N92-27789

MAGNETIC SUSPENSION USING HIGH TEMPERATURE SUPERCONDUCTING CORES

R G Scurlock
Institute of Cryogenics, University of Southampton, UK

SUMMARY

The development of YBCO high temperature superconductor, in wire and tape forms, is rapidly approaching the point where the bulk transport current density j vs magnetic field H characteristics with liquid nitrogen cooling will enable its use in model cores. On the other hand, BSCCO high temperature superconductor in wire form has poor j-H characteristics at 77K today, although with liquid helium or hydrogen cooling, it appears to be superior to NbTi superconductor.

Since liquid nitrogen cooling is approximately 100 times cheaper than liquid helium cooling, the use of YBCO is very attractive for use in magnetic suspension.

This paper discusses the design of a model core to accommodate lift and drag loads up to 6000 and 3000 N respectively. A comparison is made between the design performance of a liquid helium cooled NbTi (or BSCCO) superconducting core and a liquid nitrogen cooled YBCO superconducting core.

INTRODUCTION

The concept of using a superconducting core with a persistent mode energising current, contained within a free-flying, liquid helium cooled cryostat was successfully demonstrated with a Mark I model at Southampton, UK in a wind-tunnel magnetic suspension system in 1981(1)(2). A subsequent design for a Mark 2 free-flying cryostat 800 mm long 126 mm diameter with a liquid helium cooled superconducting core was made in 1984(3). This cryostat accommodated lift and drag loads up to 6000N and 3000N respectively and had a sufficiently low liquid helium boil-off to enable polars to be taken over a working period of 3 hours. The solenoid design used a 40A NbTi conductor operating in a central field of 6.5T at a current density of 3 10^4A/cm^2 yielding a magnetic moment of approximately 30 x 10^{-3} Weber metre. A further design(4) for a shortened (450 mm long) version called the Mark 1½ cryostat, was made in 1985 which included all the featurs of the Mark 2 cryostat; the shorter length enabled the cryostat to be flight tested in the existing magnetic suspension system at Southampton. An additional feature was the introduction of superconducting roll coils in the bore of the main solenoid.

With the discovery and development of high temperature superconductors with critical temperatures above 90K, it is particularly worthwhile to examine the use of these new materials, in the persistent energised mode, for the model cores of a magnetic suspension system.

HIGH TEMPERATURE SUPERCONDUCTORS

Since 1986, a number of materials have been discovered with superconducting transition temperatures significantly higher than those of the liquid helium cooled Type II superconductors of the 1960's and 1970's.

Figure 1 gives a summary of the present position (August 1991) regarding the j-H bulk current density versus magnetic field performance of these new superconductors in comparison with the performance of the widely used liquid helium cooled NbTi and Nb_3Sn superconductors. The data in Figure 1 is for current carrying conductors in wire, tape or thick film form - not thin films ($< 1\mu$ thick) for which much higher current densities j are observed.

The most significant indication from Figure 1 is that current densities in excess of $10^4 A/cm^2$ at 6.5T can be achieved at a temperature of 77K with YBCO and at 20K with BSCCO. There are, of course, development problems to be overcome at this stage, because these high temperature superconductors are composed of brittle ceramic materials. However, many research laboratories throughout the world are addressing these problems in order to realise the potential of high temperature superconductors in a wide range of applications. For example, current contacts, superconducting joints, persistent current switches, and the construction of composite thermally stabilised and load bearing conductors, are all areas being widely addressed.

THE COOLING OF HIGH TEMPERATURE SUPERCONDUCTORS

While the performance of BSCCO may be realised using liquid hydrogen at 20K, the performance of YBCO requires liquid nitrogen cooling at 77K. No expensive liquid cryogen is required; only low cost liquid nitrogen at perhaps 1-5% of the cost of liquid helium. Unlike liquid helium with its low heat of vaporisation, liquid nitrogen has a latent heat per unit mass some 10 times larger. Taking into account the density difference (a ratio of approximately 6), the volume of liquid nitrogen required to absorb a given heat load is therefore about 60 times smaller. Alternatively, for the same volume of cryogen, one can accept a heat influx 60 times larger and maintain the same operating time.

