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Topical Review

Superconducting magnet technology for the outer coils of resistive-superconducting hybrid magnets

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Abstract

The world's highest-field dc magnets have, for more than 50 years, consisted of a combination of resistive and superconducting (SC) coils that we refer to as a 'hybrid'. These magnets use SC technology for the outer coils, where the magnetic field is moderate, and resistive-magnet technology for the inner coils, where the field is highest. In such a configuration, higher fields have been attained than was possible with purely SC magnet technology, and lower lifecycle costs are attained than with a purely resistive magnet. The peak field available has been 45 T for over 20 years in Tallahassee, Florida, USA. There is presently a 'revolution' underway in hybrid magnet development. A second 45 T hybrid was completed in 2022 in Hefei, China that might be upgraded to 48 T in a few years. The high field lab in Grenoble, France is also testing a hybrid magnet intended to reach 43.5 T but which also might be upgraded to 46 T in a few years. In addition, the lab in Nijmegen, The Netherlands is presently assembling a hybrid magnet intended to operate at 46 T. Papers have been presented and published with conceptual designs of hybrid magnets with fields up to 60 T. Given the developments underway, this is an appropriate time to review the history of such systems, with a particular focus on the larger, more expensive part of the magnets: the SC outsert coils. The demands placed on the SC coils of these magnet systems are unique due to their coupling with resistive coils that are operated at very high stress and wear out regularly, resulting in large field transients and fault forces. The evolution of the technology used for the SC coils of these hybrid systems is presented, evolving from ventilated windings to cable-in-conduit to cryogen-free.

Keywords: superconducting magnet, hybrid magnet, high field magnet

1. Introduction

The highest field dc magnets in the world provide a flux density of 45.2 T in a 32 mm bore to researchers at the National High Magnetic Field Laboratory in Tallahassee [1, 2], Florida and the Steady High Magnetic Field Facility Hefei, China [3, 4]. Both magnets are resistive-superconducting (SC) hybrids using cable-in-conduit-conductor [5] for the SC 'outserts' and Florida-Bitter technology for the resistive inserts [6]. These magnets are some of the more recent ones of a series of twenty-three hybrid magnets developed wordwide to provide very intense dc magnetic fields (figure 1, table 1).

Users of high-field magnet facilities want high flux densities for experiments in condensed-matter physics and other subjects. While pulsed magnets provide the most intense fields [7], many experiments require more than a few milliseconds of applied field. Traditionally, SC magnets have been made from the low temperature SC (LTS) materials (NbTi and Nb_3Sn) and have been able to provide fields ranging from ∼10 T in the early 1970s to ∼20 T at the turn of the millennium. To achieve higher dc field than this, resistive magnet technology has been used. While there is no known fundamental technological limit to the field available from an all-resistive magnet, the power consumption increases faster than the square of the field due to the need to trade of low-strength, high conductivity conductors for stronger ones that have lower electrical conductivity [8].

Given the costs of power supplies and chilled water-cooling systems, all the major high dc field facilities have relied on resistive SC hybrid magnets for the most intense fields [6]. In such a system, SC technology is used for the outer coils where the field is modest (<15 T) and resistive technology is used for the inner coils where the fields are higher, and the resulting current density of a SC magnet would be too low. The idea of combining SC and resistive magnet technologies to build a hybrid magnet is widely credited to Wood and Montgomery, who proposed the concept in 1966 [9] A basic consideration of the costs of hybrid systems compared with both all-resistive and all-SC systems was presented by Montgomery in 1966 [10].

At least twenty-three hybrid magnets have been developed for facilities worldwide as indicated in table 1.

2. Hybrid magnet design basics

Figure 2 is a vertical section of the first hybrid magnet to be put into service for the scientific community, Oxford I (see section 5.1). It shows the features that are typically found in hybrid magnets. Other important subsystems include the cryogenic system that maintains the outsert at low temperature, the chilled water system to cool the resistive magnet (which might consume up to 30 MW of power), the power systems for both the insert & outsert, and the instrumentation, protection, and control systems.

There are multiple operating conditions that need to be considered during the design of a hybrid outsert. After the initial assembly, the outsert is at room temperature and needs to be cooled down to operating temperature, historically between 1.5 K and 4.5 K. Because the mass of the outsert coils and cold support structure is a few tons, the cool-down process needs to be included in the design process. Frequently the designer tries to maintain a small temperature gradient across the outsert during cooldown to minimize the chances of damage due to thermal strain.

Once the outsert is cold, it can be energized to its normal operating current. Traditionally the insert is energized by a separate power supply and the outsert will be charged in the morning and remain at field all day. The insert's field will be swept up and down periodically as required by the experiment being conducted, collecting data as a function of magnetic field. This sweeping of the insert field results in ac losses (heating) in the outsert due to the fringe field of the insert interacting with the outsert. When the insert and outsert are fully energized, the return flux of the insert subtracts from the field the outsert experiences, increasing the margin in the SC wire. Two recent magnets connected the resistive and SC coils electrically in series, see sections 7.4 and 7.5.

High field resistive magnets are usually designed to reach maximum possible field and are much cheaper to build than the SC magnets described herein. Hence, they might be designed to operate at close to the yield strength of the materials with 90% of yield strength being a common operating point. Consequently, the resistive inserts of these hybrid systems do, intentionally, wear out due to metal fatigue. There are typically protection systems that monitor the resistive magnets. If the resistance of the magnet changes too much, the power supply is tripped off and current will decay exponentially with a time constant usually between 250 and 500 ms. There are a number of other reasons the power supplies for the resistive insert might trip off. There could be sags in the incoming voltage to the power supplies or problems within the power supplies themselves.

Any of these events will result in the field from the resistive magnet decaying suddenly and quickly. This drop in field will induce a current rise in the outsert (transformer effect) in a magnet with a traditional, two-power-supply design. In some hybrid magnets, this induced current and resulting heating is enough to cause the outsert to quench. In addition, when the resistive insert wears out, it might do so in a manner that is not symmetric about the mid-plane. If this happens, the resistive and SC coils can exert large axial forces on each other. Some hybrids have been designed to allow the resistive magnet housing to move inside the bore of the cryostat in such an event to allow the coils to re-centre thereby reducing the forces [12] while other system provide stiff structural support to prevent the coils from moving. (The cryostat and support structure for the SC coils of the 45 T hybrid magnet in Tallahassee are designed to accommodate an axial fault force of 6 MN [13].) One of the main design challenges of a hybrid outsert is protecting the outsert from these insert trips.

In some hybrid magnets, the outsert is designed to accommodate this jump in current, magnetic field, and temperature. The 45 T hybrid at the MagLab in Tallahassee was one such example [13].

With either design philosophy, the outsert needs to be cooled down again after a resistive magnet trip and returned

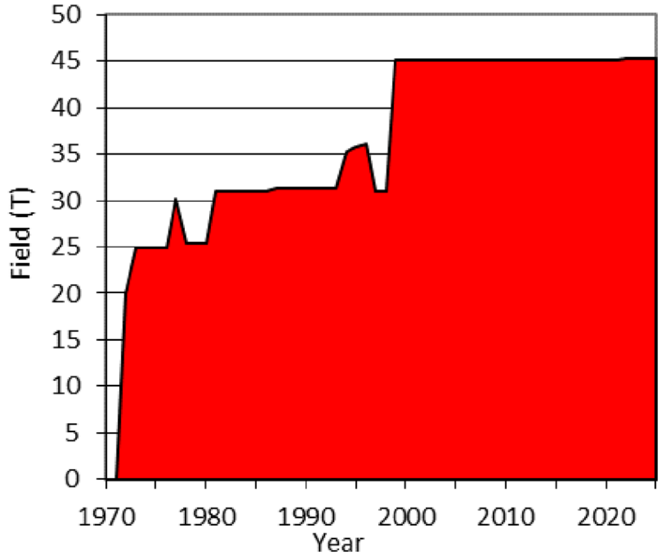

Figure 1. Fields available from hybrid magnets versus time.

