnetic field at the coil (Hall probe). Magnetic flux through the useful volume (pick-up coil).
- Forces: Axial asymmetrical forces on the 2 x 4 tension rods on the ends of the cryostat (load cells at room temperature). Forces on 10 selected tension rods in the vacuum chamber at 80 K (strain gauges).
- Magnet current: Working current in the magnet (precision shunt).

Forty limiting values selected from all of the measured values are processed in the alarm system and they release, in the case of a response, one of the following three alarms:

A1: Visual and audible alarm on all faults which do not endanger the magnet and which service personnel can remove in a short time.

A2: In addition to A1, slow de-energizing of the magnet on all faults which would initiate A3 if full operation of the magnet were continued.

A3: Rapid de-energizing of the magnet.

All of the alarms A1 to A3 are indicated centrally on an annunciator. Fig. 11 shows the block diagram of the system with some selected limit values. Suitable interlocks prevent inadvertently wrong operation of the plant.

3. Refrigerating system

To cool the superconducting magnet system described, a refrigerating system was designed with the following values of refrigerating capacity:

- 20 W at 4.4 K to make up for insulation losses of the cryostat
- 25 W at 4.4 K corresponding to 7 l/h of liquid helium for cooling the current leads of the magnet

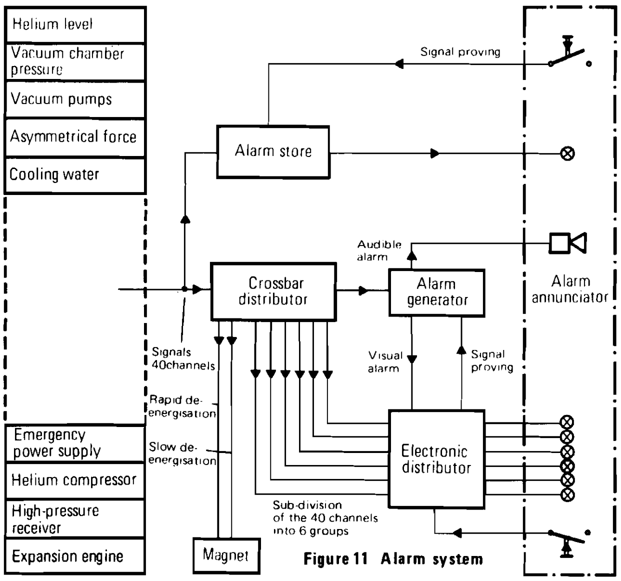


Figure 11 Alarm system

- 10 W at 4.4 K to make up for transfer losses of the liquid helium from the refrigerator to the magnet
- 40 W at 4.4 K as a reserve and for removal of liquid helium from the system.

The system was designed and built by LINDE AG with the use of standardized components. Main components:

- Helium refrigerator - Transfer and storage system for liquid helium - Helium recompression and purifying plant - Liquid nitrogen supply.

gines with the performance of work and finally through the isenthalpic expansion of the third partial stream in the Joule-Thomson valve PC 22. For compressing the circulating gas, use is made of a 4-stage water-cooled dry operating compressor. The inlet and discharge pressure of the compressor are controlled by the automatic pressure regulators PC 11 (1.05 bar) and PC 12 (34 bar) in such a manner that a small partial stream of compressed helium in the by-pass is continually conveyed via the regulators to the compressor. Thus the medium-pressure buffer receiver can accept or give up gas. During liquefaction, purified helium is supplied to the medium-pressure buffer receiver at a pressure of 10 bar via PC 13.

The refrigerator is installed at a distance of about 10 m from the magnet and consists of the following components:

- a steel housing in which the cold box, the piston expansion engine and also the necessary valves and measuring instruments are assembled
- the cold box, built into a Dewar vessel which contains the heat exchanger, adsorber for N_2/O_2 and Ne/H_2 and the necessary cold valves
- two piston expansion engines, type EM 50, each built into a separate Dewar vessel and connected to the cold box through a transfer line.

