COOLING DOWN AND FIRST POWERING OF THE COMET SUPERCONDUCTING COILS

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*The new proton cyclotron COMET (**co**mpact **me**dical **t**herapy cyclotron) is under construction at the German company ACCEL Instruments GmbH in Bergisch-Gladbach near Cologne. The magnetic field of the cyclotron is generated by a superconducting coil manufactured using a Niobium-Titanium conductor. The quench test of this coil was successfully completed in December 2003. This paper gives a short description of the magnetic and the cooling system of the cyclotron. The results of the first cooling down, the first powering of the coil and the quench test are presented.*

INTRODUCTION

The testing of the magnetic and cryogenic systems is one of the main steps on the way to a well operating cyclotron. A short description of these systems and the testing procedure which took place at the workshop of the manufacturer ACCEL is given.

Magnet system

The magnet system of the cyclotron consists of two circular coils with a diameter of 1.835 m and a cross section of 128 mm x 93 mm placed 63 mm above and below the proton beam plane. Each coil has 3130 windings of a niobium-titanium superconductor (wire in channel type) with rectangular cross section (2.4 mm x 1.6 mm) of the copper matrix [1]. The design current is 160 Ampere which leads to a magnetic field up to 3.8 Tesla in the beam plane. Fig. 1 shows the winding mandrel and Fig. 2 the winding process of the coil. The coil is assembled in the iron yoke which has a total weight of 90 tons.

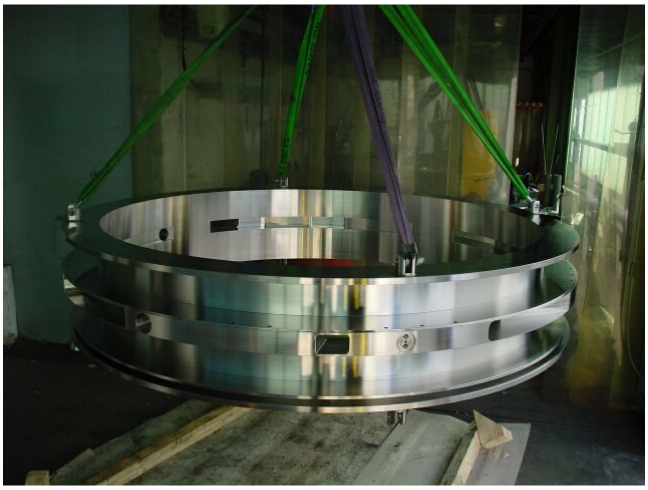

Fig. 1: The winding mandrel of the superconducting coil before winding (Photo by courtesy ACCEL).

Cooling system

The superconducting coil has to be kept at 4.2 Kelvin to allow the resistance free current transport. In order to achieve this, the coil is placed in a bath of liquid helium. To minimise the heat load in the 4.2 Kelvin cold area, the coil has to be mounted in an isolating cryostat. This magnet cryostat consists of several parts. The coil is surrounded by a stainless steel tank which holds the liquid helium. This tank is at liquid helium temperature and is placed in a second stainless steel tank at environmental temperature (~300 Kelvin). The space between these two tanks has to provide the thermal isolation. It is evacuated to prevent heat transport by convection (isolation vacuum). However, the heat transport by thermal radiation to the inner tank would be too high (>70 Watt) if no additional isolation scheme were used. A copper radiation shield is therefore placed in the isolation vacuum between the tanks. This thermal radiation shield is separately cooled to about 60 Kelvin. It shields the cold inner tank from thermal radiation from the warm outer tank.

In order to get even more thermal isolation, so-called super isolation foil is placed in several layers between inner tank, radiation shield and outer tank. With this isolation, the heat load is reduced to an estimated value of 2.14 Watt. It is then possible to keep the coil cold with active cooling using integrated cooling machines.

Fig. 2: Winding of the coil.