Table 1. Hybrid magnets.

				Outsert					
Name	Total field (T)	Power (MW)	Year	Field (T)	Temp (K)	Cold bore (cm)	Current (kA)	Energy (MJ)	Energy density (J/cc)
Generation 0: No Twist									
MIT I	20	5	1972	5.8	4.2	40	1.5	2	16
McGill	25		1972	15	4.2	18.5	0.8		
Generation 1: <30 T, <10 T SC, <10 MJ, NbTi, 4 K, no reinforcement									
Oxford I	16	2	1973	6.5	4.2	28.4	0.63		
Moscow	25	6	1973	7.5	4.2	37.6			
Nijm I	25–30	9	1978	8.5	4.2	40.6	1.5		
MIT II	30	9	1981	7.5		40	1.5	3.4	25
Sendai I	20	3	1983	7.7	4.2	29	0.78	1.2	34
Sendai II	24	7	1984	8	4.2	42	1.47	6.1	19
Hefei I	20	3	1992	7	4.2	33.2	0.9	1.4	29
Generation 2: 30–35 T, >10 T SC, 10–25 MJ, 1.8 K or reinforcement									
Sendai III	31	7.4	1985	12	4.2	43	1.46	22.5	39
Nijm II	30	6	1985	10.5	1.8	42	2	10.6	37
Grenoble I	31	10	1987	11	1.8	50	0.84	22	40
MIT III	34	9	1991	13	1.8	43	2.3	20.8	74
3rd Generation: >35 T (except HZB), >25 MJ									
TML	36	15	1995	15	4.2	47	1.48	63.4	46
MagLab I	45	26	1999	14.2	1.6	71	10	98	59
Grenoble II	40	24	2006	8	1.8	110	1.35	60.4	54
Berlin	26	4.4	2015	13	4.5	60	20	50	81
MagLab II	36	14	2017	13	4.5	60	20	50	81
Hefei II	45	25	2016	11	4.5	93	13.4	102	74
Grenoble III	*43*	*24*	*2024?*	*8*	*1.8*	*110*	*7.1*	*76*	33
Nijm III	*46*	*20*	*2025?*	*14*	*4.5*	*72*	*20*	*47.5*	61
4th Generation: Cryogen-free									
Sendai IV	22.7	7.4	2003	8	3.5	40	0.15 0.2	2.7	42
Sendai V	27.5	7.9	2005	11.1	4–8	40	0.35 0.30		45

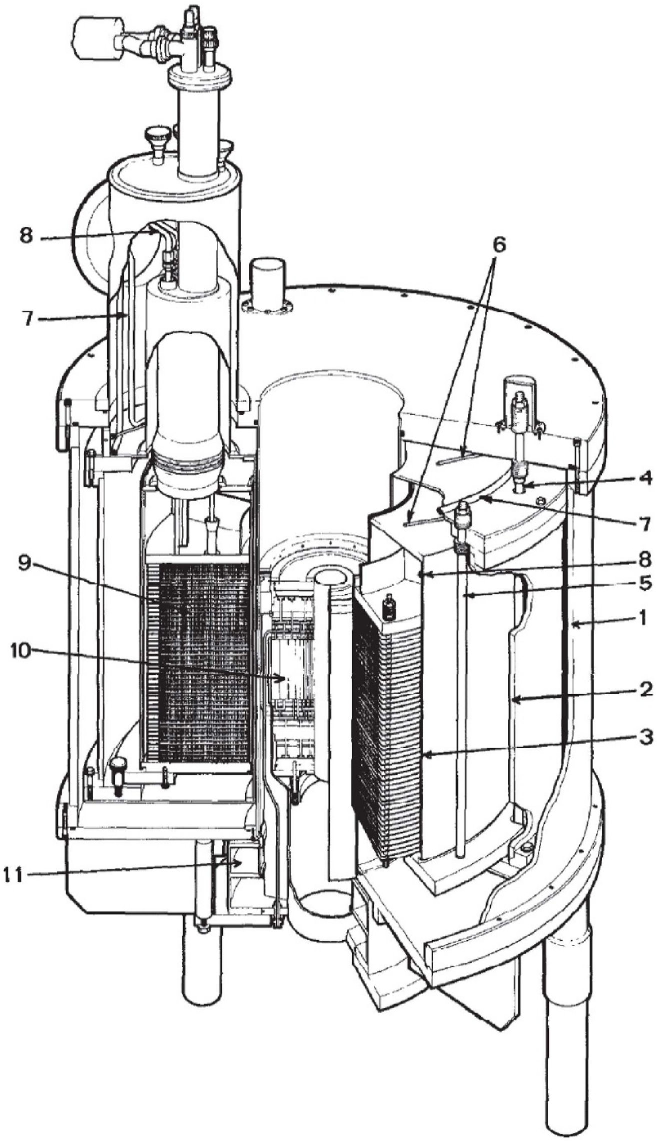

Figure 2. Isometric drawing with partial vertical section of the first hybrid magnet to be put into service [11]. Components (1) Outer vacuum vessel (2) Radiation Shield (3) Liquid helium can. (4) Support tube–outer case to radiation shield. (5) Support tube–radiation shield to helium can. (6) Radial support rods (7) 50 K refrigeration lines. (8) 20 K refrigeration lines (9) Superconducting magnet. (10) Water-cooled magnet. (11) Cooling water manifold and current terminals.

to normal operations. For helium-cooled magnets that quench as a result of an insert trip, this might take a day. For ones that can survive without quenching, it might only be 15 min.

3. Early SC magnet technology

The first SC magnets to be put into reliable service were made from Nb_3Sn. By the late 1960s, Nb_3Sn was available in both wire and tape formats and large bore magnets up to 10 T were being made [14, 15]. While both layer (helical) an pancake (spiral) winding were used, the tape conductor became preferred and was typically used with pancake-winding. The single-pancake technique used a terminal at both the inner and out diameter while double-pancakes could also be wound from a single piece of conductor leaving both terminals at the outer diameter [16]. The double-pancake approach not only reduces the number of joints that need to be made, but it also can result in less stress concentration at the inner diameter which is important for high field systems. Insulation is provided between the turns and layers. For the early hybrid magnets the insulation was installed with gaps to allow helium to contact the conductor between the turns and increase the stability. The pancakes are then stacked with insulators between them. Usually these inter-pancake insulators allow helium to flow between the pancakes. Joints are made between pancakes (or double-pancakes) to form coils [17]. Interestingly, it was already appreciated in the 1960s that tape conductors would have screening currents that would result in a distortion of the magnetic field [17] and that the critical current of the conductor needed to be controlled to prevent flux jumping [15].

4. Early attempts: untwisted SC wire

The two earliest hybrid magnets were energized in the early 1970s, when large-scale superconductivity was in its infancy. These projects were rather novel and, perhaps, speculative, and can be thought of as pioneers of hybrid magnet technology. Both of them use pancake construction. Both of them concluded afterwards that multi-filamentary conductors should be used in the future. However, many SC magnets were built between 1965 and 1980 from Nb_3Sn tape that did work reliably [18–20].

