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## Solid-Cryogen Cooling Technique for Superconducting Magnets of NMR and MRI

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### Abstract

This paper describes a solid-cryogen cooling technique currently being developed at the M.I.T. Francis Bitter Magnet Laboratory for application to superconducting magnets of NMR and MRI. The technique is particularly appropriate for “dry” magnets that do not rely on *liquid* cryogen, e.g., liquid helium (LHe), as their primary cooling sources. In addition, the advantages of a cryocirculator (a combination of a cryocooler and a working fluid circulator) over a cryocooler as the primary cooling source for dry magnets are described. The four magnets described here, all incorporating this cooling technique described and currently being developed at the FBML, are: 1) a solid-nitrogen (SN<sub>2</sub>)-cooled Nb<sub>3</sub>Sn 500-MHz/200-mm MRI magnet with an operating temperature range between 4.2 K (nominal) and 6.0 K (maximum with its primary cooling source off); 2) an SN<sub>2</sub>-cooled MgB<sub>2</sub> 0.5-T/800-mm MRI magnet, 10-15 K; 3) an SN<sub>2</sub>-cooled compact YBCO “annulus” 100-MHz/9-mm NMR magnet, 10-15 K; 4) an SN<sub>2</sub>-cooled 1.5-T/75-mm NbTi magnet for slow magic-angle-spinning NMR/MRI, 4.5-5.5 K.

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### 1. Introduction

Generally, a superconducting magnet, LTS or HTS, remains fully superconducting and operates “stably” over a temperature range from its nominal operating temperature  $T_{op}$  to a maximum operating temperature,  $T_{op} + \Delta T_{op}$ . Chiefly because of a much greater critical temperature,  $T_c$ , of HTS compared with that of LTS, this range,  $\Delta T_{op}$ , is an order of magnitude greater for an HTS magnet than that for an

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LTS magnet of comparable size and field performance: typically  $\Delta T_{op} > 1$  K for HTS, while typically  $\Delta T_{op} \leq 1$  K for LTS [1].

The solid-cryogen cooling technique being developed at the M.I.T. Francis Bitter Magnet Laboratory (FBML) recognizes this large  $\Delta T_{op}$  of HTS magnets and combines it with the large heat capacities of solid cryogens [1-3]. In this cooling technique,  $\Delta T_{op}$  is no longer considered a transitory excursion permitted in LTS magnets, but a *new opportunity* for magnet design and operation.

This combination of an expanded operating range, possible primarily with HTS *but not altogether impossible with LTS*, and an enhanced heat capacity offers operating options [4-6] that are infeasible with “conventional” cooling techniques, i.e., “dry,” cooled by cryocooler (cryocooled) but *without* solid cryogen, or “wet,” immersed in a bath of cryogen or force-cooled by cryogen. Note that even for a solid cryogen-cooled magnet, the primary cooling source is a cryocooler or a cryocirculator (a cryocooler with a built-in circulator to force high-pressure cold helium through a cooling coil integrated with the magnet). Typically, such a magnet, surrounded by a volume of solid cryogen, is housed in the cold chamber.

Ideally, every superconducting magnet, LTS or HTS, should operate without reliance on liquid helium (LHe). By the end of this decade, we expect LHe-free magnets will overtake LHe-cooled magnets. Indeed, in the early 1990s, an LHe-free, all-Nb<sub>3</sub>Sn whole-body MRI magnet operating at 10 K was marketed by General Electric.

Although because of a great progress made in cryocooler technology, LHe-free NbTi-based superconducting magnets with an operating temperature,  $T_{op}$ , of 4.2 K are now feasible, and because NbTi is  $\sim 1/10$  less expensive than Nb<sub>3</sub>Sn, NbTi magnets operating at 4.2 K can be price-competitive with Nb<sub>3</sub>Sn magnets operating at 10 K. However,  $\leq 4.2$  K-NbTi magnets have energy margins considerably smaller than those of Nb<sub>3</sub>Sn/10 K and HTS-based magnets. Table 1 gives typical energy margins of magnets with the following  $T_{op}$ /superconductor combinations: 2.5 K/NbTi; 4.2 K/NbTi; 10 K/Nb<sub>3</sub>Sn; 10 K/MgB<sub>2</sub>; and 20 K/YBCO. A temperature margin,  $\Delta T_{op}$ , chosen for each magnet is also typical. The energy margins here are net enthalpy densities of copper over the temperature range covered by  $\Delta T_{op}$ .