CRYOSTAT CONTAINMENT AND THERMAL INSULATION

With liquid nitrogen cooling, the limitations of vacuum insulation are no longer necessary for containment. This means that the simplicity of plastic foam insulations is available to provide the necessary thermal insulation. However in the case of the model core, the volume of insulation space needs to be minimised to accommodate the necessary volume of superconducting solenoid to provide the maximum magnetic moment. It would therefore appear that this is one exception where vacuum insulation can be retained beneficially. The core cylindrical geometry, of course, lends itself to vacuum anyway. Table I provides an indication of the relative performance of different types of insulation across 2.5 cm thickness between 300 and 77K.

Table I shows quite clearly that 4mm of multi-layer insulation MLI in vacuum yields a heat flux approximately 100 times lower than 25mm of polyurethane foam, and 4 times lower than 25mm of evacuated perlite powder.

The conclusion is quite clear; keep to evacuated MLI for minimum heat flux if the thickness of the insulation space is to be minimised.

HIGH LIFT AND DRAG LOADS

The lift and drag loads have to be transferred from the solenoid core to the outer wall of the cryostat through the insulation space, and thence to the model. A number of options are available for transferring these loads. With a high temperature superconducting core, it is tempting to consider the use of plastic foam (Option A) to provide the insulation as well as to transfer the flight loads. The alternative option, Option B, is to use an array of suitable high strength struts in an evacuated enclosure of MLI.

In examining these 2 options, it should be noted that there are 2 operational modes (I) high load flight conditions during polars (II) low load, holding conditions in between polars.

Option A and mode I require a foam capable of transmitting a transverse (radial) load of 6000 N across an area of approximately 50 cm^2 representing a loading of 1 MPa at 77 K; and a longitudinal load of 3000 N across an area of approximately 25 cm^2 representing the same loading per unit area. For acceptable nesting of the core, the foam must clearly not suffer any permanent deformation, otherwise the required tight fit of the core will be lost. We therefore need a high density, load-bearing foam which retains its elasticity at 77K up to 1 MPa.

Option A and mode II require the foam to carry zero flight loads only. However, the heat flux is likely to be relatively insensitive to loading, up to the elastic limit of the foam. It follows that Option A will lead to the same high heating loads during both operating modes.

Option B in Mode I requires the use of high strength radial struts to carry the flight loads. To transmit a radial load of 6000 N in compression, the minimum cross section of 304 stainless steel strut would be 6 mm^2. For epoxy glass fibre laminate in compression, the minimum cross section would be 12 mm^2. However, the thermal conductance of the epoxy laminate strut would be 5-10 times lower. The drag load of 3000N may be carried by one or more axial rods of epoxy glass fibre in tension.

Option B in mode II requires a much lower strength strut system to yield minimum heat flux during extended periods of holding. The simplest approach is to adopt a dual suspension system, a weak one for B (II) which holds off a strong B(I) system from any thermal contact thereby maintaining a low thermal conductance state in mode II. The system distorts elastically under high flight loads in mode I operation to allow the strong system to take over in a higher thermal conductance state. These dual suspension systems have been used successfully in the past for rocket-launching cryogenic equipment into space. The weak suspension can be achieved via a dished or cone-shaped strut system, while the strong suspension has a co-planar structure such as an 8-pointed star cut from a thick sheet of epoxy resin. (Figures 2, 3, and 4). While such a dual suspension is essential for the liquid helium cooled superconducting core, it may not be necessary for the liquid nitrogen cooled core.