4.1. Massachussetts Institute of Technology (MIT) I (1972)

The first hybrid to be energized was at the Francis Bitter National Magnet Lab (FBNML) at the MIT in 1972. The first paper on the outsert was authored by Montgomery *et al* [12]. It was intended to provide 6 T with a 400 mm inner diameter and consisted of 24 ventilated double pancakes made from a 10 mm $\times$ 2 mm copper-stabilized untwisted NbTi conductor with 60 NbTi ‘strands’ (today we would call them filaments) of 0.23 mm diameter. Ventilation was provided in both the axial and radial direction such that helium was able to contact 75% of each conductors inner and outer surface and 20% of each conductor’s top and bottom edge. It was expected to be ‘fully stable (i.e. have a recovery current higher than the operating current). The stability calculations assumed a heat flux of 0.25 W cm^{-2} could be attained [21].

The protection system consisted of comparing the voltages across the two halves of the coil and opening a breaker when a threshold was reached. The magnet was intended to be maintained at 20 K when not being operated and then cooled to 4.2 K for operations. Unfortunately, it did not operate reliably. The wire purchase preceded the recognition of the advantages of twisting. The coil was charged at a rate of 2 A s^{-1}. Flux jumps occurred almost every second for current below 500 A and decreased to once every 10 s at currents above 1200 A. The coil quenched at 1440 A (5.8 T), at 96% of the design current [22, 23].

4.2. McGill

McGill University and RCA developed a hybrid using both Nb_3Sn and NbTi conductors. The outsert's outer coil used 7.9 mm × 1.2 mm copper-stabilized untwisted NbTi conductors with 36 filaments of NbTi ranging between 0.22 and 0.27 mm diameter. These conductors were wound into six nested coils each of which consisted of about 60 pancakes. It was fabricated by Ferranti-Packard Ltd [24].

The inner (Nb_3Sn) coil was fabricated by RCA Electronic Components. There were nine grades of Nb_3Sn conductor used in the outsert's inner coil. All consisted of vapour deposition on a Hastelloy tape measuring 12.7 mm × 0.5 mm. The Nb_3Sn ranged from 63 to 89 μms thick with the thickest being in the highest field regions. One might assume this grading of conductor was employed to minimize the cost of the conductor, but the designers seemed to be early to understand a basic principle of stability: 'since magnet stability is generally greatest for the smallest volume of superconductor, it is desirable to fabricate ribbons with just enough Nb_3Sn to assure a superconductive capability … within each selected field region' [24].

The inner coil was a stack of single-pancakes. Unusually, this coil employed forced-flow helium. The inter-turn insulation allowed flow between turns and perforated insulating sheets between pancakes allowed helium to continue to the next pancake.

The Nb_3Sn coil included steel cylinders at both the inner and outer diameters. There were four steel plates placed between some of the pancakes near the ends of the coil and joined to the steel cylinders. In this way, the axial compression at the mid-plane of the magnet was reduced.

The two SC coils were successfully tested separately. The combined system suffered significant damage during testing, perhaps due to 'previously neglected diamagnetic forces' (screening current effects). The team recommended, among other things, the use of twisted superconductors thereafter [16, 25].

5. First generation of user magnets: $\leqslant$30 T

There were seven hybrid outserts completed between 1973 and 1992 that had goals of 30 T or less. All of these used outserts operating at <10 T that were constructed from NbTi pancakes. They also all ran at 4.2 K, stored less than 10 MJ of energy, and had cold bores between 28 and 41 cm, and little additional reinforcement in the SC coils. Their stored energy densities were also less than 35 J/cc.

5.1. Oxford I (1st put into service, 15 T, 1973)

The first hybrid to serve its intended purpose was the first one developed by Oxford Instruments for Oxford University and completed in 1973. Figure 2 shows an isometric drawing of the magnet with partial vertical section. Similar to the MIT and McGill systems, it used rectangular Cu-stabilized NbTi conductor (6 mm × 1 mm) wound into double-pancakes. Unlike the previous two, it was the first to use twisted conductor with filaments of 90 μms and a 30 mm twist pitch. 46 pancakes were built and stacked. It also used an external resistor for quench protection. The magnet was upgraded from 15 T to 20 T by replacing the resistive insert and served the scientific community until at least 1987 (>14 years).

Seventy-five percent of the conductor surface area is directly cooled. The magnet relies on heat transfer up to 0.38 W cm^{-2} in a cryostable mode as described by Maddock, *et al* [11, 26].

5.2. Moscow (1st 25 T, 1975)

The Kurchatov Atomic Energy Institute (KAEI) and the Efremov Scientific Research Institute of Electrophysical Apparatus jointly designed and built a 25 T hybrid that was put into operation at the KAEI in Dec. 1973. Cheremnykh led the development of the outsert which consisted of 25 double-pancakes of Cu-stabilized NbTi and NbZr multifilamentary wire, 10 mm × 1 mm. The filament diameter was 0.25 mm and there were 30 filaments of NbTi and 18 of NbZr. The SC strip was spiral wrapped with a glass-epoxy cord and then spiral wound to form a ventilated winding with NbTi conductor in the inner diameter and NbZr in the outer section. The magnet was in service for several years. In 1980 there was an attempt to replace the power system [27]. This magnet provided the highest dc field worldwide at its completion, 2.5 T higher than was available in dc resistive magnets.

5.3. Nijmegen I (1977)

The FBNML developed a 25 T, 6 MW hybrid magnet for the magnet lab in Nijmegen, the Netherlands which was completed in 1977. The twisted Cu/NbTi conductor was 10.8 mm wide. The high field grade was 2.9 mm thick while the low-field grade was 1.9 mm thick. Again, conductor was wound into ventilated double pancakes, in this case 22 were used. A second insert was built for this magnet that reached 30 T at 9 MW at the FBNML prior to shipping the outsert to Nijmegen [28, 29]. The magnet was operated until the lab moved to a new building around 2002.

5.4. MIT II (1st 30 T, 1981)

The FBNML completed the first 30 T hybrid worldwide in 1981. The outsert consisted of 22 double-pancakes wound from Cu/NbTi conductor 10 mm × 1.67 mm. 0.5 W cm^{-2} [29]. It was also a 6 T increase in field worldwide.

5.5. Sendai I (1st not ventilated, 1983)

The magnet lab at Tohoku University in Sendai, Japan developed three hybrid magnets in the 1980s. The first to be completed (HM-3 in their notation) was unusual in that it used a 'compact winding' without cooling channels. It would avoid quenching even during a fast ramp of the resistive insert from full field (13 T at 11.5 kA) to zero in 40 s [30–32].

5.6. Sendai II (1983)

The second hybrid outsert in Sendai provided the same field as the first (8 T) but in a bore twice as large (42 cm vs 29 cm cold bore). This magnet was a more typical design for the time using ventilated double pancakes and being fully cryostable per the Steckly criterion [32, 33]. It operated at a heat flux of 0.35 W cm^{-2}.

5.7. Hefei I (1992)

In 1992 the high field lab in Hefei, China completed a 20 T hybrid. Unlike the other 'first generation' hybrids, this one was not cryostable, not ventilated. It used an adiabatic design for the SC coil [34].

6. Second generation: 30 T $\leqslant B <$35 T

They were four hybrids completed between 1985 and 1991 that were designed for central field in the 30 T to 35 T range. To reach these higher field, the magnet designers felt that the outserts needed to provide >10 T in cold bores ranging from 42 to 50 cm. To attain such high fields in such large bores, new approaches were adopted. Of these four magnets, three operated at 1.8 K and two used Nb_3Sn to increase the current density of the superconductors. Three used cold-worked copper within the winding packs to increase the strength. All had a stored energy density >35 J/cc.