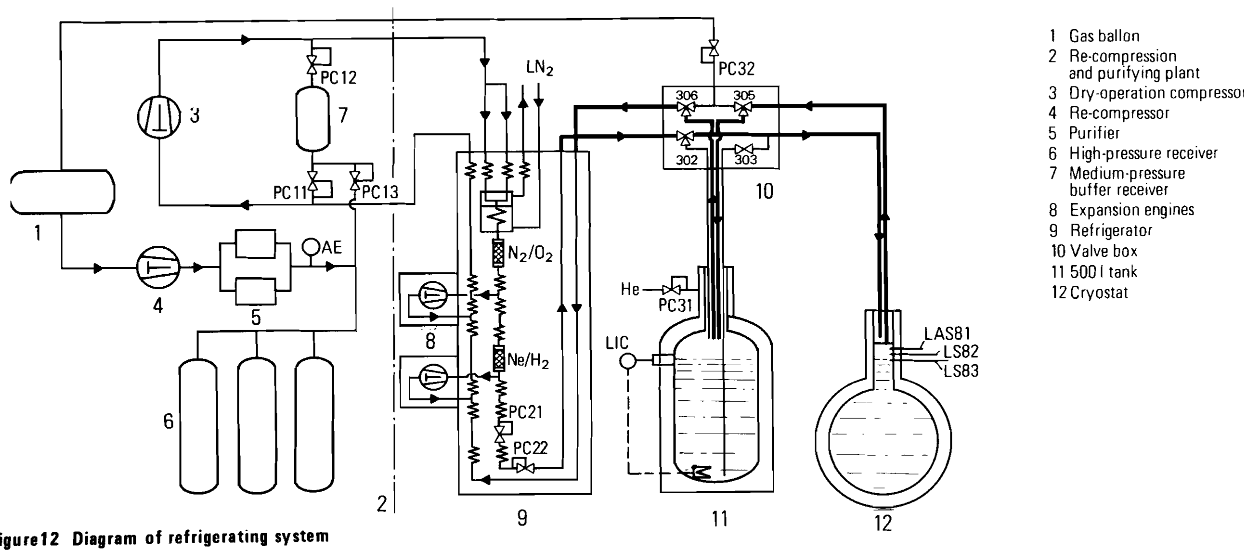


Figure 12 Diagram of refrigerating system

3.1 Helium refrigerator

Fig. 12 shows a simplified diagram of the refrigerating system. Liquefaction of the helium is carried out first by pre-cooling the high-pressure helium with liquid nitrogen (LN_2), then by expansion of two partial streams in piston expansion en-

3.2 Transfer and storage system for liquid helium (LHe)

The transfer and storage system is designed to permit interruption of refrigerator operation for servicing of up to 10 h, removal of LHe for other experiments, operation with little maintenance, automatic change-over on disturbances and automatic adjustment of the refrigerator capacity. The components include

- LHe storage tank having a volume of 500 l, fitted with pressure built-up and pressure limiting devices, level gauge and a level probe coupled with a heater for limiting the level.
- Vacuum-insulated valve box with the cold valve required for changing over and the couplings of the transfer line to the refrigerator and magnet. The valve box is mounted directly onto the 500 l tank.
- Transfer line between refrigerator and valve box.
- Transfer line between valve box and magnet. This vacuum-insulated line is three cored and contains a further pipe for the LN_2 supply for the cryostat in addition to the liquid helium pipe.

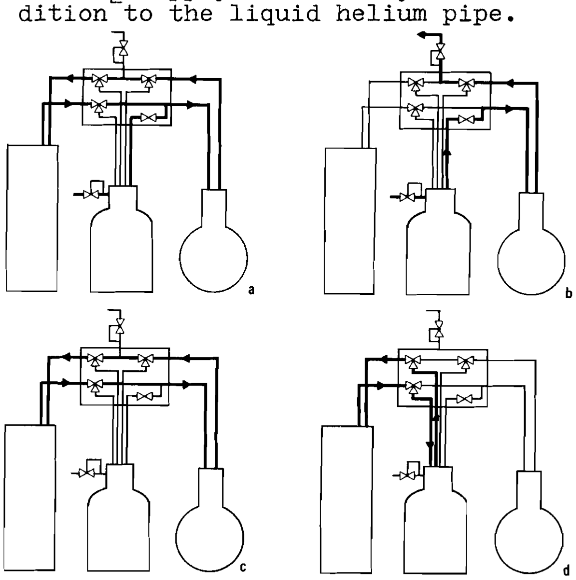


Figure 13 a-d. Possible methods of cryogen supply

For the supply of cryogen to the cryostat, the following possibilities are available:

1. During steady-state operation of the refrigerating system (Fig. 12), the liquid-vapor mixture flows out of the refrigerator via the transfer line and the valve box into the service column of the cryostat which is filled with LHe. The liquid level is kept constant through on overflow pipe, excess liquid and helium vapour escaping through this overflow to the valve box and to the tank, where the liquid and vapour are separated. When the tank is full the excess capacity of the refrigerator is consumed at a constant LHe level through the automatic heat control LIC. When liquid is removed from the tank, the heater is switched off, so that the full excess capacity of the refrigerator is available for helium liquefaction.
2. If the liquid level in the cryostat falls below the nominal value maintained by the overflow, either as a result of higher losses in the cryostat or due to a reduced refrigerating capacity, valves 305 and 306 in the valve box are switched over due to the level indicator LAS 81 and thus the tank is shut off from the refrigerator. At the same time, a pressure exceeding that in the cryostat by 0.1 bar is produced in the tank through PC 31. The level indicators LS 82 and LS 83 now control valve 303 in such a manner that an amount of liquid from the tank required to maintain the level is added to the initial flow to the refrigerator (Fig. 13a). This arrangement enables, for example, one expansion engine of the refrigerator to be serviced without interrupting refrigerating operation and with the lowest possible losses.
3. When switching off the refrigerator by hand or by one of its monitoring devices, helium is supplied to the cryostat from the tank only (Fig. 13b). This operating method differs from method 2 only in the position of valves 302 and 306 (separation of the refrigerator from the magnet) and the fact the vapour coming from the cryostat escapes via the pressure equalizing valve PC 32 to the re-compression unit.
4. For cooling down of the cryostat independently of the tank, or for liquifying the helium directly in the tank, the circuits in accordance with Figs. 13c and 13d can be selected. The arrangement in Fig. 13d corresponds at the same time with the safety circuit provided for the eventuality of coil quenching which - when initiated through pressure switch PAS 81 at 1.6 bar - shuts off the cryostat completely from the refrigerator and the tank.

3.3 Re-compression and purifying plant

This part of the assembly consists of a 30 m^3 gas balloon, a compressor with a delivery rate of 2,5 g/s at a discharge pressure of 150 bar, two alternately operating low-temperature adsorption purifiers and a high-pressure reservoir for 115 kg helium. The tubing is arranged in such a manner that the helium to be supplied to the refrigerator can only be filled in via one of the two low-temperature purifiers on the high-pressure reservoir. The performance of the purifiers is controlled through an analyzer.

The LN_2 supply to the low-temperature purifier of the refrigerator and the radiation shield in the cryostat is obtained from a 6000 l storage tank. The greater part of the liquid-nitrogen line is vacuum-insulated.

4. Test results

The tests on the PLUTO magnet system embraced essentially the electro-magnetic and the cryogenic characteristics of the magnet and of the system as a whole.

4.1 Electro-magnetic measurements

The magnet can be energized within 715 s to the working current I_b = 1270 A with a maximum start-up voltage of 10 V. The magnetic flux density in the magnetic centre point is then 2.165 T. The current, voltage and flux density as a function of time are shown in Fig. 14. The de-energizing time constant for slow de-energizing is 1350 s and 11.5 s for rapid de-energizing. The maximum potential to earth occurring is $\pm$ 350 V. The self-inductance of the magnet calculated from the linear part of the current rise (Fig. 14) is 5.295 H. The stored energy is 4.25 MJ.

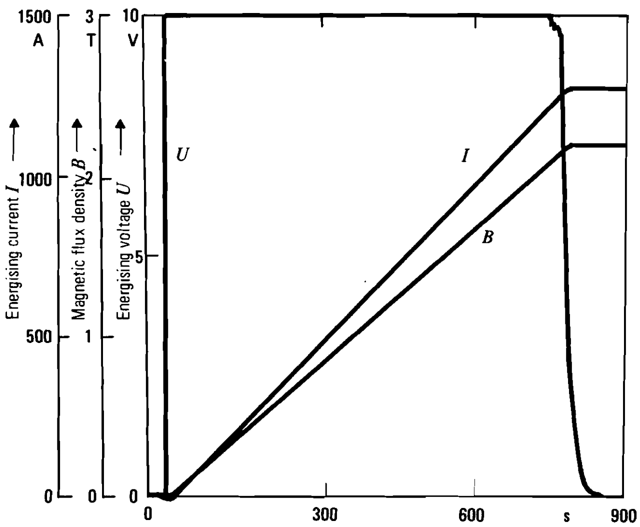


Figure14 Flux density, current and voltage during energising as a funktion of time

