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Discoveries in Superconductivity, Persistent-Switch Magnets, and Magnetic Cooling

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Abstract A historical review of developments in superconducting magnets begins with Kamerlingh Onnes' construction of the first one in 1914 and extends to the invention of the superconducting persistent switch reported in 1963. A section on magnetic cooling includes refrigeration by paramagnetic salts and by nuclei in metals, as well as direct nuclear demagnetization in which only the nuclei are cooled.

Keywords Superconducting magnets · Persistent switch · Magnetic cooling

1 Introduction

1.1 Personal Remarks on my Association with Horst Meyer

In my final year of work for my Ph.D. degree at Duke University, Horst Meyer replaced William Fairbank, who had moved to Stanford University. One or two other graduate students and I had more work to do to complete our research and write our dissertations. Although Horst's interests in physics were, of course, different from Bill's, he took us all on as his responsibility to see us through to completion of our graduate studies.

My thesis work was published with both Horst Meyer and Bill Fairbank as my co-authors, and the two of them were co-directors of the work. Both of them signed my dissertation. Ever since, Horst and I have continued our close and enjoyable association.

As a professor at the University of Florida, I have sent one or two who received bachelors' degrees at UF to Duke for their graduate work. There they have usually

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chosen to work with Horst. One of Horst's Ph.D. students did a productive postdoctoral stint with me.

In addition to a continuing scientific association by frequently attending the same meetings, Horst and I have kept in contact through exchange of yearly letters. In one letter, Horst graciously congratulated me on the installation of the original Straty–Adams gauge in the Smithsonian.

We have a common appreciation of nature, with Horst being an avid bird-watcher with the Audubon Society, while I have been active in the Sierra Club. In one letter, Horst mentioned that he would take part in a bald eagle count with Audubon. He visited the low-temperature group at the University of Florida several times. I was always happy to take him on bird-watching trips to Cedar Key, FL, where we would have lunch and bird-watch for numerous shore birds.

1.2 Discoveries in Superconductivity

Just 3 years after he won the race to liquefy helium, Heike Kamerlingh Onnes discovered superconductivity, the phenomenon in which some metals lose all resistance below a certain temperature [1]. Soon afterward, he suggested that magnets be constructed of wires made of such superconductors. The objective was to avoid joule heating in the windings.

Kamerlingh Onnes constructed the world's first "superconducting solenoid," which was 1 cm long, 1 cm in diameter and could carry a current of only 0.8 A, beyond which the wire "went normal." The wire had reached its critical field, also discovered by Kamerlingh Onnes [2]. This discovery discouraged further efforts to produce high-field solenoids.

In 1931, deHaas and Voogd made the important discovery that a lead–bismuth alloy had a critical field of 20 kilogauss [3]. This again raised hopes for using superconductors to produce high magnetic fields. However, superconducting magnets producing 20 kG were not yet possible. Wires near their critical field will not carry the high current necessary for such fields. deHaas and Voogd had used a small current to detect the high field of Pb–Bi [4].

Efforts to produce high fields were resumed in 1955 and the following few years. Groups using cold-worked niobium wire [5] and cold-worked molybdenum–rhenium wire [6] achieved fields of 7 and 15 kG, respectively. The latter workers used a novel means of insulating the windings of their solenoid. They gold plated it. Gold, a very good conductor, is an insulator for a superconductor with zero resistance.

Significantly higher fields of 43 kG using niobium–zirconium [7] and 69 kG using niobium–tin (Nb3–Sn) operating at 1.5 K were soon reported by Frazer et al. [8], and by Kunzler et al., respectively. The critical field of Nb3–Sn of 260 kG is much higher than the field of only 69 kG achieved by this solenoid. This is the same situation as was seen earlier by deHaas and Voogd for the Pb–Bi alloy.

Previously, the primary emphasis had been in producing the maximum field without regard to other factors that would be required for more useful applications. Superconducting solenoids capable of producing fields of 50 kG were available from several sources by 1962. At present (2015), fields of 20 T can be produced with superconduc-

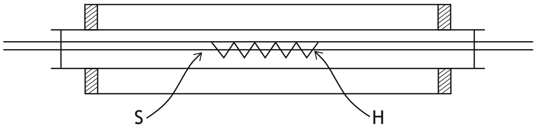

Fig. 1 Construction of the switch with the vacuum-jacked capsule. S—the shunt, a superconducting wire short, and H—the heater, for heating the shunt above T_C, the transition temperature of the short

tors, 45 T by hybrids (both superconducting portions and resistive ones), 100 T using pulsed fields and still higher ones using flux compression, e.g., using explosives to provide the compression of the flux.