6.1. Sendai III (1st 31 T, 1st Nb_3Sn, 1st > 10 MJ, 1985)

Sendai's third hybrid outsert (SM-1 in their notation, figure 3) was a significant step beyond their second one in that it provided 12 T in a bore one centimetre larger than the older 8 T outsert provided. Comparing it globally, it was only 1 T higher field (31 T versus 30 T) than MIT II which was completed a few years earlier, but partly because it used 18% less power than MIT II (7.4 vs 9 MW), the Sendai III outsert had to provide 60% more field than the MIT II version (12 T vs 7.5 T). Providing this significantly higher field than any previous hybrid outsert pushed it into the region of being the first of the second generation of hybrids. While the earlier outserts Sendai I & II were designed based on full cryostatbility (ignoring conduction along the length of the conductor) it was recognized that the magnet could become nearly half the mass if the stability were based on the cold-end recovery current defined by Williams which accounts for heat-conduction along the length of the conductor [26, 35]. (The earler stability criterion This approach resulted in nearly a factor of two reduction in coil mass compared with their earlier design process based on a fully cryostable coil. This was also the first hybrid to successfully use Nb_3Sn as well as the first to report using cold-worked copper to increase the strength of the winding pack to support the hoop tension resulting from the Lorenz forces [32].

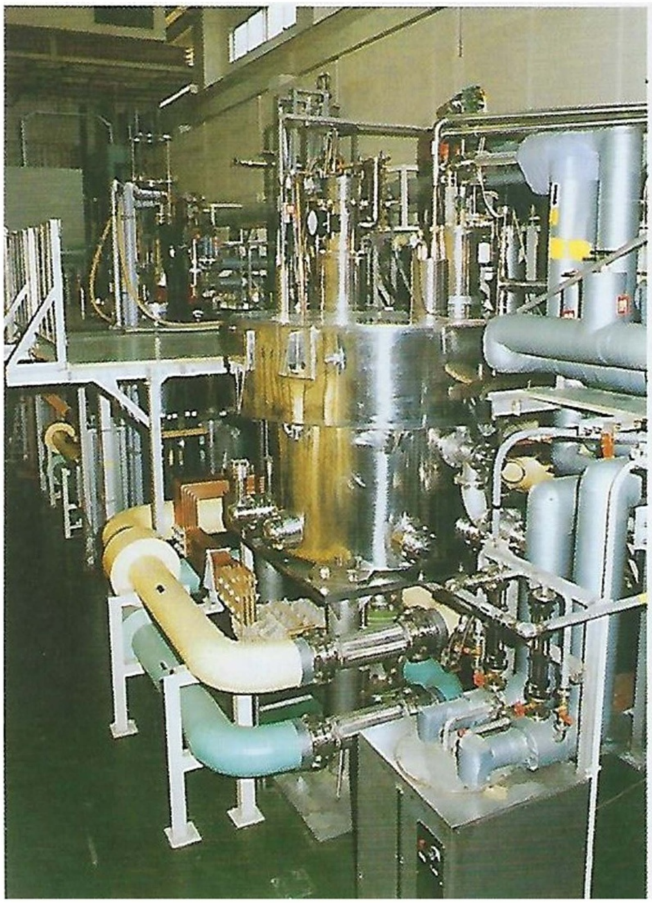

Figure 3. The first of the 2nd generation of hybrid magnets: Sendai III.

6.2. Nijmegen II (1st 1.8 K, 1985)

The FBNML delivered a second hybrid to the Nijmegen magnet lab (4th hybrid developed by the FBNML) that was the first to use 1.8 K helium to increase the current density of the NbTi superconductor and avoid using Nb_3Sn despite pursuing 32 T. The magnet was designed to operate at 0.4 W cm^{-2} and is not fully cryostable [36].

6.3. Grenoble I (1st 31 T in 50 mm bore, 1987)

The joint French–German lab in Grenoble, France reached 30.4 T in a 50 mm room temperature bore in 1987. Like Nijmegen II it used superfluid helium cooling to increase the achievable current density. The outsert provides 11 T in a very large (50 cm) cold bore. The magnet was unique at the time by employing two coils in the outsert. The inner coil is layer wound while the outer one is double-pancakes. 40% of the surface of the conductor is available for cooling [37, 38].

6.4. MIT III (1st 34 T, 1991)

MIT completed their third hybrid for in-house use (plus two delivered to Nijmegen) in 1991, reaching 34 T for the first time. It was only the second hybrid to successfully employ

Nb_3Sn conductor in a react-and-wind approach. By reacting prior to winding, it was possible to use cold-worked copper co-wound with the superconductor to help support the hoop tension. The inner Nb_3Sn coil was layer-wound while the outer NbTi coil was double pancakes. The Nb_3Sn coil had spacers to provide helium ventilation between both the turns and the layers [39].

An early design was fully cryostable, but was excessively large. To reduce the size, a 'quasi-adiabatic' approach was taken for the NbTi coil that eliminated cooling channels as well as used cold-worked copper for re-inforcement. Adiabatic coils are mechanically advantageous in that the outer turns support the inner ones, reducing their hoop stress as well as having higher radial modulus. They also have an advantage during quench in that quenches propagate quickly resulting in relatively uniform temperatures after quench. The quasi-adiabatic approach eliminates cooling channels between turns of the double-pancakes to provide a more compact coil with high radial modulus but retains the cooling channels between pancakes to enhance stability. The SC coil also had unusually high current density and stored 74 J/cc, nearly twice that of other magnets in this range of field and stored energy [40].

7. Third generation: >35 T

Eight hybrids have been constructed to reach fields >35 T. Six of them have been put into operation while one is presently being tested [41] and one is in final assembly. All of them store more than 25 MJ in the SC coils and require significant reinforcement to contain the Lorentz forces.

The conductor/coil technology being used during this most recent period shows significant innovation compared with earlier ones. Five of the eight outserts in this generation use cable-in-conduit conductor (CICC), an approach initially developed for the fusion community (figure 4). This approach uses a steel conduit to support the Lorentz forces and protect the conductor from axial compressive stress at the midplane. Super-critical helium usually flows through the voids in the cable providing stability during insert trips. One magnet used copper clamshells around the conductor to support the Lorentz forces. Another used stainless steel strip co-wound with Rutherford cables to provide re-inforcement. One being tested presently uses Rutherford cable soldered to a copper channel (figure 10). Most of them store more than 45 J/cc.

7.1. Tsukuba (1st 36 T, 1995)

In 1995 the Tsukuba Magnet Lab (TML) and Toshiba Corp. completed a hybrid that eventually reached >37 T. This was the world record at the time. While there was only a single SC coil, it included four grades of cryostable superconductor wound into double-pancakes. The outer two conductors are NbTi monolithic multi-filamentary rectangular conductors while the inner two are $(Nb, Ti)_3Sn$ multifilamentary monoliths with copper clamshells to provide strength. The space between the clamshells and composite superconductor are filled with solder on three sides while the fourth side is

Figure 4. A piece of cable-in-conduit conductor (CICC) from the 45 T hybrid magnet in Tallahassee (MagLab I). This approach has now been incorporated into five different hybrids worldwide.

intentionally left with a void between the clamshells and the conductors so that axial compressive forces in the coil are borne by the Cu-cladding, without compressing the strain-sensitive $(Nb,Ti)_3Sn$ conductor. These conductors also contain pure aluminium wire to maintain the spacing between the composite and the clamshell. It is assumed that heat fluxes up to 0.41 W cm^{-2} can handled. The Sn-based conductors are oxidized to increase the heat transfer coefficient while the Ti-based conductors are coated with polyvinylformal [42, 43].

