APPLICATION CONCEPTS OF SMALL REGENERATIVE CRYOCOOLERS IN SUPERCONDUCTING MAGNET SYSTEMS

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Superconducting magnets are in growing use outside laboratories for example MRI scanners in hospitals. Other applications under development are magnet systems for separation, levitated trains and ship propulsion. The application of cryocoolers can make these systems more practical. Interfacing these cryocoolers to the magnets can be designed in several different ways. The four basic methods will be dealt with. Test results of a realized GM cryocooler-SC magnet system will be shown. It handles about a 1:3 scale MRI magnet of which one of the six coils has been successfully tested at temperatures between 10 and 14 K.

INTRODUCTION

Relatively small SC magnets can be economically cooled by cryocoolers. Each application has its own user needs but most of them have in common [1]:

- high reliability (an MTBF > 8000 hrs)
- minimum maintenance
- quiet and noiseless
- efficient
- small in size compared with the object to be cooled
- cost competitive
- no interference with the magnetic field

The cryocoolers to be used are most likely Stirling, Vuilleumier or Gifford-McMahon machines. The temperatures that can be reached are typically 8 K. When a thermal load and the interface between cooler and magnet is added the temperature of the magnet will be in the range 10-14 K depending on the system. In any case it implies the use of Nb₃Sn superconductor or in the future HTc conductors like Bi based tapes. When a JT-loop is added to the cooling system then it is possible to use the reliable and inexpensive NbTi.

INTERFACING CRYOCOOLERS AND SC MAGNETS

Basically there exist four types of interfaces:

- He bath cooling with an added JT-loop [2]
- indirect LHe cooling using a thermosifon and a JT-loop [3]
- indirect GHe cooling using a forced flow system
- cooling by means of conduction only [4].

A JT-loop requires a more complex system although there is the advantage to use NbTi. When the cooling is involved with LHe or GHe it is the cryostat which becomes more complex. A conduction cooled system is inherently simple, reliable and deficient in maintenance. It depends on the type of magnet system which type of interface and cryocooler is preferable. We will consider five examples of SC magnets as there are MRI [4], high gradient magnetic separation [5], magnetic train levitation [6], homopolar motors for ship propulsion [7], and linear motors application in steel making processes [8]. The preferable configurations are shown in Table 1. To our opinion the combination of GM coolers and a dry MRI system for 10-14 K is a good solution, as presented in the next section.

A MAGNET SYSTEM INCORPORATING CRYOCOOLERS

In our laboratory a conduction cooled magnet system has been developed which can be

Table 1 Preferable configurations for cooling interfaces

Interface		He bath	ind. LHe	ind. GHe	conduction
Temperature (K)		JT 4.2	JT 4.2	10-14	10-14
Magnet	MRI	GM	S	S	GM
	HGMS	GM	S	S	GM
	MAGLEV	GM	S	S	GM
	Ship	GM	S	S	GM
	LIM	V	S	S	V

S: Stirling V: Vuilleumier GM: Gifford-McMahon

seen as a 1:3 scale MRI magnet. It is cooled by two GM cryocoolers [9], [10]. The general layout and the winding cross section is shown in Figure 1 and Figure 2. The conductor is a Nb₃Sn wire with a diameter of 0.6 mm and is isolated with a glass braid. The coil is wound, then reacted followed by a vacuum impregnating process. The heat loads on the system are shown in Table 2 while the main magnet parameters are given in Table 3.

Table 2 Heat loads on the system in W

	Shield 50 K	Magnet 12 K
Radiation	20	0.008
Conduction	2.2	0.012
Power leads	9.2	0.78
Summation	31.4	0.8

Table 3 Main magnet parameters

Magnet bore	400 mm	Central field	1.0 T
Warm bore	330 mm	Max. field	1.9 T
Magnet length	600 mm	Shield mass	45 kg
Operating current	100 A	12 K cold mass	65 kg

TEST RESULTS

The first tests were performed with one of the six coils e.g. the third coil from the cold head side. The cold mass of this coil including all thermal, electrical and mechanical connections is 13 kg. The cooldown curves are shown in Figure 3. With two cold heads and two compressors of the types RGD 580 and RW 5 from Leybold respectively connected to a shield of 45 kg the cooldown time was roughly about 1 hr/kg. A similar performance was observed for other previously installed cold masses varying unto 45 kg.

The temperature gradients over the magnet when it was energized are shown in Figure 4. The origin of this gradient lies in the fact that the lead terminals are opposing each other. At 140 A the coil quenched. There were no training effects noticed to reach this current. The maximum temperature gradient over the magnet during a quench is shown in Figure 5. The coil is ramped to 140 A and the temperature starts slowly to rise while the quench follows after some 6 minutes.

These results are obtained with cold heads where the second stage regenerator

material is the usual Pb. The regenerator matrix was then replaced by the new material Er3Ni and the cooling down was repeated showing practically the same curves as in the case of the Pb matrix. The end temperatures of the cold heads and the magnet are indeed lower and are summarized in Table 4.

Table 4 End temperatures for two regenerator materials in K

		Cold head	Coil
Regenerator:	Pb	9.2 K	10.3 K
	Er3Ni	7.3 K	8.9 K

CONCLUSIONS

It was shown that it is possible to create a conduction cooled Nb3Sn magnet system which can be cooled down within a reasonable time and reaching its maximum current without training.

The exchange of the Pb regenerator matrix by Er3Ni showed no difference in the cooldown behaviour of the system. The end temperatures of the magnet are indeed lowered with 1.4 K.

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Figure 1 General layout of the magnet system

Figure 2 The construction of coil number 3

Figure 3 The cooling down of coil number 3

Figure 4 The maximum temperature gradients over the coil windings as a function of the energizing current

Figure 5 The maximum temperature gradient over the coil winding after a quench at 140 A