The magnetic flux density as a function of the energizing current is shown in Fig. 15. Over the greater part of the operating range, it is approximately linear with an initial steepness of 1.736×10^{-3} T/A. The first measurements showed a field curve as in Figs. 16 and 17 in the useful volume. The azimuth variations of < 1 % show that the hexagonal geometry of the iron yoke represents a good approximation to cylindrical symmetry. The radial and axial deviations from the central field within the useful volume do not exceed $\pm$ 5 %. The stray field was measured on the outer surface of the iron yoke and also in the vicinity of the openings at the ends. In the whole space, the stray field is $\leq$ 40 A/cm at a distance of > 3cm from the iron surfaces.

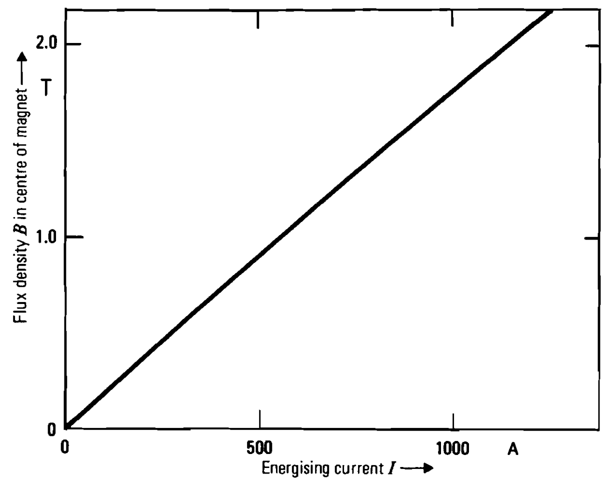


Figure15 Magnetisation curve *B (I)*

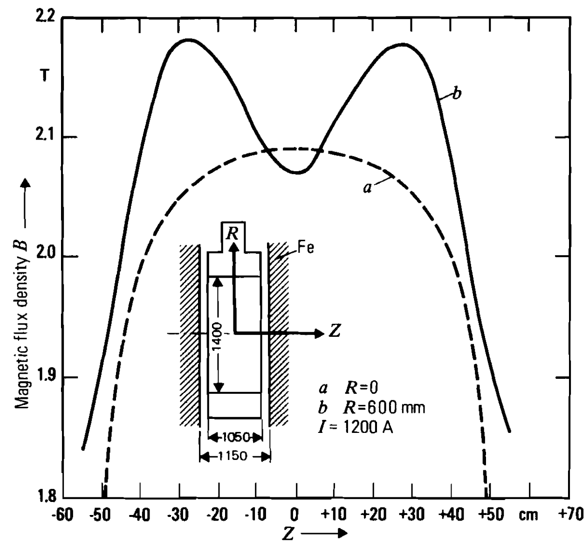


Figure 16 Axial field curve

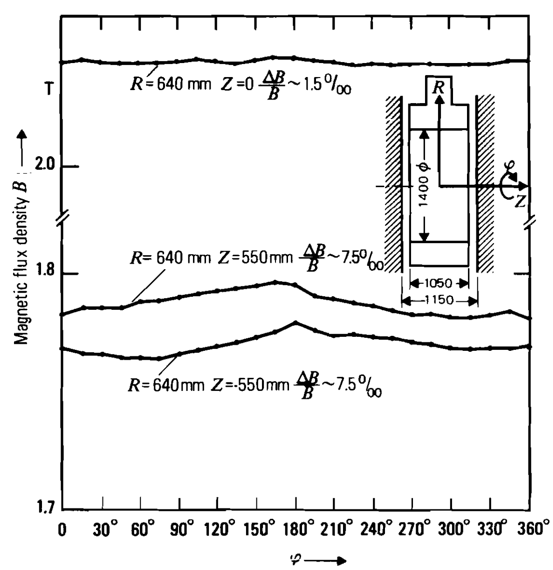


Figure 17 Azimuth field curve

After reaching the working current, the magnet was slowly de-energized to about 500 A, followed by rapid de-energization. After de-energizing the magnet to 0 A, there remained at first a field varying with time, caused by eddy and superconductive compensating currents. The decay time constant of these currents is about 63 s. The measured steady residual field of 3.3×10^{-4} T corresponds to the value to be expected from the geometry and the remanence of the iron yoke. Thus, the twisted super-conductor does not store up any compensating current with a long decay period. The individual double pancake windings are connected to one another and to the current leads through 38 non-superconductive soldered contacts. The mean resistance is 1.7×10^{-8} Ohm per contact point, measured at a magnet current of 1200 A.

