High Temperature Superconducting Magnets for use in Electron Cyclotron Resonance Ion Sources

Stephen Harrison, Steve Milward, Richard McMahon, Claude Bieth, Saïd Kantas, and Pascal Sortais

***Abstract*—Ion sources using electron cyclotron resonance (ECR) require magnets to generate a particular field profile. High temperature superconducting (HTS) magnets offer advantages in power density, efficiency and the overall simplicity of the system. Space Cryomagnetics Ltd of Culham, England, has designed and manufactured HTS magnets for an ion source for Pantechnik in France, and is currently developing a second, more powerful system for the Laboratoire de Physique Subatomique et de Cosmologie (LPSC) in Grenoble, France. This paper describes the design, manufacture and test results of the first of these systems, and the current status of the design and manufacture of the second.**

***Index Terms*—High-temperature superconductors, Superconducting magnets, Ion sources, Cyclotron resonance.**

I. INTRODUCTION

THE standard ECR ion sources manufactured by Pantechnik operate at frequencies up to 14.5 GHz, producing more than 550 μAe of Ar8+ and 15 μAe of Pb25+ ions. They employ a pair of water-cooled resistive magnets to generate axial fields of up to 1.3 T. By replacing the resistive coils with HTS magnets, the axial field has been increased to 1.8 T while preserving the dimensions of the system. This allows the source to operate at 18 GHz with enhanced performance, at the same time reducing the power consumption from 200 kW to 20 kW.

Following the successful operation of the ion source - with the HTS magnets fully integrated - a second project has been started at LPSC to build a more powerful source, using HTS magnets to generate the higher fields required. The demands placed on the magnets are significantly higher.

II. MAGNETIC DESIGN

A description of the design of the HTS magnets for the Pantechnik system has been published previously [1]. Table I shows some of the key parameters of the magnets for Pantechnik and LPSC together, to illustrate some of the differences between them.

TABLE I
KEY PARAMETERS OF THE HTS MAGNETS

Parameter	Pantechnik magnet	LPSC magnet
Conductor	BSCCO-2223	BSCCO-2223
Operating temperature	23 K	20 K
Operating current	181 A (injection coil) 145 A (extraction coil)	175 A (both coils)
Peak field on the axis	1.8 T	3.1 T
Peak conductor field	3.0 T	4.1 T
Peak radial field	1.4 T	2.0 T
Number of pancakes	10	16
Inner coil diameter	240 mm	160 mm
Outer coil diameter	320 mm	288 mm

The new magnet for LPSC will operate at a very similar current, but the smaller inner diameter ensures that the fields are considerably higher: this impacts on both the thermal and mechanical designs.

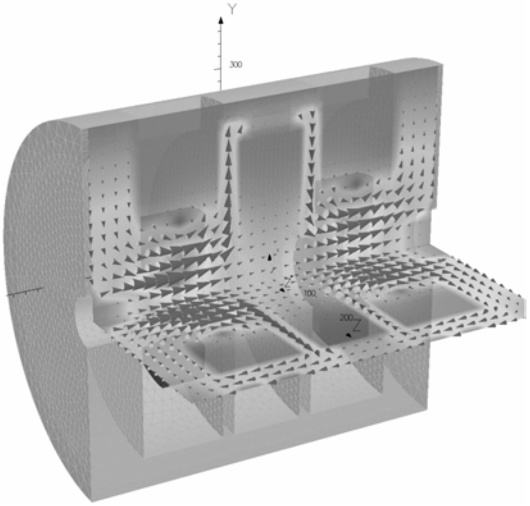

Fig. 1. Magnetic model of the LPSC magnets inside the iron. The coils and iron are designed to meet the required field profile.

Fig. 1 shows a cross-section through the coils and iron of the LPSC system, from the magnetic finite element model. The two coils and iron together produce a field along the axis with two carefully-defined peaks (Fig. 2). As in the

---

Manuscript received October 4, 2004.

