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FOR 10 TESLA SUPERCONDUCTING MAGNET MODELS

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CRYOGENICS OF THE 1.8 K TEST STATION FOR 10 TESLA SUPERCONDUCTING MAGNET MODELS

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CERN has built a test station in which 1 m long superconducting high field magnet models can be tested at temperatures between 4.2 K and 1.6 K. It mainly consists of a vertical double-bath cryostat with helium II at atmospheric pressure, a 100 l/h refrigerator/liquifier, a low loss helium transfer system and a 20 kA power supply. Refrigeration of the helium II bath is done with a refrigeration circuit of the "Joule-Thomson" type. Cooling performances measured at 1.8 K are 9 W and thermal losses into the helium II bath 2 W. Test of the first of a series of dipole magnets fabricated by European industry were successful and magnetic fields of 9.0 T were exceeded at 1.6 K and 2.0 K. No pressure rise occurred in the helium II bath following a quench and superfluid helium temperature could be maintained.

INTRODUCTION

At CERN the Large Hadron Collider (LHC) consisting of twin aperture superconducting magnets with fields of 8 to 10 Tesla, is proposed as a future powerful proton-proton collider. In collaboration with European industry, CERN is developing a series of 1 m long single and twin aperture dipole magnets which shall be tested at CERN⁽¹⁾. For this purpose a 1.8 K test station has been built and put into operation. The components of this test station are described. The cool-down and sub-cooling procedure of the first 8 Tesla dipole magnet model is explained and data on performance of the refrigeration system for the helium II bath below T_λ are presented. Preliminary results on magnet performance are given.

CRYOGENIC SYSTEM

The simplified flow scheme of the cryogenic system of the 1.8 K test station is shown in Fig. 1. Its major components are the helium refrigerator/liquifier with its associated compressor (I), the helium transfer line (II), the vertical double bath cryostat (III), the heat exchanger (IV), the roots pump station (V) and the current leads (VI). Various containers are used to store gaseous helium.

The multipurpose helium refrigerator/liquefier plant is mainly composed of a cold box with 5 heat exchangers, 2 turbo-expanders, a cold and a warm ejector and a 380 kW two-stage piston compressor. The compressor is located at 200 m from the experimental zone and the cold box, and connected to it by underground pipe runs. Refrigeration performance varies from several kilowatt at ambient temperature to 400 W at 4.4 K in closed circuit operation. Liquefaction rate is at around 100 l/h⁽²⁾. During liquefaction mixed duty is applied in our experiments, whereby a partial helium stream is used for cooling the current leads and returned warm to the warm ejector. The other part is returned cold to the cold ejector via the helium transfer line.

The helium transfer line mainly consists of two independent parts : a rigid part built into the cryostat and a 10 m long semiflexible transfer line linking the cold box to the rigid part. The design of the terminals of the semiflexible transfer line and the rigid part allow for quick connection/disconnection and therefore dismounting of the cryostat for various experiments with different components. The semiflexible part of the transfer line is made of four coaxial corrugated stainless steel tubes developed by Kabelmetal⁽³⁾. The inner channel is used to supply gaseous or liquid helium to the cryostat. The annular channel between the second

and the third tube takes the return flow of gaseous helium and thereby screens the supply pipe. The other two annular channels are evacuated for thermal insulation and contain helically wound polymer spacers. An activated charcoal adsorbent fleece and thirty layers of aluminized Mylar superinsulation are wound around the return pipe. Performance measurements of similar 50 m long transfer lines used before at the CERN Intersection Storage Ring (ISR) indicate low thermal losses of approximately 60 mW/m in selfscreening operation⁽⁴⁾. However, in our experiments mass flow rate through the annular screen channel is significantly higher than under selfscreening conditions. In liquefaction mode at stationary operating conditions inlet temperature of the screening gas measured at the refrigerator is at less than 6 K indicating practically zero losses of the supply pipe. A valve inside the rigid part allows to direct the helium flow either to the bottom or to the upper part of the double-bath cryostat depending on experimental requirements.

The cryostat, a vertical double-bath system as proposed by Claudet et al.⁽⁴⁾, is approximately 3 m long and its inner diameter is 0.8 m. A separation plate made of insulating fiber glass epoxy defines two baths ; the helium I bath above and the helium II bath below the plate both at atmospheric pressure (see Fig. 2). The applied technique for operating the subcooled 1.8 K bath is to keep the fluid pressure at approximately 1 bar as the liquid contracts or expands with change of temperature. The constant pressure condition is achieved by hydraulically connecting the helium II bath with the helium I bath. In our design hydraulic connection and flow passage is controlled by the position of a safety valve assembly (poppet valve) in the separation plate (see Fig. 2). In the event of a magnet quench, however, rapid volume changes demand a large exit area from the lower bath and the poppet safety valve is pushed open by the pressure difference leading to pressure relief. In this case gas is recuperated in a 120 m³ recuperation balloon.