4.2 Cryogenic measurements

The liquefaction capacity of the refrigerator is 26 l/h and the refrigerating power is 97 W at 4.4 K measured in the 500 l tank. The evaporation rate of the tank is 1.3 l/h. The losses in the 10 m long tank-cryostat transfer line in operation under-steady-state conditions are 5 W, i.e. 0.5 W/m.

Fig. 18 shows the temperature curve in relation to time at the lowest point of the coil during cooling. The cooling time from room temperature to the working temperature of 4.4 K is 120 h; a further 40 h are required to fill the cryostat with about 300 l liquid helium and to make the cryostat ready for operation.

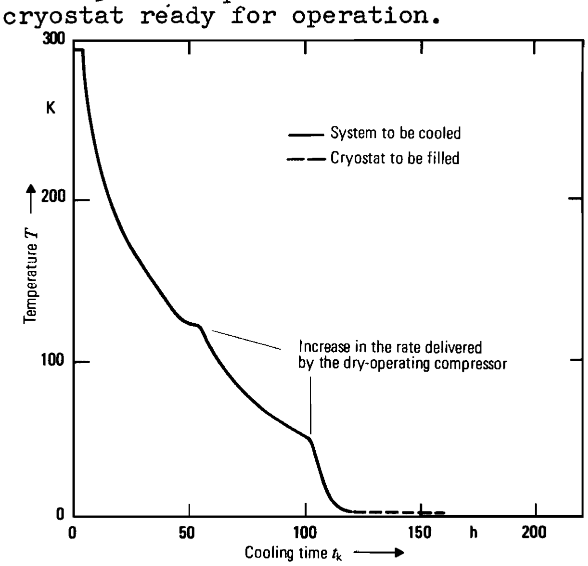


Figure 18 Cool-down curve and filling time of the cryostat

During normal operation, the magnet and current leads are cooled by the refrigerator in the closed cycle. A system of this kind can be characterised by two values obtainable by measurement, i.e. the excess capacity Q_e and the amount of conductor cooling gas $\dot{m}_W$ removed as hot gas. Fig. 19 shows the excess capacity as a function of the amount of conductor cooling gas for the two working conditions I = 0 A and I = 1200 A. With the results from Fig. 19, a static cold loss of about 18 W is obtained in accordance with[7] for the cryostat including the tank-cryostat transfer pipe, but without the current leads. For the entire 3-pole lead assembly, a conductor loss of 12.5 W occurs at I = 0 A and 4.5 m^3/h cooling gas rate, and a conductor loss of 15 W at I = 1200 A, and 8 m^3/h cooling gas rate.

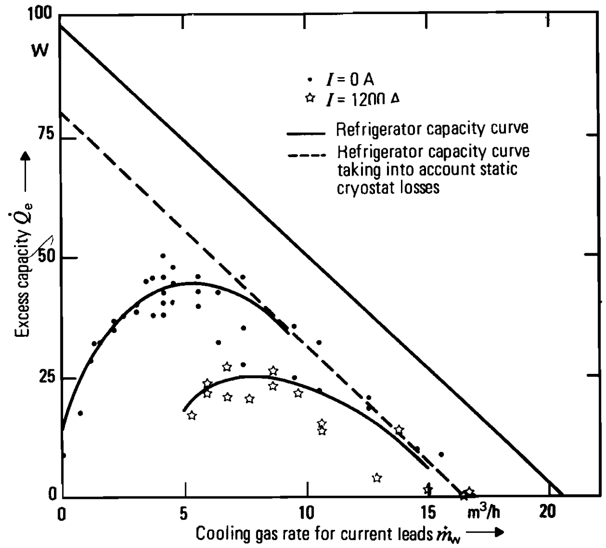


Figure 19 Excess refrigerating capacity of the system as a function of the cooling gas rate for the current leads

The total loss balance as a function of the amount of cooling gas for the current leads can be obtained from Fig. 19. For the working condition I = 1200 A and $\dot{m}_W$ = 8 m^3/h, this is

Transfer pipe line + cryostat	18 W
Current leads	15 W + 5.7 l/h ($\hat{=}$ 8 m^3/h)
Excess capacity	25 W

In the event of a complete failure of the refrigerator the magnet is supplied from the tank. The total consumption including transfer and current lead loss are less than 40 l/h.