A variety of uses are met by purely superconducting magnets and by hybrids with cores of normal windings that operate above the critical fields of superconductors and superconducting outer windings. These uses include research on behavior of materials in magnetic fields, for example at the National High Magnetic Field Laboratory [9] or in various laboratories in universities or other locations. Particle accelerators use a large variety of superconducting magnets, some of large physical dimensions.

In the last section of the paper, magnetic cooling by adiabatic demagnetization of paramagnetic salts and of nuclei, made possible by invention of the persistent switch, is discussed briefly.

2 The Superconducting Persistent Switch

The earliest motivation for using superconductors for construction of magnets was to eliminate the joule heating of the current flowing in resistive magnets constructed with materials such as copper. Another source of heating was that in leads from room temperature to the superconducting magnet. The significant amount of heating by the current in the leads from the external power supply could also be eliminated (except when charging or discharging the magnet) if some means of establishing a persistent current in the magnet could be devised. This was destined to occur through the effort of two Stanford University Postdoctoral Associates (P.D.). Many new applications made possible by the invention of the persistent switch lead to a flurry of research activity.

A widely used procedure in medicine, magnetic resonance imaging (MRI), relies on features of persistent switches that are essential for its success. This is an application of the persistent switch outside the interest in pure research in physics of its developers.

Some of the earliest research that relied on magnets employing the newly invented persistent switch is discussed briefly in sect. 3. Figure 1 in this paper shows the construction of the persistent switch. (It is unknown why details of the switch construction were not included in the 1963 paper by Adams and Goodkind, Ref. [10].)

Marcel LeBlanc, a P.D. at Stanford University in 1960, was the first to construct persistent superconducting solenoids (M. LeBlanc, Private Communication). LeBlanc used hard-drawn niobium wire manufactured by Wah Chang Corp. (M. LeBlanc, Private Communication). A short length of the wire, i.e., "*a short*" was spot welded across the windings to form a closed loop. The short had to be made resistive, that is normal, so that the current would go through the windings instead of through the short. LeBlanc achieved this simply by increasing the current through the shunt until its critical value was exceeded. The current at which this occurred could not be controlled, i.e., you just had to take whatever current was in the magnet at the time the short was driven normal by the current passing through it. Turning the current in the magnet back down to zero (or any lower value) similarly occurred in an uncontrolled manner.

LeBlanc's procedure that did not allow control of value of the current at which the magnet persisted was far from satisfactory. *A superconducting persistent switch* that could be made resistive in a controlled manner to establish the current in the magnet and then made superconducting to allow the current to persist was needed. This would allow the current in the leads to the power source to be discontinued, eliminating the Joule heating in them. An even more important benefit would be that the current in the magnet windings would persist at the desired, constant value, i.e., the field would have the steady value desired (or a very long L/R time constant) that was needed for numerous applications, some of which will be mentioned and discussed briefly below.

A device that allowed the field in the persistent magnet to be established in a controlled way was invented by Dwight Adams, also a P.D. at Stanford University at the same time as LeBlanc [10]. Just as LeBlanc had done, Adams welded a "short" consisting of a length of wire across the magnet windings. Instead of relying on the "take what you get" approach of Le Blanc of increasing the current until it went normal, Adams ran the short, along with a heater made of resistance wire through a vacuum jacketed capsule. As shown in Fig. 1, this capsule was made of small inner and outer stainless steel tubes with small metal "beads" silver soldered in place to close the annular space between the tubes at each end. The inner tube through which the superconducting short and the heater wire ran was completely filled with epoxy to insulate it from the helium bath. This construction is the same as described in Lichti's 1963 University of Florida M.S. thesis [11].

The vacuum jackets of the first switches turned out to be unnecessary. A much simpler design just imbeds the superconducting wire and heater in epoxy (e.g., Stycast FT 2850) that is contained in a short piece of small, single-walled tubing, as shown in Lang's 1996 University of Florida Ph.D. dissertation [12]. Also, the design shown by Lang, with the shorting wire bent into a "hairpin" shape, makes positioning the switch simpler since wires emerge from only one end of it.