Refrigeration of the helium II bath is done with a heat exchanger unit immersed into the bath. The heat exchanger contains a small amount of saturated liquid helium (pool) vaporizing under reduced pressure and serves as a heat sink of the cryostat system. A Roots pumping unit provides the low pressure required by extracting the vapour generated. It consists of a backing pump and a Roots pump with a maximum pumping speed of 1000 m³/h at around 10 mbar. At steady state operation the mass flow evaporated is replaced by a continuous liquid flow from the helium I bath through a connecting capillary to a Joule-Thomson valve located inside the heat exchanger. In the Joule-Thomson valve the liquid is then expanded to the actual pressure. To achieve high Joule-Thomson efficiency the liquid transported in the helically wound capillary is precooled in the counterflowing vapor extracted by the pumping unit. The cryostat and the heat exchanger had originally been built and used for other purposes at the General Cryogenics Engineering Group at CERN. They have been modified and adapted to the requirements for the testing of superconducting magnet models which includes also an upgrading of the cooling performance of the heat exchanger by the factor of two at 1.8 K.

Vapor-cooled current leads are used to bring magnet current down to the He II reservoir area where the magnet is suspended from the separation plate. Two different types of 18 kA current leads have been developed : one by ABB (Asea Brown Boveri Co) and one by CERN. They have been successfully tested and are currently used at the 1.8 K test station. The specific losses in both lead types is in the order of 1.2 W/kA at nominal current. A more detailed description of the current leads and their characteristics is given in ref. 6, 7.

The current supply system consists mainly of a 20 kA power supply and watercooled bus bars connected to the current leads. For magnet protection current breakers are triggered by quench detectors. A detailed description of the electrical scheme is given in ref. 8.

CHARACTERISTICS OF THE LHC 8 TESLA MAGNET MODEL

The 8 Tesla NbTi single aperture dipole magnet model was designed and built as a joint project of ANSALDO Componenti, Italy, and CERN. This magnet has recently been tested at the 1.8 K test station of CERN. Some of the main magnet parameters are

listed. A more detailed list can be found in ref. 9.

Overall magnet length	1.38	m
Shrinking cylinder outer diameter	0.412	m
Weight	1210	kg
Coil inner diameter	0.050	m
Nominal induction B_0	8.0	T
Operation current at B_0	9.14	kA
Stored energy at B_0	160	kJ

COOLDOWN

Cooldown of the magnet and the cryostat is accomplished by circulating cold helium gas from the cold box through the transfer line to the magnet bottom (see fig. 2). Part of the helium flow is directed into the central bore and cools the coils, the other part flows alongside the shrinking cylinder. This provision helps to reduce temperature gradients between the coils and shrinking cylinder and hence unnecessary additional compression of the coils with respect to solely outside cooling of the shrinking cylinder.

Cooldown is done semi-automatically by using the temperature difference between the magnet and the cooling gas as controlled variable for the cooling performance of the microprocessor controlled cold box and cooldown speed can be regulated accordingly. At temperatures > 120 K temperature difference at any two points of the magnet should not exceed 50 K. Additional requirements are to keep the temperature difference between coils and shrinking cylinder as small as possible. During cooldown process temperatures of the magnet at various locations were recorded and compared with limits. The average temperature of the coils is determined indirectly by measuring the electrical resistance.

Cooldown of the magnet from 300 K to approximately 20 K is achieved in 50 hours without exceeding any of the limits. In Fig. 3 temperature variation of the cold gas at the cold box outlet, the temperature of the magnet shrinking cylinder and the coil temperature are plotted versus temperature. Average cooling speed is at approximately 6 K/h. The temperature difference between magnet and gas is less than 50 K. During the complete cooldown process the temperature of the coil did not exceed that of the shrinking cylinder assuring that additional strain and stress originating from shrinkage is a minimum. Cooling power at the magnet was around 1 kW at temperatures close to ambient. Mass flow rate was approximately 10 g/s. After cooldown to around 15 K liquefaction automatically sets in and further cooldown to 4.2 K and filling of the cryostat takes place. The time required for this procedure is around 20 hours (see Table 1).