7.2. MagLab I (1st CICC, 1st 45 T, 2000)

In 1999 the MagLab in Tallahassee, Florida energized a hybrid magnet to 44 T [2]. This was the first hybrid to use Cable-in-Conduit-Conductor, a technology developed for the fusion power community (figure 4), and the first to go beyond 38 T. It might also have been the first hybrid outsert designed with a specific fatigue life specification. It also had an unusual feature of not only operating at 1.8 K but having the top of the cryostat clear to allow maximum access for the users to set up experiments on the top of the magnet cryostat. In addition, it was designed to reach full design current in only 15 min [13].

The inner two coils were made of layer-wound Nb_3Sn CICC while the outermost was 29 NbTi CICC double-pancakes. The magnet was designed to operate at 10 kA, more than four times the current of any other hybrid at that time. The stored energy was the largest to date at 98 MJ, compared with 64 MJ for the previously largest hybrid (Tsukuba). The conductor included 40% void space inside the conduit to provide high enthalpy (stability margin) with a minimum temperature margin of 0.5 K [2, 13]. The use of a temperature margin is common in the design of CICC magnets, but this might be the first time it was used in a hybrid outsert. Figure 5 shows the SC coils after winding, reaction, stacking, jointing, and assembly, prior to the helium vessel being closed.

The SC magnet experienced an unprotected quench in June of 2000 which prevents it from operating at more than 8 kA

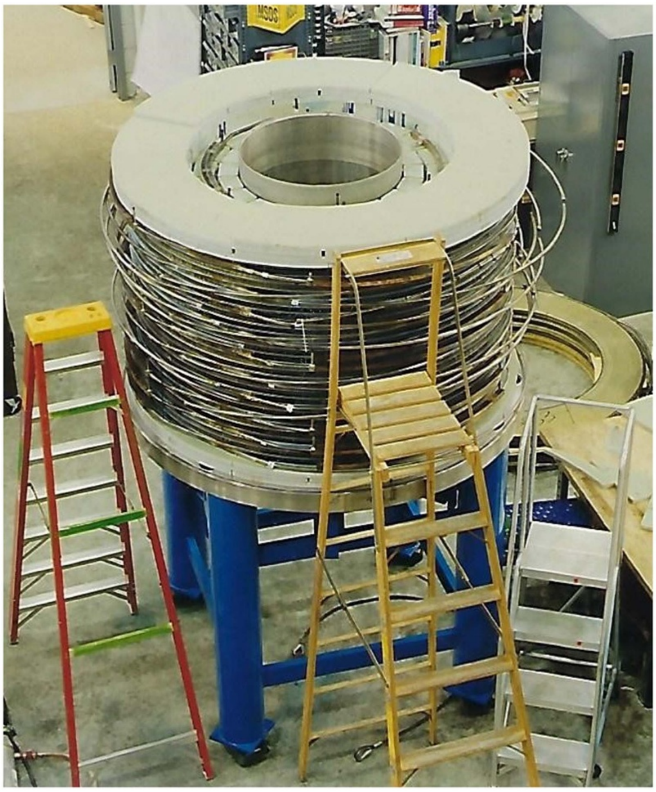

Figure 5. Photo of CICC coils of MagLab I after being assembled and prior to the helium vessel being closed. [Photo Credit: MagLab archives].

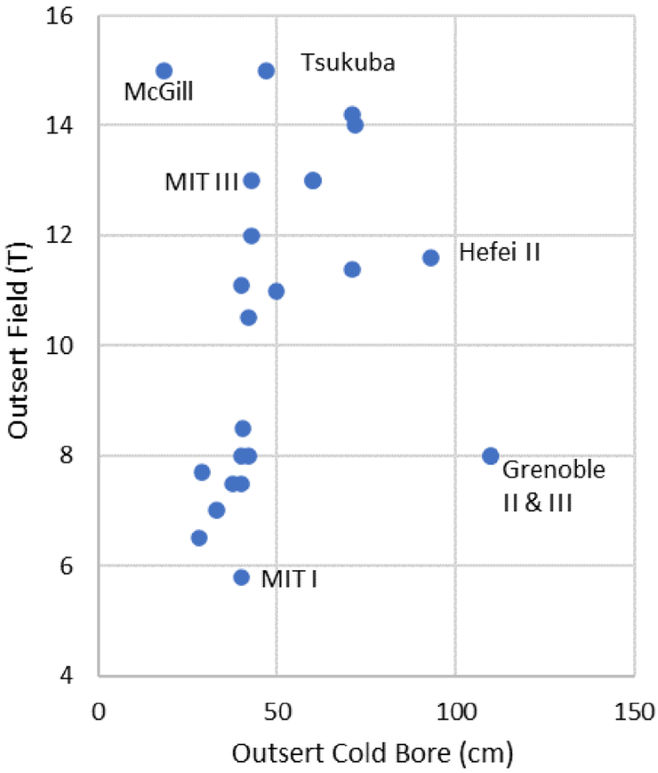

Figure 6. Field vs bore of hybrid outserts. The Grenoble II and III magnets have an extremely large bore for their fields.

[44, 45]. The resistive magnet was upgraded to return the system to 45 T in February 2001, albeit at a higher current and power than initially intended [46, 47]. It has held the world record for 23 years.

7.3. Grenoble II (1st NbTi Rutherford cable, largest bore)

The first Grenoble hybrid magnet was taken out of service around 1995 or 1996 due to becoming 'dissipative' [48]. In 1996 a paper was published with magnet design concepts for a new hybrid to reach in excess of 40 T [49]. The project started in 1997. Oxford Instruments was contracted to deliver most of the system except the resistive coils which would be provided by the Grenoble lab. The outsert had an exceptionally large bore combined with modest field: only 8 T in 1100 mm cold bore (see figure 6). It used an unusual design: impregnated coils of NbTi Rutherford cable operating at 1.8 K. The Rutherford cable includes a stainless-steel strip insert to support hoop stress, reduce coupling currents, and increase the specific heat of the conductor. The three coils were kept slender to allow sufficient heat to transfer to the helium bath during an insert trip. The stored energy is only 30 J/cc, about half that of other third-generation hybrids [50, 51].

This magnet was also intended to survive the resistive magnet tripping off without quenching. To accomplish this, there is a copper cylinder, reinforced by a stainless-steel cylinder, between the outer diameter of the resistive coils and the inner diameter of the SC coils. If the resistive magnet trips off, the decaying field induces current in the quench shield which then decays. This slows the transient $\Delta B/\Delta t$ that the SC coils experience (Δt increases from 0.6 s to 5 s). Given that the power associated with coupling loss is proportional to $(\mathrm{d}B/\mathrm{d}t)^2$, this results in significant reduction in ac loss. The quench shield is located inside the SC magnet cryostat and is maintained at 50 K [50].

In an unusual step, the quench protection is accomplished by a combination of an external dump resistor and internal quench heaters [52]. Testing of the SC coil started in 2002 [51]. The magnet was intentionally quenched by firing the heaters in the innermost coil and having the protection system respond. It was observed that the quench was propagating faster in the middle coil than expected resulting in higher voltages [52].

The SC coil reached guaranteed field (7 T) but was unable to ramp as quickly as planned. It was concluded that there was a short between two turns within the inner SC coil. Numerical modelling indicated that the short was in the outermost layer of the innermost coil. A plan was developed to warm up the magnet and locate the position of the short [53]. The magnet was warmed and the short repaired, but the Grenoble lab wanted the coil replaced rather than repaired. The SC coil was returned to OI for refund.

7.4. MagLab II (1st 1 ppm, series-connected, 2017)

The MagLab in Tallahassee, Florida, USA secured funding for the design of a new hybrid where the resistive and SC coils would be electrically in series in 2004. This Series-Connected

Hybrid (SCH) magnet would employ 20 kA CICCs for the SC coil. This was twice the current of the 1st MagLab hybrid and 8.6 times the current of any other hybrid worldwide at that time. The magnet operates at relatively high current density and has the highest ratio of stored energy to volume of any of the hybrids (81 J/cc).