Table 1. Comparison of Energy Margins

Magnets with $\Delta T_{op}$ / Superconductor	$\Delta T_{op}$ [K]	$\Delta e$ [mJ/cm <sup>3</sup> ]
2.5 K/NbTi	0.3	0.12
4.2-K/NbTi	0.5	0.6
10-K/Nb <sub>3</sub> Sn	1	9
10-K/MgB <sub>2</sub>	5	80
20-K/YBCO	5	1200

### 1.1. General

Most LTS (NbTi, Nb<sub>3</sub>Sn) superconducting magnets are still operated “wet,” immersed in a bath of liquid helium at 4.2 K or below. The external heating from room temperature and any dissipation in the magnet are absorbed through evaporation of liquid helium, which has a latent heat of 2.6 J/cm<sup>3</sup> at 4.2 K. This “large” enthalpy density of LHe at 4.2 K—“large” in comparison with copper’s enthalpy density, say, from 4.2 K to 4.5 K of  $\sim 0.3$  mJ/cm<sup>3</sup>,  $\sim 10,000$  times greater than copper’s—essentially “anchors” the magnet at its operating temperature *most* of the time. The solid-cryogen cooling technique described here, currently being developed at FBML, is applicable primarily to dry magnets. By providing a large thermal mass to the magnet cold chamber, in this cooling technique a volume of solid cryogen complements a cryocooler, which is the primary cooling source [1,2].

Solid cryogen is an excellent source of thermal mass, particularly in the temperature range 10-60 K, which matches that of most HTS magnets. Fig. 1(a) presents heat capacity,  $C_p$  vs.  $T$  plots of solid cryogens—neon (SNe), nitrogen ( $\text{SN}_2$ ), and argon (SAr)—and metals, lead (Pb), silver (Ag), and copper (Cu). Solid hydrogen is excluded because of its low heat capacity,  $\sim 0.2 \text{ J/cm}^3 \text{ K}$  at  $\sim 14 \text{ K}$ . Lead is used often as a heat capacity enhancer in cryogenic equipment, copper is the most widely used matrix metal in LTS and YBCO, and silver is the matrix metal associated with BSCCO [1].

Fig. 1(b) shows  $T(t)$  plots of 1-liter volumes of Cu, Pb, SNe, and  $\text{SN}_2$ , subjected to a constant heat input of 1 W with an initial temperature of 4.2 K and a final temperature of 60 K (25 K for SNe)—it also includes a dotted horizontal line at 4.2 K showing that the duration required to boil off 1 liter of 4.2-K LHe is  $\sim 0.7 \text{ hr}$  [1]. The figure clearly demonstrates that among these substances, at least on a *volume basis*, SNe in the range 4-25 K and  $\text{SN}_2$  in the range 25-60 K are the best heat capacity enhancers. Because specific densities of SNe ( $1.25 \text{ g/cm}^3$  at 25 K) and  $\text{SN}_2$  ( $1 \text{ g/cm}^3$  at 25 K) are an order of magnitude less than those of Pb ( $\sim 11 \text{ g/cm}^3$ ) and Cu ( $\sim 9 \text{ g/cm}^3$ ), for the same extra volume in the cold body occupied by a heat-capacity-enhancing substance, either of these solid cryogens not only performs its task well but also adds only a modest extra mass to the system.

### 1.2. Application to Persistent-Mode Magnets

One application of this solid-cryogen cooling technique is for constant-field magnets such as of NMR and MRI that normally operate in persistent mode. With the magnet designed to span a “large” operating temperature range, this cooling technique enables such a magnet to maintain a constant operating field over a period of time even after its primary cooling source is turned off and thermally decoupled from the cold body. The cooling source may be turned off intentionally, e.g., to create a measurement environment free of the cooling source vibration or for cooling source maintenance, or under fault mode, e.g., a power outage. Note that this concept is applicable even to an all-LTS magnet, as illustrated below with two such magnet systems at FBML, one completed [7] and the other under development.