Table 5 shows the essential measuring results.

Table 5 Measuring results

Maximum current	1300 A
Maximum magnetic flux density in the magnet centre	2.24 T
Working current	1270 A
Magnetic flux density in the magnetic centre point	2.165 T
Working temperature	4.4 K
Effective current density	2860 A/cm^2
Ampere-turns	1.98×10^6 A

Inductance	5.295 H
Energy	4.25 MJ
Field homogeneity in the useful volume	± 5 %
Stray field	≤ 40 A/cm
Energizing time	715 s
Normal de-energizing time constant	1350 s
Rapid de-energizing time constant	11.5 s
Decay time constant of the superconducting compensating currents	63 s
Residual field at I = 0	3.3×10^{-4} T
Mean contact resistance	1.7×10^{-8}
Liquefaction rate	26 l/h
Refrigerating power at 4.4 K	97 W
Cooling time of the magnet	120 h
Filling time for the cryostat	40 h
Static losses in the cryostat	13 W
Helium consumption during failure of refrigerator and I = 1200 A	< 40 l/h

Acknowledgement

The authors wish to express their thanks to the Board of Directors and the experimenting groups of DESY, particularly to Messrs. E. Lohrmann, M.W. Teucher and P. Waloschek, for their efforts and suggestions in support of the project. Thanks are also extended to Mr. D. Kullmann (Siemens AG) for his collaboration in the design, Messrs. K. Wilhelm (Siemens AG), A. Kunz (Linde AG), W. Eschricht, H.-J. Fiebig, U. Knopf, K.-D. Nowakowski, O. Peters, W. Stahlschmidt, and the technicians and operators of DESY for their effords rendered during commissioning of the plant.

Our special thanks go to Messrs. G. Bogner (Siemens AG) and H. Brechna (Nuclear Research Centre, Karlsruhe) whose advice and experience contributed greatly to the success of the project.

References

1. W. Eschricht, H.-J. Fiebig, G. Horlitz, U. Knopf, G. Knust, K.-D. Nowakowski, O. Peters, W. Stahlschmidt, S. Wolff - DESY Hamburg - "A Superconducting Field Compensating Coil for the 1.4m/2.2Tesla Superconducting Detector Magnet PLUTO at DESY," Fourth International Conference on Magnet Technology, Brookhaven, 1972.

2. G. Horlitz, G. Knust, S. Wolff, "Spezifikation eines supraleitenden Magneten mit einem Maximalfeld von 20.000 Oerstedt und einem nutzbaren Volumen von 140 cm Durchmesser und 115 cm Lange," Spezifikation DESY/Bl/Ho/Knu/Wo/E/Ve of 26.9.1969.

3. Z.J.J. Stekly, J.L. Zar, "Stable Superconducting Coils," IEEE Transactions on Nuclear Science, June 1965, p. 367.

4. M.N. Wilson et al., "Experimental and theoretical studies of filamentary superconducting composites. I. Basic ideas and theory," Journal of Physics D, Applied Physics, Vol. 3, No. 11, 1970, p. 1518.

5. R. Hampshire, J. Sutton, M.T. Taylor, "Effects of temperature on the critical current density of Nb-44 Ti alloy," Conference on Low Temperature and Electric Power, London, 1969.

6. C. Albrecht, H. Lamatsch, "Development of a Superconducting High Current Conductor - Measurement Techniques and Quality Control," Third International Conference on Magnet Technology, Hamburg 1970, p. 1071.

7. G. Horlitz, C.P. Parsch, S. Wolff, "Helium Gas Cooled Current Leads in a Refrigerator Cooled Superconductive Magnet System," Fourth International Conference on Magnet Technology, Brookhaven 1972.