Series-connection was chosen for a few reasons. First: the inductance of the SC coils are orders of magnitude higher than those of the resistive coils (200 mH vs 9 mH in this case). By connecting them in series, the field ripple due to the thyristor-based power supply would be significantly reduced compared with if the inductance of the SC coil was not in the resistive magnet circuit. This was important because this magnet was also unique in being designed mainly for nuclear magnetic resonance (NMR) experiments where field stability is much more important than for a typical hybrid magnet. Second: in a standard hybrid that uses separate power supplies for the resistive and SC coils, if the power supply for the resistive coils trips off, a large current is induced in the SC coil which results in a higher field on the coil as well as high temperature due to ac losses. In addition, the fringe field of the resistive coils is of opposite sign as that of the self-field of the SC coils. When the resistive coil drops, the field on the outsert jumps, even if there were no current increase in the outsert. Consequently, the SC coil needs to be designed for this high current, high field, and high temperature operating condition which is not a normal operating condition. Series-connection of the coils eliminates these effects. When the power supply for the resistive magnet trips off, the current decays much slower. Third: this approach avoids the need to build a separate power supply for the SC coil: one could use the existing power supply of the resistive magnet. Fourth: the magnet would be able to sweep from positive full field (+36 T) to negative full field (−36 T) in one hour. Data could be collected over 72 T of field change. A traditional hybrid design would have the outsert field on all day (13 T) and sweeping to collect data would be limited between 13 T and 36 T [1, 54].

The main disadvantage of this approach is that in a traditional hybrid, the SC coil is only cycled to high field once per day and the insert is cycled multiple times. In the SCH approach, the SC coil would see far more fatigue cycles during a 20 year lifetime than a traditional design would.

At the time the 'construction' proposal for this project was submitted in 2005, Nb_3Sn CICC magnet technology had been around for >24 years [5] and the MagLab had developed its 45 T hybrid (MagLab I) which had been in operation for about six years. Developing another Nb_3Sn CICC magnet was seen as being relatively straight-forward. However, in early 2006, test results of Nb_3Sn CICCs for the European DIPOle and ITER became available showing Nb_3Sn CICCs only carrying 50% to 65% of the expected current [55–57]. Researchers at the MagLab set out to explain the low performance of these conductors and developed the Florida Electro-Mechanical Cable Model.

During cooldown, Nb_3Sn strand experiences much less thermal contraction than steel does. Consequently, after cooldown of a Nb_3Sn CICC, the SC cable is in axial compression of approximately 0.6% while the stainless-steel conduit has slight axial tension. Traditionally, this compression had been assumed to be simple axial compression, uniform across all strands. In reality, because the strands are twisted to make the cable, applying axial compression to the cable means individual strands have significant bending. In addition, when the magnet is energized, Lorenz forces are applied which create some hoop tension and more bending. The result is that the strain in the strands is not uniformly −0.6%. The strain can be tensile in some places and compressive in others with values exceeding 1% compression. The tensile strains can result in cracking of the filaments of the strand and degradation of the CICC. A warm-up/cool-down cycle can also induce more degradation [55, 58]. Extensive testing of Nb_3Sn CICCs was undertaken at the MagLab to demonstrate these concepts experimentally and to prove the performance of the final CICC design. Figure 7 shows the split 12 T magnet with 150 mm bore provided by Oxford Instruments assembled with a CICC in its gap. The assembly is about to be lowered into the cryostat for measuring critical current as a function of applied magnetic field, transport current, and applied tensile strain.

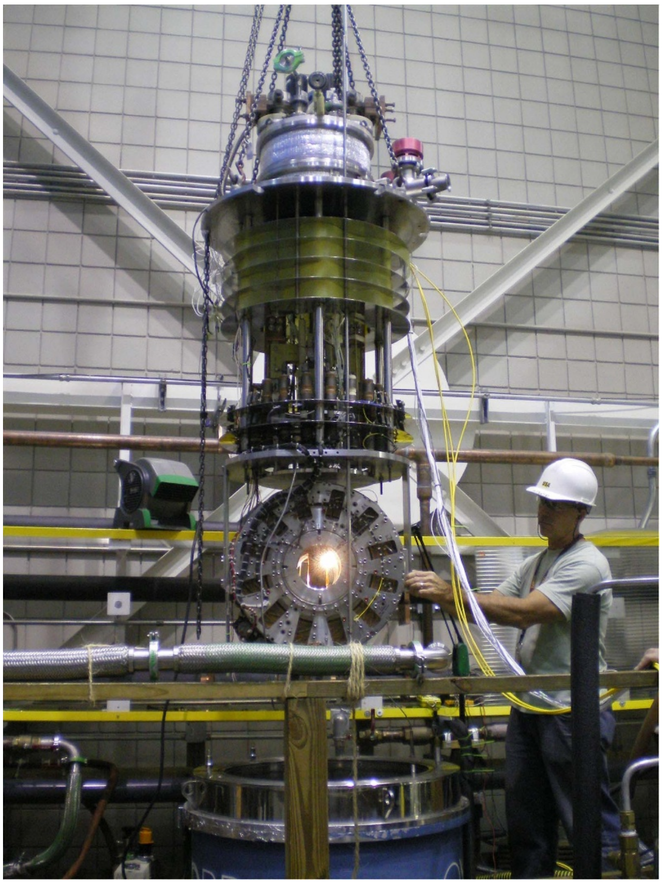

Figure 7. Preparing a Nb_3Sn CICC for testing to high field and current while applying axial tension. (Photo Credit: MagLab Archives).

The magnet took the unusual approach of using a single Nb_3Sn coil. At this time, high field solenoids typically use Nb_3Sn only for the section of the coils that operate above ∼10 T. The lower-field regions are usually made from NbTi. However, in a design consisting of single Nb_3Sn coil, the coil has radial compression and the high Lorentz forces in the inner layers is supported partly by the outer layers which have lower Lorentz forces. In contrast, nested coils would result in the inner Nb_3Sn coil having hoop tension which would require significantly thicker steel conduit to support the Lorenz force. In addition, there would need to be gaps between the coils to allow assembly. These two effects together result in a significantly large SC magnet with multiple coils than with a single coil. The total cost was estimated to be lower with the single coil. There was some concern about flux jumps in the outer region of the Nb_3Sn coil that would be operating at <2 T. Conductor tests allayed these concerns and the magnet was built without a NbTi section. It did have three grades of conductor all using the same Nb_3Sn wire but more strands in the high field section than other two [59, 60]. The single coil approach was chosen.

The magnet was cooled by forced-flow super-critical helium (10 g s^{-1} at 4.5 bara) that flows in parallel through all the layers of the magnet. Like other CICCs, the stability criterion was a temperature margin, in this case 1.0 K [61].

As mentioned above, this magnet was intended mainly for NMR experiments. Consequently, there was significant effort made to stabilize the power supplies resulting in field ripple less than 0.3 ppm [62]. In addition, it was necessary to shim the magnet to less than 1 ppm over 1 cm DSV. This was accomplished by a combination of ferroshims and resistive shims. While SC magnets are routinely shimmed to 1 ppb for NMR, this magnet included a high field resistive magnet. High homogeneity SC magnets are typically made with long coils to reduce the z2 and z4 terms. Gaps and notches are used to generate negative z2 and z4 terms that cancel the residual terms in the other coils. With high field resistive magnets, long coils are not practical because they consume more power than short coils and one is always seeking the highest possible field. Consequently, the homogenization process relies purely on gaps and thicker turns at the mid-planes of some coils. This results in a sum of z2 and z4 turns that can be acceptable, but the magnitude of each term is much larger than in a magnet with long coils. Consequently, the field profile is much more sensitive to misalignment than in a long-coil magnet [63, 64].