Because of the limited space in the iron yoke, it is not possible to integrate the cooling machines into the magnet cryostat. To solve this problem, an additional so-called supply cryostat is placed outside the iron yoke connected by a pipe to the magnet cryostat inside the iron yoke (Fig. 3 and Fig. 4). The supply cryostat holds a repository volume of liquid helium and contains four re-liquefier cold heads (2-stage Gifford-McMahon cold head from the company Sumitomo) with a cooling power of 1.5 Watt each at the 4 Kelvin level. Evaporating helium gas is condensed at the second stage of the cold head and falls back into the liquid helium reservoir. The first stages of the four cold heads are connected to the copper radiation shield and hold it at a temperature of 60 Kelvin (Fig. 5). Since no helium is lost during operation, this cooling system does not need replenishing with liquid helium. Additional components placed in the supply cryostat are the pressure feedback system and the electrical joints from the superconducting coil to the power supply. The latter are realised by HTC current leads. The pressure of the helium gas atmosphere above the liquid helium in the supply cryostat is held at a value slightly above atmospheric pressure (1.1 bar) by powering a small electrical heater at the bottom of the helium tank. Without this feedback system, the pressure in the supply cryostat would decrease due to the surplus cooling power and a contamination of the helium atmosphere could occur. The controlled pressure of 1.1 bar keeps the gas pure.

Fig. 3: Assembly of the magnet cryostat (Photo by courtesy of ACCEL).

FIRST TEST OF THE MAGNET AND COOLING SYSTEM

After the assembly of all relevant components of the magnet and cooling system, a test was scheduled to ensure the functionality of the cyclotron. The test takes place at the manufacturer's workshop and includes the following steps:

- The first cool down of the coil and cryostat to liquid helium temperature.
- The first powering of the coil to the design value (or a little bit higher).
- The quench test followed by a re-cooling and re-powering of the coil to the design values.

Cool down of the cryogenic system

For the cool down, it is important to control the temperature of the coil and the cryostat at several points. Therefore, four temperature sensors are placed at the coil and additional sensors at the radiation shield, the cold heads and the current leads. During cool down, the temperature differences within the coil should be smaller than 70 Kelvin because of mechanical stresses in the coil and winding mandrel.

The cool down procedure started with the controlled filling of the cryostat with liquid nitrogen. Liquid nitrogen was used because it is much cheaper and has a ten times higher enthalpy of vaporisation than liquid helium. When the liquid nitrogen temperature (77 Kelvin) was reached, the liquid nitrogen had to be removed from the cryostat. The liquid nitrogen was pumped back into the transportation dewar and the remaining liquid nitrogen was evaporated by an electrical heater at the bottom of the cryostat. The whole cryostat was then purged with helium gas.

Fig. 4: Mounting of the magnet cryostat in the iron yoke (Photo by courtesy of ACCEL).

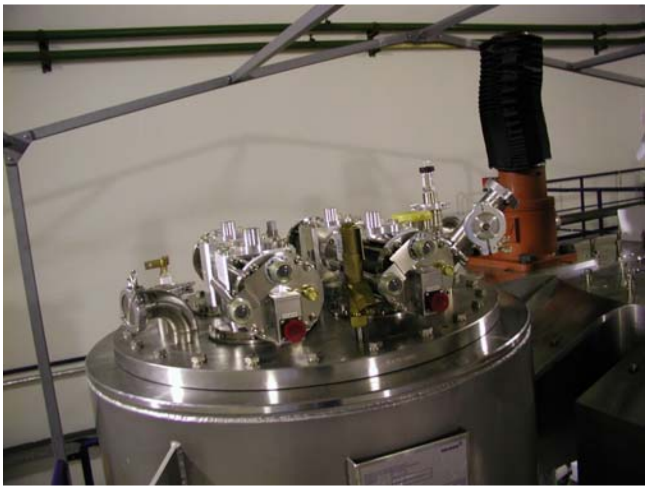

Fig. 5: The supply cryostat with four cold heads and instrumentation.

The cooling machines were then switched on and the cryostat filled with liquid helium. After the liquid helium temperature was reached, the cryostat was closed and the pressure feedback system switched on. The whole cooling down procedure required about 1500 litres of liquid nitrogen and 1500 litres of liquid helium and took roughly five days.

Using the data from the pressure feedback system, the heat balance of the cryogenic system could be measured. The power consumption of the feedback heater was 4 Watt. This would relate well to the expected cooling power of the cold heads (6 Watt) together with the estimated heat losses (2.14 Watt).