LIQUID HANDLING, FILLING AND LOW BOIL OFF

The model core geometry requires the liquid fill and vapour vent lines to be at one, or both, ends. One end is preferred to enable unimpeded differential thermal contraction to take place. Since the cryostat is required to operate with its axis horizontal and at variable angles to the horizontal, the liquid fill line must contain a cold liquid/vapour separator. The simplest solution is for the liquid fill line to include a single turn 360° helical turn inside the insulated space. This requirement is not required for the vent-line, provided a vapour/liquid separator is included inside the cryostat. However, vapour cooling of the current leads to the solenoid must be provided, and the simplest solution is to enclose the current leads in the vapour vent line. If the cooled length of the leads cannot be met via a re-entrant vacuum insulated end bush, then it may be necessary to include a segment of a helical turn, say 90° in the insulated space.

DESIGN AND PREDICTED PERFORMANCE

The performance of a Mark 2 LHe cooled NbTi superconductor core and cryostat is compared in Table II with that of a Mark 3 LIN cooled YBCO core and cryostat designed to the same overall dimensions of 800 mm length, 126 mm diameter. Figure 2 is a schematic diagram of the 2 cryostats, while Figures 3 and 4 indicate the detailed construction of the ends of the 2 cryostats respectively. The main difference in construction lies with the absence of the intermediate temperature, vapour-cooled shield around the YBCO core, which was a necessity with the NbTi core in order to reduce the liquid helium boil-off to an acceptable performance level. This allows an increase in diameter of the winding space of some 5 mm, and an increase in length of 50 mm. Together, these changes allow an increase in volume of 16% of the winding volume, and a corresponding increase in magnetic moment for the same current density.

CONCLUSIONS

(i) For the liquid helium cooled core, the difference in heat leak between Mode I and Mode II operation is a factor of 5. For the liquid nitrogen cooled core, on the other hand, the estimated difference in heat leak is much smaller at 25%. It is therefore concluded that while the dual suspension system is vital for incorporation in the liquid helium cooled cryostat, it may be unnecessary to introduce this complication with the liquid nitrogen cooled cryostat.

(ii) While the duration of cryogen for the liquid helium cooled system meets the specification for 3 hours operation under Mode I operation, the liquid nitrogen hold times are excessively long. It might therefore be advantageous to increase the winding volume of the solenoid by 1.5 10^6 mm^3 thereby reducing the liquid nitrogen volume by 50%.

(iii) The energisation of a NbTi superconducting solenoid in the persistent current state is standard practise using superconducting switches or shunts across the solenoid windings. The use of YBCO superconductor in a persistent current state is yet to be demonstrated. However the formation of truly superconducting (zero resistance) joints with zero Joule heating between ceramic wires or tapes, which a conventional liquid helium cooled superconducting switch requires, may not be essential bearing in mind that the excess cooling capacity by evaporation of the liquid nitrogen would be capable of absorbing a few watts of Joule heating.

(iv) Associated with (iii), another source of Joule heating with an YBCO solenoid in the persistent current state is the phenomenon of flux creep and decay. As observed at present, the magnetisation decays exponentially to a lower steady-state value. Depending on the time constant and the magnitude of the decay (the order of a few per cent) this might be a problem until the steady state magnetisation state was reached.

(v) Like other applications of high temperature superconductors, the ease with which liquid nitrogen cooling can be used, together with the simplicity of the cryogenic engineering design of the necessary cryostat, makes the future use of these materials in a magnetic suspension system extremely attractive.

REFERENCES

1. Wu, Y.Y.: "Design of a horizontal liquid helium cryostat for refrigerating a flying superconducting magnet in a wind-tunnel". University of Southampton M.Sc thesis (December 1981) NASA-CR-165980, August 1982

2. Britcher, C.P.; Goodyer, M.J.; Scurlock, R.G.; and Wu, Y.Y.: "A flying superconducting magnet and cryostat for magnetic suspension of wind tunnel models". Cryogenics 24, pp 185-189 1989