The magnet was also unique in that is included a shield to reduce the fringe field. Initially the plan was to use an SC shield coil with roughly twice the diameter as the outer diameter of the main SC coil. However, an octagonal wall of low-carbon steel was eventually chosen in light of cost considerations.

7.5. Berlin (series-connected for neutrons)

In 2007 the Hahn–Meitner Institute (now Helmholtz Zentrum Berlin, HZB) partnered with the MagLab in Tallahassee to build a new neutron scattering beamline at their existing reactor to be used for neutron scattering in high magnetic field. HZB wanted a magnet with a vertical field and a split at the mid-plane. A split hybrid magnet was seen to be too large an undertaking given that the MagLab's magnet development team was already developing a resistive split 25 T magnet as well as the 36 T hybrid (MagLab II) described above. An agreement was made to develop a magnet with the same outer SC coil as the one for MagLab II but mounted with the bore horizontal and making the bore a converging-diverging cone with a half-angle of 15 degrees. Furthermore, the magnet was to be mounted such that it can swivel ±15 degrees about a vertical axis passing through field-centre. In such a manner, scattering data can be collected in a horizontal plane ±30 degrees from the beamline, on both the downstream and upstream sides of the magnet [65, 66].

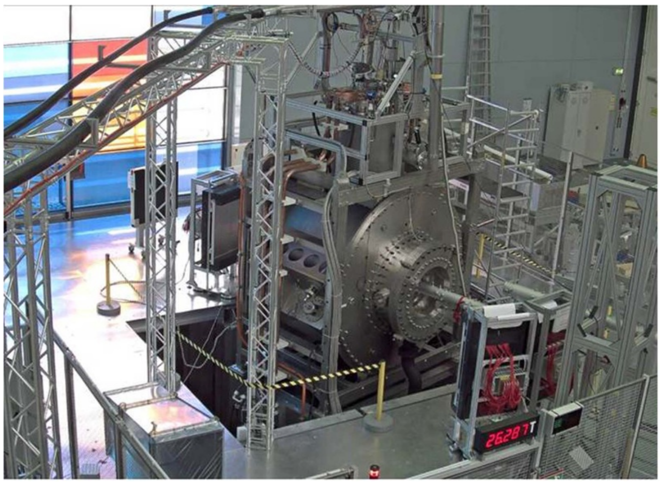

Figure 8. The 26 T hybrid magnet from the MagLab operating at the Helmholtz Zentrum Berlin in 2015. The neutron beamline enters the magnet from the right. Some neutron detectors are visible on the left of the magnet. (Photo Credit: MagLab Archives).

By developing the HZB magnet concurrently with the MagLab II magnet, design and development costs did not need to be borne exclusively by either organization. In addition, the MagLab was conducting a design study for another neutron scattering magnet for the Spallation Neutron Source at Oak Ridge National Lab (ORNL) in Tennessee [65] which further diversified the funding base.

While the magnet was being developed in Tallahassee, the Berlin team had to design and build the 4 MW power supply, chilled water system, cryogenic system, control system, and the building to house them.

The cold mass for the HZB magnet left Tallahassee in October 2013 and went to Chivasso, Italy where Criotec Impianti assembled most of the cryostat around it. The assembled outsert and cryostat was then shipped to HZB where the 20 kA current leads developed by EPFL in Villingen, Switzerland were installed followed by the cryostat being closed. The magnet reached full field in a test facility at HZB in October 2014 and was then moved into the neutron guide hall in December 2014 where it was operated with the beamline in summer 2015 (figure 8) [67].

In March 2011 the Fukushima Daiichi power plant in Japan experienced a nuclear accident due to an earthquake, a tsunami, and other factors. Sometime later, the German government decided to close many nuclear reactors in Germany including the one at HZB. Consequently, it was known before the magnet arrived in Berlin that there would be no neutron scattering after 1 January 2020. The magnet operated 4.5 years and was quite successful. In 2022 an agreement was signed between HZB and ORNL to move the magnet to ORNL. The intention is to replace the resistive coils with ones constructed from high-temperature SC (HTS) materials and install the magnet for neutron scattering at the Second Target Station.

7.6. Hefei II (2nd 45 T, 2022)

The magnet lab in Hefei, China built a new dc magnet facility with 24 MW of installed power. The first resistive magnets were running in 2014. The development of a hybrid magnet to provide 40 T or more was initiated around 2009. The magnet had an unusually large bore at the time it was completed, as shown in table 1 and figure 6 at 11 T in an 80 cm bore.

Like the recent magnets developed in Tallahassee, it used Nb_3Sn CICC with three nested coils and four grades of conductor (two in the innermost coil). The inner two coils were layer-wound while the outermost was pancake-wound. The magnet reached its official goal of 40 T in 2016. However, most of the papers published about the project indicated that it was intended to reach 45 T. The resistive coils were improved and 45 T was reached in August 2022 [68–70]. The magnet reached ∼0.1% higher field than MagLab I.

7.7. Grenoble III (1st Rutherford Cable on Conduit Conductor (RCOCC), largest bore)

After returning the SC coils built for the Grenoble II hybrid to Oxford Instruments, the Grenoble magnet lab initiated a third hybrid magnet project using the cryostat and resistive coils from the Grenoble II project, this time partnering with CEA-Saclay and Alstom. The conductor chosen was a NbTi Rutherford cable soldered to a copper tube, similar to what was used in the SULTAN magnet [71]. It uses NbTi Rutherford cable brazed onto a hollow copper alloy tube of rectangular cross-section. Super-fluid helium at 1.8 K fills the inside of the copper tube. This conductor is referred to as RCOCC (figure 9). One goal of the project is to avoid quench of the SC coil if the resistive insert trips off. The quench shield from the Grenoble II magnet is employed to reduce the dB/dt the SC coil experiences. In addition, the conduit is Cu–Ag0.04%, the silver being added to keep the RRR $<$ 60, thereby limiting the ac losses during such a trip [72].

This magnet has been fully assembled and testing started in 2022. The 24.4 ton cold-mass was cooled down to 1.8 K, passing the superfluid transition on October 22. The system was warmed up to 4.4 K where power tests up to 2 kA (design value of 8.5 kA) were performed. The magnet was warmed up for repairs and improvements. In 2023 a second phase of tests of the SC coil alone were undertaken to full current. In addition, the bitter coils were energized and ramped down quickly to verify ac losses in the outsert during such cases. The magnet was warmed up again. The third phase of testing was expected to start in September 2023 [41]. As of this writing (July 2024) no additional information is available. Perhaps something will be presented at the upcoming Applied Superconductivity Conference. Figure 10 shows the final magnet assembled in its cryostat.

Figure 9. Rutherford Cable On Conduit conductor for the Grenoble III hybrid. The NbTi strands are. © (2011) IEEE. Reprinted, with permission, from [73].

7.8. Nijmegen III (>45 T)

In 2012 the magnet lab in Nijmegen, The Netherlands entered an agreement with the MagLab in Tallahassee to develop the SC coil for a 45 T hybrid magnet. In 2015 the design was modified to possibly allow for operation to 46 T [74]. The SC coil was to be Nb_3Sn CICC using forced-flow SHe. The fabrication specifications and processes for the cables was to be the same as those used for the earlier MagLab II and HZB hybrids. The operating current was to also be 20 kA. The conduit wall thickness was to be slightly thicker than that of the earlier magnets to accommodate the higher hoop stress due to the inner diameter of the coil being slightly larger than those of the other two magnets. The cold mass was shipped from Tallahassee in March 2018 [75–77].