The arrangement of the switch, S, relative to other parts is shown here in Fig. 2. R is a normal resistance short of $\sim$0.001 ohms, made from a small length of stainless steel tubing. This R, in parallel with the switch, maintains a sufficiently long L/R time constant to prevent damage to the magnet when the switch is in the normal state with a larger resistance. Lichti and other users who made their own superconducting magnets before they were commercially available used this arrangement as well [11]. The energy released by the spot welder could not be precisely controlled and occasionally would cut the wire, a disastrous outcome. Locating the terminals between the spot weld and the magnet windings alleviated this problem.

Anyone who wants to substantiate the invention of the superconducting persistent switch may not be able to do so through an Internet search. The switch and its use in the superconducting magnet circuit was described only briefly, however clearly, and without fanfare in the Cryogenics article by Adams and Goodkind [10]. The description of the construction of the persistent switch and its use in magnetizing

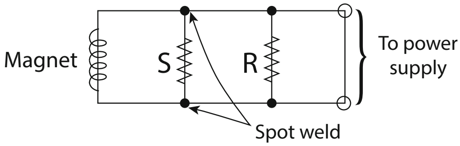

Fig. 2 Configuration of the switch in the superconducting magnet circuit. S—switch, consisting of the components shown in Fig. 2. It is spot-welded to the magnet windings to provide a closed loop. R—parallel resistance of ∼0.001 ohm to provide a "long" time-constant for preventing possible damage because of rapid change in current

and demagnetizing was quite thorough in Litchi's M.S. thesis [11]. M.S. theses and, of course, *Cryogenics* are valid as references for scholarly works. However, lacking prominence, these references may consign them to obscurity. Failure to be picked up by search engines seems to confirm this; even the Cryogenics article is not listed in the Web of Science database [13].

Further evidence of the obscurity of the invention of the superconducting persistent switch is contained in an article on "superconducting magnets" in *Wikipedia the free encyclopedia* [14]. This gives a rather thorough description of superconducting magnets, including their operation in the persistent mode. Several references are included with this Wikipedia article, some published prior to 1963, the year of publication of both Ref. [10] and [11]. There is no reference to the persistent switch.

The persistent switch, invented by Adams at Stanford and reported in 1963 [10], has probably been destroyed. However, the one built by Lichti and described in his 1963 M.S. thesis [11], which is the second superconducting persistent switch made in the world, has survived. It and the accompanying superconducting solenoid are on display in the lobby of the Department of Physics at the University of Florida. Also the display at UF contains a poster on the Straty-Adams pressure transducer, now in the *Smithsonian Institution.*

(Since this manuscript was submitted, the Wikipedia article has been edited to include Ref. [10], the Adams and Goodkind article. Also, in a history section, the invention of the switch by Adams is indicated, including the fact that the one built by Lichti is on display in the UF Physics building lobby.)

3 Magnetic Cooling

One of the anticipated uses of persistent-current superconducting solenoids, by Adams and LeBlanc, was magnetic cooling of materials of interest. Magnetic cooling is a general term that does not indicate the specifics of several methods to which it might refer. At the time of Adams's and LeBlanc's work, magnetic cooling employed paramagnetic salts as the refrigerant material [15,16].

Temperatures in the range of a few mK, depending on the particular salt and the precooling technology employed, can be obtained. The elaborate cryostat described by Adams and Goodkind [10], employing a ^{3}He refrigerator and two stages of cooling by paramagnetic salts, reached only 14 mK. It had been expected to reach about 3 mK, the approximate ordering temperature of the second-stage salt, cerium magnesium nitrate [15–17].

Using a ^{3}He refrigerator that reached a pre-cooling temperature of 0.35 K and a single paramagnetic salt "potassium chromium alum" [15–17], Scribner et. al. [18] cooled a sample of liquid and solid ^{3}He to measure the melting curve to 14 mK. These measurements and subsequent ones eventually led to the adoption of the ^{3}He melting pressure for the thermometry standard to 0.009 K [19,20].