S. Harrison, S. Milward, and R. McMahon are with Space Cryomagnetics Ltd, E1 Culham Science Centre, Abingdon OX14 3DB, UK (phone: +44-1865-409200; fax: +44-1865-409222; e-mail: info@spacecryo.co.uk).

C. Bieth and S. Kantas are with Pantechnik, 12 rue Alfred Kastler, 14000 Caen, France.

P. Sortais is with the Laboratoire de Physique Subatomique et de Cosmologie, 53 Avenue des Martyrs, 38026 Grenoble, France.

Pantechnik ion source, the peak field at the injection coil has to be slightly higher than that at the extraction coil. In the Pantechnik system, the two coils are identical but the different fields are generated by charging the coils to different currents. In the LPSC system, the coils are again identical but they run at the same current: the variation in field strength is achieved by careful design of the iron.

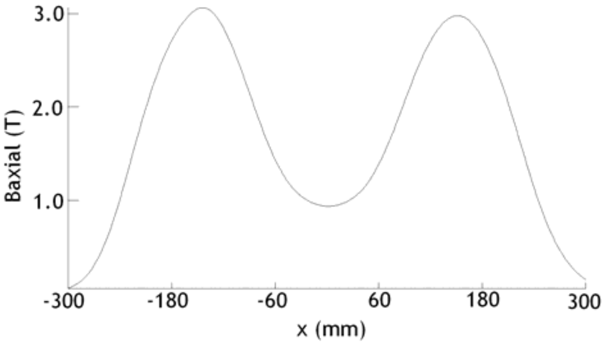

Fig. 2. Calculated axial magnetic flux density along the LPSC ion source axis.

III. CRYOGENIC DESIGN

The magnets are designed to operate without cryogens, using single-stage Gifford McMahon cryocoolers: for operational reasons, each coil is required to have its own cooler. In principle, two-stage coolers could be used. This would allow the coils to be operated at a lower temperature using less of the expensive HTS wire at a higher current. However, the increased complexity of the cryostat probably more than accounts for any cost saving in the conductor.

The size of the cryocooler is determined essentially by the operating current of the magnet and the radial field on the HTS conductor. By far the majority of the heat load comes from the current leads, and can be estimated from the equation

$$Q = I\sqrt{L_0\left(T_1^2 - T_2^2\right)}$$

where Q is the heat load per lead, I is the lead current, L_0 is the Lorentz ratio, and T_1 and T_2 are the temperatures of the ends of the lead [2]. A magnet operating at 175 A, with a pair of current leads thermally anchored at room temperature and at 25 K, will therefore require more than 16 W of cooling at the 25 K heat sink, just to allow the leads to operate stably.

Because the transition from superconducting to resistive behaviour takes place over a wide temperature range, detailed thermal modeling is required to establish the maximum operating temperature of the coil. This is very sensitive to the magnetic field perpendicular to the plane of the conductor: field in the radial direction is crucial. For this reason, the LPSC magnets will have to operate at a lower temperature than the Pantechnik coils – even though the current is lower – as the radial field has been increased from 1.4 to 2.0 T (see Table I).

The operating temperature together with the heat loads from the current leads and other sources (chiefly radiation and mechanical supports) can be used to specify the performance of the cryocoolers. The Pantechnik coils used Al-230 cryocoolers supplied by Cryomech, capable of removing 29 W at 23 K. Because the operating temperature of the LPSC magnets needs to be a little lower (owing to the higher radial field), the performance of the Al-230 cooler would be marginal, so for this system a larger cooler will be used.

IV. MECHANICAL DESIGN

The mechanical designs of the magnets for the two ion sources are very similar. Each coil has a separate stainless steel vacuum vessel, from which it is cantilevered on six fibreglass supports. These supports are designed to withstand the loads generated in normal operation, in fault conditions, and during transit. By far the highest loads are the magnetic forces due to faults such as displacement of one of the coils, or charging one of the coils in the wrong polarity.