3. Boom, R.W.; Eyssa, Y.M.; McIntosh, G.E.; Abdelsalem, M.K.; Scurlock, R.G.; Wu, Y.Y.; Goodyer, M.J.; Balcerek, K.; Eskins, J,; Britcher, C.P.: "Superconducting electromagnets for large wind tunnel magnetic suspension and balance systems". Proc. Applied Superconductivity Conference, San Diego, Paper FL-3, 1984

4. Goodyer, M.J.; and Scurlock, R.G.: "Research into superconducting solenoid models for large MSB systems". NASA NSG 7523, 1985

TABLE I. - PERFORMANCE OF INSULATION

Material	**Heat flow (W) across 2.5 cm thickness 1 m^2 area between 300 and 77 K**
Stainless steel	160,000
Epoxy-glass fibre laminate	2,800
Polyurethane foam	200
Perlite powder + vacuum	8
Multi-layer reflectors + vacuum	0.3
Vacuum in glass (across 1-4mm)	500
Vacuum in glass with silvering (across 1-4mm)	8
Vacuum in metal with multi-layer reflectors (across 4mm)	2

TABLE II. - CRYOSTAT DESIGNS

	NbTi core Mark 2 Helium cryostat	YBCO core Mark 3 LIN cryostat
Overall length (mm)	800	800
Overall diameter (mm)	126.2	126.2
Overall volume (mm^3)	$9.90\ 10^{6}$	$9.90\ 10^{6}$
Length of winding space (mm)	650	700
OD of winding space (mm)	107	112
ID of winding space (mm)	75	75
Current density in winding space A/cm^2	$3\ 10^{4}$	$3\ 10^{4}$
Field at centre (Tesla)	6.5	6.5
Magnetic moment (Weber m)	$29.5\ 10^{-3}$	$34.8\ 10^{-3}$
Magnetic moment of Vanadium/Permender occupying cryostat volume	$15.7\ 10^{-3}$	$15.7\ 10^{-3}$
S/C magnet moment/VP moment	1.88	2.22
Length of cryogen container (mm)	690	720
OD of cryogen container (mm)	108	115
Volume of cryogen container (mm^3)	$6.3\ 10^{6}$	$7.4\ 10^{6}$
Volume of cryogen (allowing for core) cm^3	3000	3400
Heat inleak Mode I operation (mW)	700	2300
Boil-off rate Mode I (cm^3/hr)	1000	60
Duration of cryogen Mode I operation (hours)	3	50
Heat inleak Mode II operation (mW)	140	1800
Boil-off rate Mode II operation (cm^3/hr)	200	45
Duration of cryogen Mode II operation (hours)	15	66