In the quest to reach lower temperatures than available using paramagnetic salts, magnetic cooling of nuclei of metals, such as copper, usually as thin wires, has come into wide use [15,16,21]. By this method, which might be called nuclear refrigeration (to distinguish it from nuclear cooling in which only the nuclei are cooled), temperatures well into the μK range Have been achieved. A temperature of the electrons of 10–12 μK was reported in the pioneering work of Pobell et. al in 1988 [22].

Nuclear cooling, or direct nuclear demagnetization [12,23,24] that cools only the nuclei themselves, not the electrons or phonons, is the ultimate step in magnetic cooling. A most notable achievement by this technique was observation of the expected [25] ferromagnetic ordering in the hexagonal closest-packed phase of solid ^{3}He [12,23].

In direct nuclear demagnetization, where the nuclei are decoupled from other degrees of freedom, the temperature cannot be measured. In Tien's experiment, thermodynamic analysis showed that the spins had ordered ferromagnetically at $T \sim 10$ μK. This observation of ferromagnetic ordering by Tien Lang in research for his Ph.D. dissertation represents the Holy Grail in the study of the magnetic properties of solid ^{3}He.

The record low temperature of the spins of rhodium of 250 pK is held by the Helsinki group [24].

Books on techniques for producing low temperatures by magnetic cooling, among other topics, include the still important one by Lounasmaa [15], a later one by Pobell, now in a third edition [16], and one by Enss and Hunklinger [21].

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References

1. H.K. Onnes, Commun. Phys. Lab. Univ. Leiden, no. 122b, (1911)
2. H.K. Onnes, Commun. Phys. Lab. Univ. Leiden, no. 130f, (1914)
3. W.J. deHaas, J. Voogd, Commun. Phys. Lab. Univ. Leiden, no. 214b, (1931)
4. W.H. Keesom, Commun. Phys. Lab. Leiden, no. 234f, (1935)
5. G.B. Yntema, Phys. Rev. **98**, 1197 (1955)
6. J.E. Kunzler, E. Buehler, F.S.L. Hsu, B.T. Matthias, C. Wahl, J. Appl. Phys. **32**, 325 (1961)
7. M.J. Frazer, J.K. Hulm, H. Reinersa, A.J. Venturino, R.E. Wein, Cryogenics **2**, 116 (1961)
8. J.E. Kunsler, Conference High Magnetic Fields, Cambridge, 1961
9. NHMFL, Mag Lab Reports, vol. 18, no. 2 (2011), www.magnet.fsu.edu
10. E.D. Adams, J.M. Goodkind, Cryogenics **3**, 83 (1963)
11. R.D. Lichti, Thesis, University of Florida, 1963

12. T.V. Lang, Dissertation, University Florida, 1996
13. Web of Science, www.thomasreuter.com/WebofScience
14. Wikipedia, http://en.wikipedia.org/wiki/Wikipedia
15. O.V. Lounasmaa, *Experimental Principles and Methods Below 1 K* (Academic Press, New York, 1974)
16. F. Pobell, *Matter and Methods at Low Temperatures* (Springer, Berlin, 1992). Third Edition, 2007
17. R.P. Hudson, *Principles and Applications of Magnetic Cooling* (North-Holland, Amsterdam, 1972)
18. R.A. Scribner, M.F. Panczyk, E.D. Adams, Phys. Rev. Lett. **21**, 427 (1968)
19. E.D. Adams, in *Progress in Low Temperature Physics*, ed. by W.P. Halperin (Elsevier, Amsterdam, 2005), p. 432
20. R.L. Rusby, M. Durieux, A.L. Reesnik, R.P. Hudson, G. Schuster, M. Kuehne, W.E. Fogle, R.J. Soulen, E.D. Adams, J. Low Temp. Phys. **126**, 633 (2002)
21. C. Enss, S. Hunklinger, *Low-Temperature Physics* (Springer, Berlin, 2005)
22. K. Gloos, P. Smeibidl, C. Kennedy, A. Singsaas, P. Sekovski, R.M. Mueller, F. Pobell, J. Low Temp. Phys. **73**, 101 (1988)
23. T.V. Lang, P.L. Moyland, D.A. Sergatskov, E.D. Adams, Y. Takano, Phys. Rev. Lett. **77**, 322 (1996)
24. J.T. Tuoriniemi, T.A. Knuuttila, Physica B **280**, 474 (2000)
25. M. Roger, J.H. Hetherington, J.M. Delrieu, Rev. Mod. Phys. **55**, 1 (1983)