The forces are strongly dependent on the magnetic field, so they are considerably higher in the LPSC coils (66 kN) than in the Pantechnik system (10 kN). Even with forces this high, the heat load from the supports is only a small fraction of that from the current leads. Nevertheless, careful design is required to avoid cold spots on the outside of the vacuum vessel, or warm regions on the surface of the coil.

V. TRANSIENT ANALYSIS

The specific heat capacities of materials at 20 or 25 K are much higher than at the temperatures typical for operation of low temperature superconductors (typically less than 5 K). This makes an HTS coil potentially more stable against quenching than an equivalent low temperature superconducting (LTS) magnet. By contrast, thermal conductivities of materials typically used in magnets are much lower at the higher temperature, so a quench – once initiated – propagates more slowly.

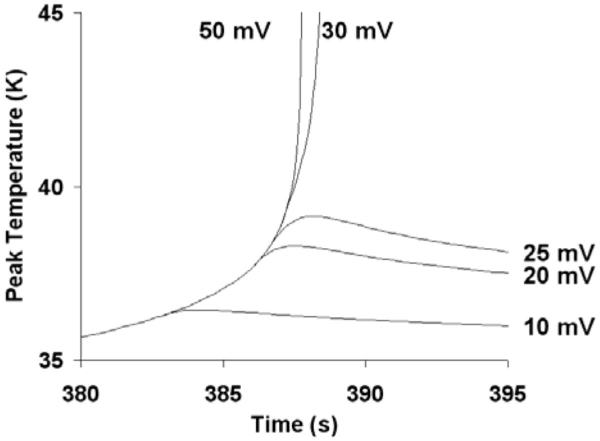

Fig. 3. Transient analysis of a single pancake winding from the LPSC coil. Cooling is removed at time t = 0: the coil gradually warms up due to dissipation and parasitic heat loads. The plot shows the maximum temperature reached in the coil as a function of time, for various quench detection thresholds.

For this reason, quench detection is required, with interlocks which discharge the magnet through an external dump resistor if voltage or temperature thresholds are exceeded. Fig. 3 shows the results of transient thermal modeling of part of an LPSC coil.

In the model, the coil is operating normally at full current (175 A). At zero time, the cryocooler is assumed to fail and no more heat is removed from the coil, which warms up due to its own dissipation and the heat load from the supports. When the voltage reaches a threshold level, a 100 mΩ external dump resistor is connected across the coil to discharge the magnet rapidly. The figure shows that if the threshold is set to 25 mV, the magnet discharges safely. At a level of 30 mV, however, thermal runaway ensues which would lead to permanent damage to the coil. For some margin of safety, voltages will be monitored across each adjacent pair of pancakes on the LPSC coils, with the threshold set to 10 mV. A similar approach was used successfully on the Pantechnik magnets.

Fig. 4. Assembly of a completed coil into its vacuum vessel.

VI. HTS COIL MANUFACTURE

Manufacture and assembly of the LPSC magnets has only just started, but will follow the same process as the Pantechnik coils described below.

The HTS conductor used was BSCCO-2223, supplied by American Superconductor Corporation (AMSC), in the form of a tape laminated with a strip of stainless steel [3]. This gives the wire considerable strength, and makes it suitably robust for coil winding using normal industrial equipment. The conductor was wound into single pancakes, joined at the inner and outer radii to build up the coils. Fibreglass was used for insulation between adjacent layers and pancakes. After winding, the coils were impregnated with epoxy resin for mechanical stability and integrity. Finally, flexible thermal links were attached to the coils, for transferring heat to the cryocoolers.

VII. CRYOSTAT ASSEMBLY

After impregnation, the coils were ready for integration into their cryostats. The cantilever supports were attached to the coils, which were then insulated using double aluminised Mylar. Each insulated coil was then lowered into its toroidal vacuum case (Fig. 4) and the flat closures fitted. Services (current leads, instrumentation wires, and the thermal link connecting the coil to the cryocooler) were brought out through a port in the outer diameter, for connection to the cryocooler and electrical interfaces.