SUBCOOLING TO SUPERFLUID HELIUM TEMPERATURES

After filling of the cryostat, subcooling of the 530 l liquid helium bath is done with the heat exchanger unit described above. Pressure and temperature of the saturated liquid pool and the liquid level in the heat exchanger are controlled by the pumping speed of the Roots pump group and the opening of the Joule-Thomson valve.

Above T_λ the temperature in the helium II bath decreases with an average rate of 0.2 K/h at the vicinity of the heat exchanger. The temperature at the bottom of the cryostat decreases with the same rate while the temperature at the top of the bath remains at 4.2 K indicating stratification in the bath. After about 9 hours the temperature at the vicinity of the heat exchanger is T_λ . After about 30 minutes the temperature at the cryostat bottom reaches also T_λ . After another 2 hours the superfluid front has moved upwards to the top of the helium II bath indicated by the sharp temperature drop from 4.2 K to T_λ .

As soon as the superfluid front touches the separation plate stratification of the helium I bath cooled via the plate starts. During the time needed for the stratification to be established the cooling speed of the helium II bath is reduced due to the increased thermal losses through the separation plate.

At steady state condition the temperature of the liquid at the separation plate is at T_λ and the temperature gradient in the vertical direction is approximately constant at 0.15 K/cm. Stratification helps to significantly reduce losses to the helium II bath. Cooling performance of the helium II bath is given by the pumping

speed of the Roots pump unit. This corresponds to approximately 13 Watts above 2.0 K, 9 W at 1.8 K and 4 W at 1.6 K. Lowest temperature reached in the bath is 1.5 K.

Estimations of thermal losses through the separation plate and its electrical and mechanical feedthroughs to the helium II bath at 1.8 K suggest values of around 1 W. However, measured thermal losses are at approximately 2 W. The difference is explained by the superfluid leaks at the valves and feedthroughs of the separation plate between the two bathes.

PRELIMINARY RESULTS ON MAGNET TESTING

The 8 Tesla dipole magnet model was tested at temperatures from around 1.6 K to 2.0 K in the 530 l helium II bath. The first quench occurred at a magnetic field of 8.5 T corresponding to a current strength of 9780 A. Around 65 % of the stored energy of 180 kJ were damped into an external resistor outside the cryostat. The remaining 65 kJ were absorbed by the coils and subsequently released into the helium II bath. No pressure rise occurred in the cryostat following the quench. The bath stayed superfluid as the temperature increased by 0.3 K only. This is due to the high heat capacity of superfluid helium and to the fairly large amount of helium in the cryostat. At subsequent tests quenches occurred at 8.9 T and at 9.0 T, respectively. Although the stored energy was slightly higher the bath temperature following a quench always remained well below 2.0 K.

CONCLUSION

The test station designed and built has proven to fulfil the requirements for the testing of a series of 1 m long dipole magnet models at temperatures as low as 1.6 K. Cooldown and subcooling procedures of the magnets have been defined and time requirements are reasonable even for series testing. Cooling performances of 9 W at 1.8 K are sufficient for all experiments envisaged. Tests of a superconducting magnet fabricated by European industry were successful and showed the advantages of superfluid helium. Magnetic fields of 9.0 Tesla could be obtained.

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Cooldown parameters	
Pressure in cryostat	1.7 bar
Mass flow rate	10 g/sec
Cooling power at the magnet (at $T > 150$ K)	1000 W
Cool down speed (magnet and auxiliary mass)	6 K/h
Temperature difference between coils and shrinking cylinder	$-15\text{K} \leq \Delta T \leq 0\text{K}$
Temperature difference between any two points of the magnet	≤ 25 K
<u>Time requirements</u>	
- Refrigeration from 300 K to 15 K	50 h
- Refrigeration to 4.2 K and filling	20 h
- Subcooling to 1.8 K	20 h
Total time	90 h

Table 1 - List of cooldown parameters

FIG.1 SIMPLIFIED FLOW SCHEME OF THE 1.8K TEST STATION

FIG.2 SCHEMATIC OF THE 1.8K CRYOGENIC TEST FACILITY

Subcooling parameters	
Average cooling speed (4.2 K - T_{λ})	0.2 K/h
Maximum cooling performance	13 W at 2.0 K
Maximum cooling performance	9 W at 1.8 K
Maximum cooling performance	4 W at 1.6 K
Lowest temperature obtained	1.5 K
Measured losses at 1.8 K	2 W

Table 2 - List of subcooling parameters