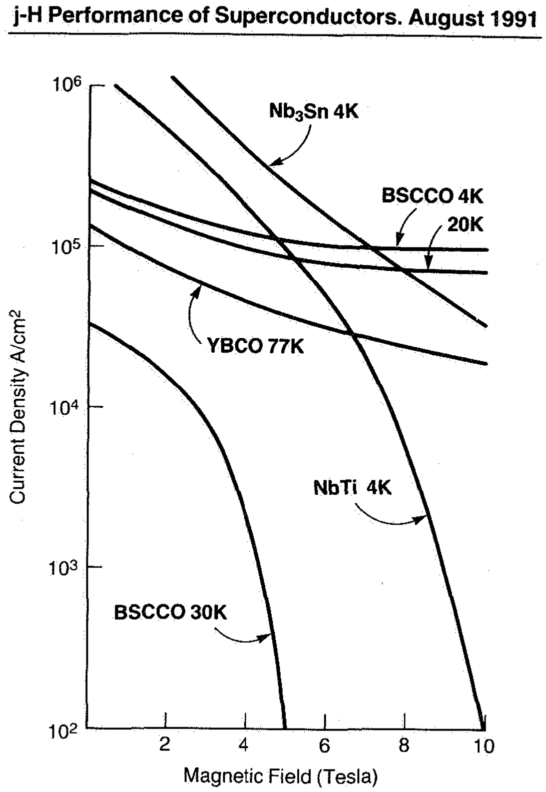
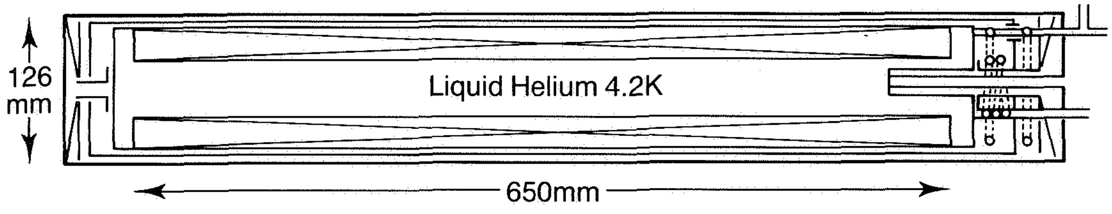
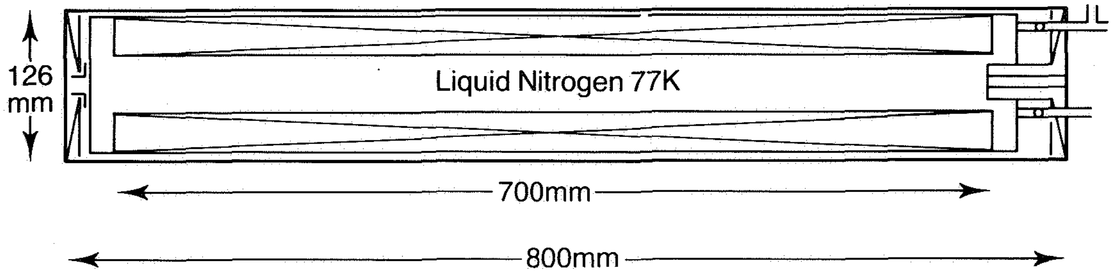


Figure 1. Current density vs magnetic field j-H performance of superconductors August 1991



Flying Cryostat and NbTi Solenoid Mark 2



Flying Cryostat and YBCO Solenoid Mark 3

Figure 2. Schematic of flying cryostats using liquid helium cooled NbTi (Mark 2) and liquid nitrogen cooled YBCO (Mark 3) solenoids