Fig. 5. Two HTS magnets integrated into the iron from the ion source.

VIII. MAGNET SYSTEM TESTING

After the magnets were assembled into their cryostats, an extensive testing programme was started. Initial testing was undertaken before assembly into the iron: this allowed the electronics and cryogenic system to be tested, but the coils could only be operated up to 83% of their nominal current because – in the absence of the iron – the radial field component was higher.

Following the successful completion of these preliminary tests, the coils were assembled into the ion source (Fig. 5) and cooled down using the cryocoolers (Fig. 6).

Both coils were then operated simultaneously at full field, with 181 A and 145 A applied to the injection and extraction coils respectively. A field plot along the axis (Fig. 7) showed that the required flux density of 1.8 T had been achieved.

At various times during testing the electronic protection

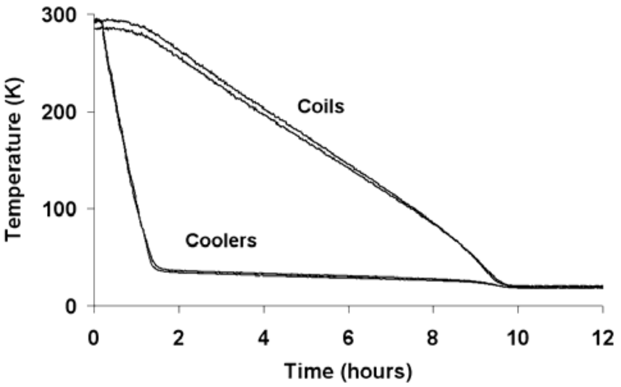

Fig. 6. Cool down of the HTS magnets. The cold heads of the cryocoolers chilled rapidly to 30 K, followed much more slowly by the coils.

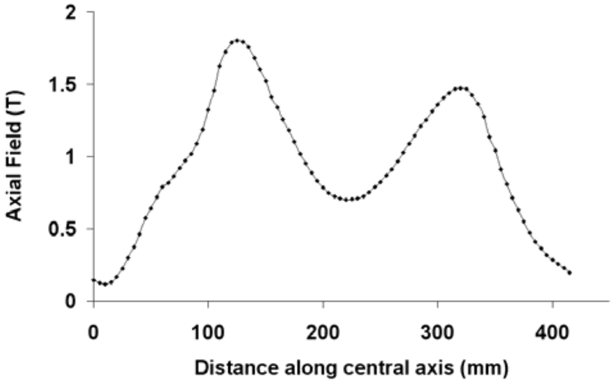

Fig. 7. Plot of the axial field along the axis of the HTS magnets in the Pantechnik ion source. The higher peak is 1.8 T.

system was checked. The coils were automatically discharged when voltage, current, and temperature thresholds were exceeded: in all cases the coils were able to operate again with no degradation of performance.

IX. CONCLUSION

After successful testing and commissioning of the HTS magnet system, the ion source underwent beam testing and was shipped to the end user at the end of 2003.

The successful conclusion to the Pantechnik project demonstrates that HTS magnets have useful applications in ECR ion sources. The new project at LPSC is an ideal opportunity to build on this success by further development of the HTS magnet technology.

REFERENCES

[1] R. McMahon, S. Harrison, S. Milward, et al., "Design and manufacture of high temperature superconducting magnets for an electron cyclotron resonance ion source," *IEEE Transactions on Applied Superconductivity*, vol. 14, no. 2, to be published.

[2] M. N. Wilson, *Superconducting Magnets*. Oxford University Press, 1983, p. 260

[3] Y. B. Huang "Progress in Bi-2223 tape performance," *Advances in Cryogenic Engineering (Materials)*, vol. 48B, pp. 717-723, July 2001.