### 1.3. Cryocoolers vs. Cryocirculator

For the primary cooling source of a dry magnet, a cryocooler is now universally used. However, a cryocirculator, as described briefly above, a combination of a cryocooler and a working fluid circulator, should be preferable to a cryocooler, particularly to a “large” dry magnet, as discussed below.

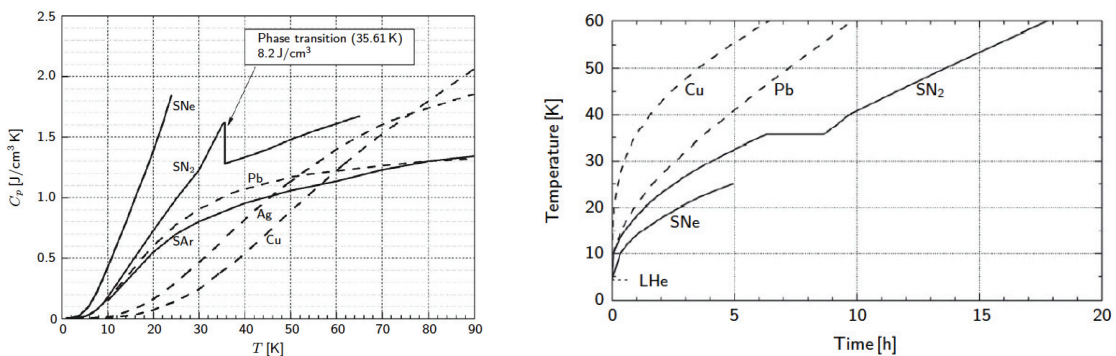


Fig. 1 (a) Heat capacity vs. temperature plots for SNe,  $\text{SN}_2$  and SAr (solid lines); and Pb, Ag, and Cu (dashed lines). Note that  $\text{SN}_2$  has a solid-to-solid phase transition at 35.61 K, absorbing an energy density of  $8.2 \text{ J/cm}^3$ ; (b)  $T(t)$  plots with an initial temperature of 4.2 K and a final temperature of 60 K (25 K, SNe) for a 1-liter volume of Cu, Pb, SNe, and  $\text{SN}_2$  subjected to a constant heat input of 1 W. The duration required to boil off 1 liter of liquid helium (LHe),  $\sim 0.7 \text{ hr}$ , is indicated by the dotted horizontal line at 4.2 K [1].

**Cryocooler** – In a cryocooled dry magnet, of LTS or HTS, the cryocooler coldhead is attached to one end of the magnet cryostat assembly. Fig. 2(a) shows a schematic drawing of a dry magnet and a 2-stage cryocooler, in which the coldhead 1<sup>st</sup> stage is thermally attached to the cryostat radiation shield and the 2<sup>nd</sup> stage to the magnet chamber [1]. For a “large” dry LTS magnet, it will be a challenge to satisfy the tenet of LTS magnet stability, i.e.,  $\Delta T_{op} \cong 0$ , where  $\Delta T_{op}$  in this case is the temperature difference between the coldest spot (at the 2<sup>nd</sup> stage) and the warmest spot (furthest from the 2<sup>nd</sup> stage).

**Cryocirculator** – To keep the magnet temperature uniform,  $\Delta T_{op} \cong 0$ , a cryocirculator is preferable to a cryocooler, particularly for dry superconducting magnets. As illustrated schematically in Fig. 2(b) and has been described briefly above, a cryocirculator is a 2-stage cryocooler equipped with a cold helium circulator (pump) for each stage [1]. Each circulator forces a stream of cold, high-pressure helium through a cooling coil, sometimes embossed, as illustrated in Fig. 2(b), over the surface of the radiation shields or the magnet coil chamber walls. The cryocirculator has two advantages over the cryocooler: 1) it provides cooling over most of the magnet chamber surface area, enabling a magnet, *regardless of its size*, to satisfy the  $\Delta T_{op} \cong 0$  condition; and 2) the cooling source and the magnet cryostat, connected by flexible helium lines, may easily be decoupled. One early (~1990) application of a cryocirculator is the Hybrid III magnet completed at the FBML [8].