First powering of the coil

The most critical point during the first powering of the coil was the force between the iron yoke and the coil. If the coil is not accurately adjusted, unbalanced forces will occur. Therefore, 12 force sensors are installed to measure such forces and give the information for an adjustment of the coil. While the current was increased in small steps, the forces are minimised by vertical adjustment. The total required correction was 0.4 mm upwards.

The magnetic field was measured with a NMR probe placed in the centre of the cyclotron. Fig. 6 shows the measured value of 2.39 Tesla at 160 Ampere which is the design value at the position of the NMR probe. The current was successfully increased up to 170 A without any problem.

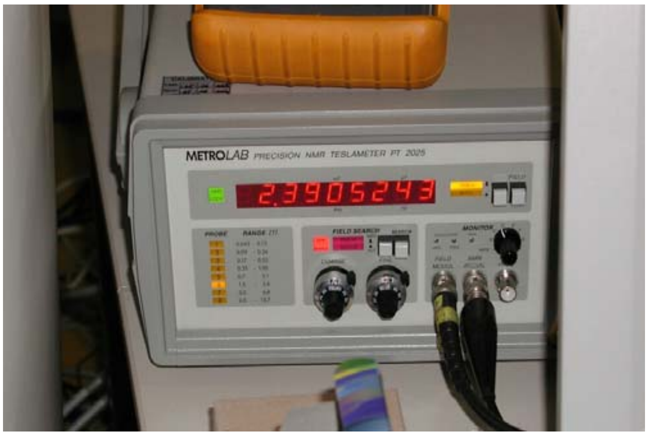

Fig. 6: NMR measurement of the magnetic field in the centre of the cyclotron with 160 A current.

Quench test

Quench is the breakdown of the superconducting condition in the conductor. This happens if the current density in the conductor is too high or the temperature is too high or the magnetic field is too high or a combination of all these factors occurs. The domain in the current density – temperature – field strength – space is characteristic for each superconducting material. For the COMET cyclotron, a conductor was chosen with a very high maximum current of over 1000 A, so that a quench is very unlikely.

In the design phase of the cyclotron project, the quench behaviour was calculated. At the point in the coil where the superconductivity breaks down, the electrical resistance of the copper matrix causes local heating. Due to the heating and heat conduction around the so-called hot spot, the surrounding windings became normal conducting as well. The velocity of the propagation of the normal conducting region was calculated at 0.3 m/s perpendicular to the wire and 1.0 m/s parallel to the wire. The coil becomes totally normal conducting about three seconds after the quench. Because of the high inductivity of ~200 Henry at 160 Ampere current, it takes about two minutes for the current to decay. The magnetic field energy of 2.4 MJ heats up the coil to ~50 Kelvin and the liquid helium is totally evaporated. The evaporating helium gas causes a pressure increase in the cryostat and a rupture disk, which was installed in the supply cryostat, breaks and the gas can escape rapidly to avoid damage by excessive pressure.

Special quench detection is implemented in the power supply of the coil. The quench detection electronics permanently measures the voltage drop over each coil. If there is a significant difference between the two voltages, a quench is identified and the power supply is switched off.

To test the functionality of the quench detection, the coil and the cryostat, a quench was intentionally initiated by powering a small heater on one coil. With a heating power of 6 Watt, a quench could be forced and the quench detection successfully tested. Fig. 7 shows the quench blow out.

To confirm the functionality of the coil and the cryostat following the quench, the coil was cooled down to liquid helium temperature and powered up to 160 A. This was successfully done and the former magnetic field was reached. The quench test was completely successful and an important milestone of the COMET project was reached.

Fig. 7: Supply cryostat with the exhausting helium gas at the quench.

CONCLUSION

The successful completion of the first cooling down, the first powering of the coil and the quenching of the coil are very important steps in the COMET project. The field mapping and shimming of the magnet are the next tasks necessary to ensure a good magnetic field for the cyclotron to operate with.

REFERENCES

[1] M.N. Wilson, *Superconducting Magnets*, Oxford, Clarendon Press, 1989.