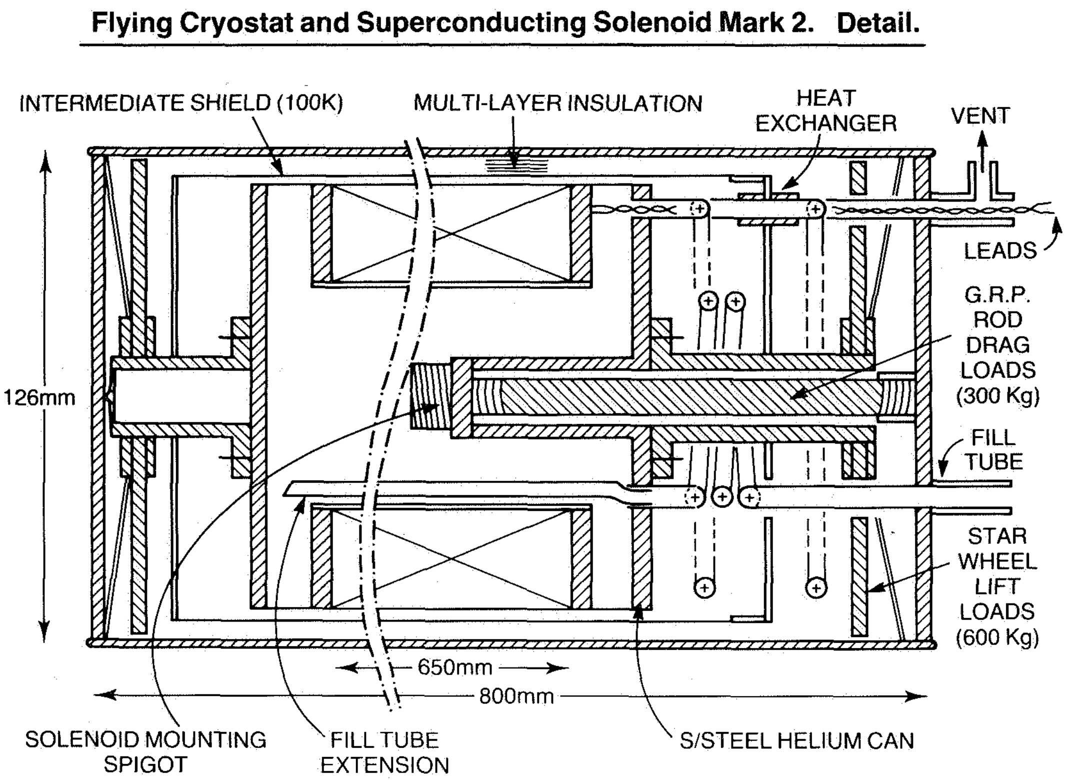


Figure 3. Detail of flying cryostat and liquid helium cooled NbTi solenoid Mark 2

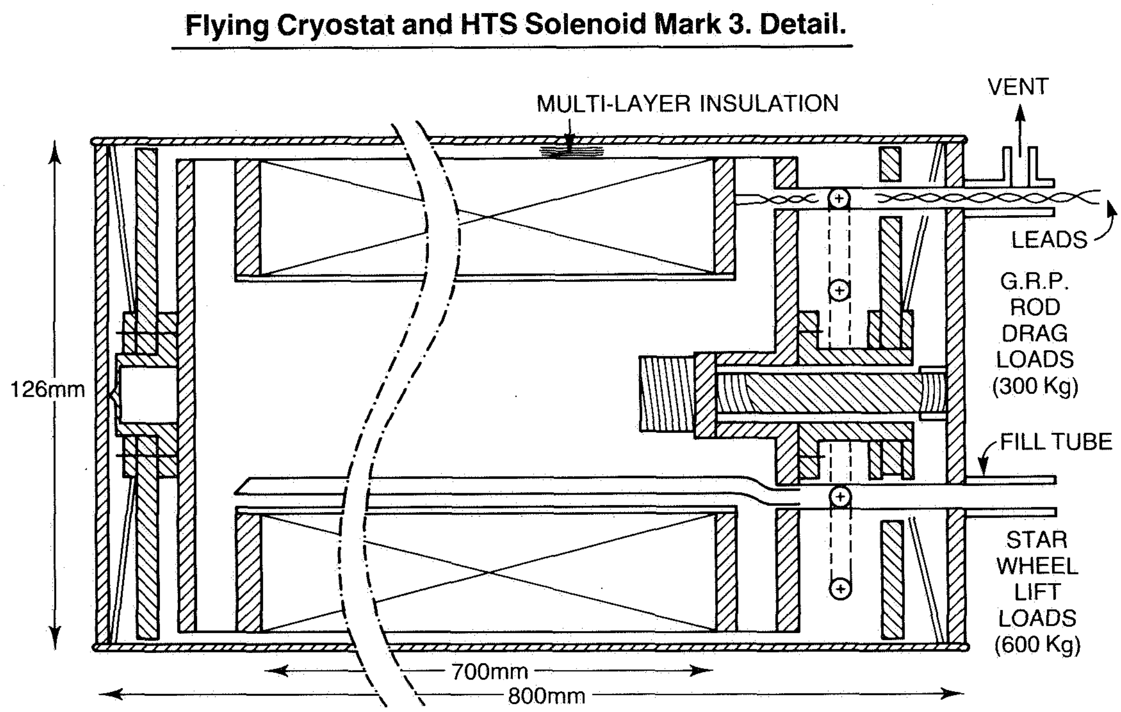


Figure 4. Detail of flying cryostat and liquid nitrogen cooled YBCO solenoid Mark 3