## 2. SN<sub>2</sub>-Cooled Nb<sub>3</sub>Sn MRI Magnet

One application of the solid-cryogen cooling technique is an all-Nb<sub>3</sub>Sn 500-MHz/200 mm RT bore MRI magnet completed at the FBML in 2009 [7]. Fig. 3 shows a drawing of the magnet system. The nominal operating temperature is 4.2 K with a maximum limit of 6.0 K with its cryocooler turned off. The magnet is surrounded by a 65-liter SN<sub>2</sub> which enables the magnet to operate up to 6.0 K with the cryocooler off over a period of ~6 hours with a net heat input to the cold chamber (magnet/SN<sub>2</sub> volume) of 0.2 W. If SN<sub>2</sub> is substituted by SNe, the operating period would be roughly doubled to ~12 hours. In actual operation, because the 2<sup>nd</sup> stage of the cryocooler (1 W at 4.2 K) proved inadequate, a volume of LHe (shown aqua) was introduced above the SN<sub>2</sub> volume to keep the magnet at 4.2 K.

## 3. SN<sub>2</sub>-Cooled MgB<sub>2</sub> MRI Magnet

The second example currently being developed at the FBML is an MgB<sub>2</sub> 0.5-T/800 mm RT bore MRI magnet [9-11]. As illustrated in Fig. 4, the system incorporates a cryocirculator as its primary cooling source. The nominal operating temperature is 10 K with a maximum limit of 15 K with its cryocooler turned off. The magnet is surrounded by a 15-liter SN<sub>2</sub> which enables the magnet to operate over a period of ~5 hours with a net heat input of 1 W to the cold chamber. The cryocirculator will force 20-atm helium through a cooling coil placed inside the magnet chamber at a flow rate of 0.6 g/s at an inlet temperature of 9.5 K and an outlet temperature of 10.5 K.

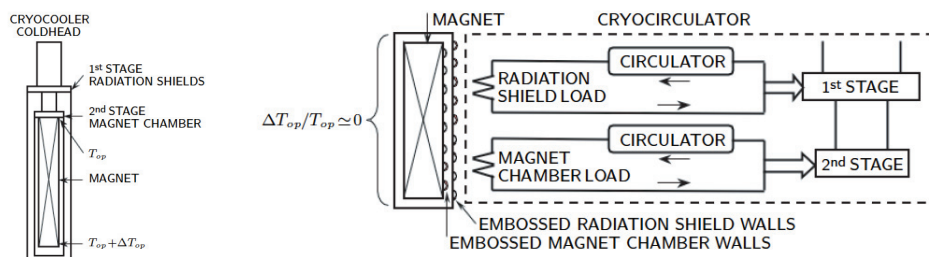


Fig. 2 (a) Schematic drawing of a cryocooled dry magnet; (b) Schematic drawing of a cryocirculator-cooled magnet [1].

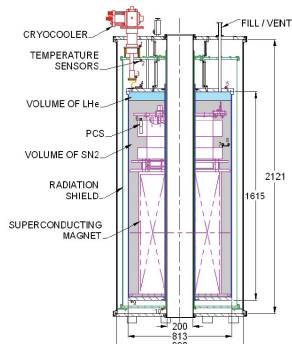


Fig. 3. Drawing of an all-Nb<sub>3</sub>Sn 500-MHz/200-mm RT bore MRI magnet with a 65-liter SN<sub>2</sub> volume [7]. In actual operation, because the 2nd stage of the cryocooler (1 W at 4.2 K) proved inadequate, a volume of LHe (shown aqua) was introduced above the SN<sub>2</sub> volume to keep the magnet at 4.2 K.

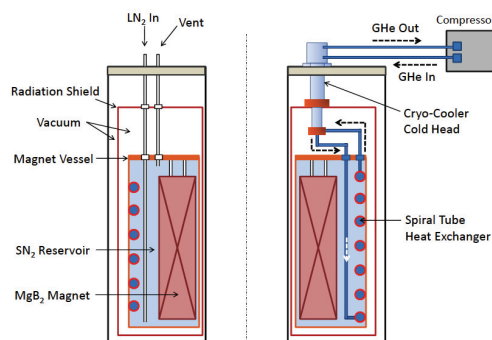


Fig. 4. Drawing of an MgB<sub>2</sub> 0.5-T/800-mm RT bore MRI magnet with a 15-liter SN<sub>2</sub> volume [9-11]. The system incorporates a cryocirculator as its primary cooling source. The cryocirculator forces 20-atm helium at a rate of 0.6 g/s through the cold chamber with an inlet temperature of 9.5 K and an outlet temperature of 10.5 K.

#### 4. SN<sub>2</sub>-Cooled Compact YBCO “Annulus” Magnet for Micro-NMR Spectroscopy

The third FBML example is a compact YBCO “annulus” magnet prototype for micro-NMR spectroscopy [1, 9, 12-14]. It is an assembly of YBCO thin-plate annuli and bulk annuli. The first prototype, with a room-temperature bore of 9 mm and a center field of 2.35 T (100 MHz), will operate in the range 10 K (nominal)-15 K (maximum). An assembly of steel annuli shown in Fig. 5 shields the environment from the fringing field of the magnet. As with the other magnets described here, this magnet runs nominally at 10 K with its cooling source on and up to 15 K with the cooling source off.

#### 5. SN<sub>2</sub>-Cooled NbTi Magnet for Slow Magic-Angle-Spinning NMR/MRI

Fig. 6 shows a drawing of an NbTi magnet for slow magic-angle-spinning NMR/MRI. The principal field of 1.5 T, in persistent mode, is tilted at a “magic” angle of 54.74° from the magnet (and rotating) axis. In Phase 1 of this 2-phase program, the cryostat housing the magnet will *not* be rotated at its ultimate frequency of 6 Hz nor its primary cooling source a cryocirculator. As shown in the figure, in Phase 1 the magnet will be force-cooled by 4.2-K helium from an LHe storage dewar. Here, a volume of SN<sub>2</sub> acts as a

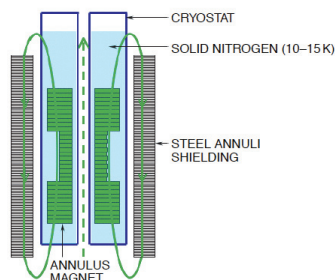


Fig. 5. Drawing of a compact (0.9-mm RT bore/100-MHz) YBCO “annulus” magnet prototype for micro-NMR spectroscopy. The primary cooling source, a cryocirculator, is not included in the drawing [1, 9].

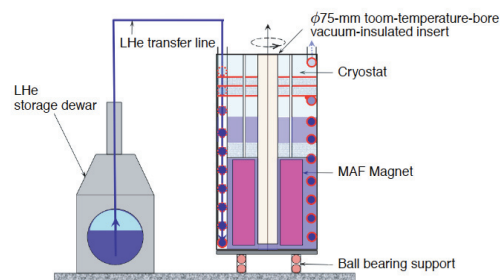


Fig. 6. Drawing of an NbTi (1.5-T/75-mm RT bore) magnet for slow magic-angle-spinning NMR/MRI. The primary cooling source in this first set is a n LHe storage dewar. In the systems to be developed later, the LHe storage dewar will be replaced by a cryocirculator.

thermal buffer to stabilize an optimal operating temperature of 4.5 K and as a cooling source when the transfer line is taken out of the cryostat and the cryostat rotated slowly (~1 Hz) to measure field harmonics under rotation.

## 6. Conclusion

We believe that the solid-cryogen cooling technique being developed at the FBML is suitable for dry magnets—those that do not rely on *liquid* cryogen as their primary cooling source. Described in this paper are four magnet systems currently under development at the FBML that incorporate the solid-cryogen cooling technique: 1) an all-Nb<sub>3</sub>Sn 500-MHz/200-mm RT bore MRI magnet in the temperature range 4.2-6.0 K; 2) an MgB<sub>2</sub> 0.5-T/800-mm RT bore MRI magnet (10-15 K); 3) a compact (0.9 mm RT bore/100 MHz) YBCO “annulus” magnet (10-15 K) for micro-NMR spectroscopy; and 4) an NbTi 1.5-T/75-mm RT magnet (4.5-5.5 K) for slow magic-angle-spinning NMR/MRI. The solid cryogen in each system adds not only a thermal mass as LHe does in a “wet” magnet but also acts as a cooling source over a period of time when its primary cooling source is off.

## Acknowledgements

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