The cryosat was designed at the Nijmegen lab and components were fabricated commercially. The resistive coils were designed in Nijmegen with input from the MagLab. Assembly is well underway (figure 11). A planning meeting for the final assembly and testing was held in March 2023.

Figure 10. View of the Grenoble hybrid magnet III assembly (52 tons) with the outer vacuum chamber of the superconducting magnet cryostat. The central part contains resistive inserts with the water cooling pipes visible on both sides of the water box located on the top of the cryostat. The cryogenic satellite producing the superfluid He can be seen in the background. It is connected to the magnet cryostat via a cryogenic line in parallel to the quench line. © (2023) IEEE. Reprinted, with permission, from [41].

8. Fourth generation: cryogen-free

With the cost of both liquid helium and the space for a helium refrigerator to re-liquify used helium becoming larger concerns, several commercial magnet manufacturers have started to provide cryogen-free SC magnets. The Sendai magnet lab has gone a step further and developed two cryogen-free hybrid magnets described below.

8.1. Sendai IV (1st cryogen-fee, 2003)

In 1998, the magnet lab in Sendai, Japan partnered with Fujikura Ltd and Sumitomo Ltd and submitted a paper describing a cryogen-free 10 T magnet with 360 mm room-temperature bore to serve as the outsert for a hybrid magnet [78]. This was based on experience with a number of cryogen-free SC magnets the lab had developed over the years [79]. To reduce the size of the cold mass and the time required for cool-down, a novel wire is used for the inner two coils: CuNb/(Nb,Ti)$_3$Sn in which a part of the common high purity Cu stabilizer is replaced with the high strength Cu-20 wt.%Nb composite [80]. The final design of a 23 T cryogen-free magnet ended up being half the size of the 23 T helium-cooled magnet (Sendai II) it was replacing.

Figure 11. The cold mass of the Nijmegen III hybrid in 2024.

To keep the heat load from the current leads to a minimum, the magnet was designed to operate at no more than 180 A. This is somewhat remarkable: the previously lowest current for a hybrid outsert was 780 A, in the Sendai I, back in 1983. However, it is only a 2.7 MJ system. The system uses four GM-cryocoolers during cool-down. The magnet also used an unusual react-and-wind approach using high tension during winding [78, 80].

Interestingly, the stability calculations for this cryogen-free hybrid are based on the temperature margin, similar to that used for CICC magnets, which have helium in direct contact with the SC strand. Another advantage of the cryogen-free concept is that the magnet can operate at <4.2 K without a complicated cryogenic system. This results in higher critical current and temperature margin in the conductor, particularly in the NbTi conductor [80].

While the magnet was the first cryogen-free hybrid, it was not particularly high field for a hybrid at that time. However, it was higher field than was available from all-SC magnets at that time. The previous helium-cooled 23 T hybrid magnet (Sendai II) that was replaced by this cryogen-free hybrid consumed 510 000 l of helium over a 17 year period [80]. A second resistive insert was developed to provide a large experimental volume (52 mm vs 32 mm at room temperature) with ~1.2 T less field [81].

8.2. Sendai V (2005)

A 30 T cryogen-free magnet project was undertaken prior to the completion of the 23 T version (Sendai IV). In this one, the SC coils provide 11 T on-axis instead of 8 T but in a bore of the same size (40 cm). The design temperature margin was 0.5 K [82]. This one operates at up to 350 A and uses four GM-cryocoolers [83]. The magnet was eventually put into service at 28 T [84].

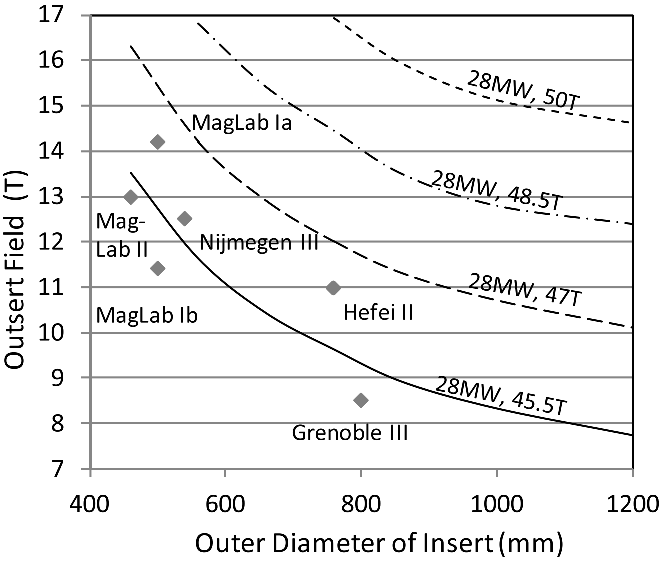

Figure 12. Field and space available for the resistive insert of several hybrid magnets worldwide along with projections of the field and bore size required for hybrid magnets extending to 50 T using 28 MW of power.

9. Potentially higher fields

The record field from a hybrid magnet has been 45.2 T since 2000 [2, 70]. As described in section 7.8, the third hybrid in Nijmegen is nearing completion and might approach 46 T [74]. Figure 12 shows points representing the field and bore of the outserts of some of the largest hybrid magnets available presently. MagLab Ia is the original version of the 45 T hybrid in Tallahassee (14.2 T at 10 kA). MagLab Ib is the present versions of it since the unprotected quench (11.4 T at 8 kA).

In addition, curves showing projections of what combination of field and bore is required from an outsert in order for the combined system to reach field values between 45.5 T and 50 T using 28 MW of power for the resistive coils are provided. These projections are based on the resistive magnet design principles used at the MagLab which have enabled ~20 record resistive magnets to be delivered over the years [6]. For example, to reach 45.5 T using 28 MW, the solid curve gives a set of field and bore combinations that would be sufficient ranging from 7.7 T in 1.2 m to 13.5 T in 0.46 m. MagLab Ia provided 45 T with 26 MW in the insert while MagLab Ib which provides less field in the same bore requires 30 MW of power to reach the same field. Twenty-eight megawatts was chosen because it is the maximum power presently available from two power supplies at the MagLab. It is also about the power level available at the Hefei, Nijmegen, and Grenoble labs.

The existing hybrid magnets are seen to cluster around the curve labelled '28 MW, 45.5 T'. This means that magnets actually on the curve could reach 45.5 T, if the insert were designed using Tallahassee design principles. The next curve up is labelled '28 MW, 47 T'. If an outsert were on this curve, then with a 28 MW magnet, the total field would be 47 T. Hence, these outserts are better suited to higher field systems than ones on the lower curve. In general, a magnet that is above a particular curve is better suited for high fields than one that is lower than the same curve, despite the fact that they might have different fields and bores. We see that MagLab Ia and Hefei II are similarly spaced between the 45.5 T and 47 T curves. Hence they are similarly useful in pursuing ultra-high fields with fixed power, despite the fact the one in Tallahassee having been completed 16 years earlier.

Furthermore, the Grenoble III magnet is below the '45 T' curve. This means that it would require more than 28 MW of power for this system to reach 45 T. But, given that its bire is very large, it is in fact feasible to constructively use more than 28 MW in this volume if it were available. In contrast, he MagLab I and MagLab II magnets have relatively small space for the resistive magnets, hence (while it is not shown here) one cannot effectively use more than about 28 MW of power in such a small bore. These magnets cannot be upgraded to higher field by upgrading the power supply and replacing the relatively inexpensive resistive magnet.

When designing a new hybrid, a design team might generate curve similar to those above. For example, if one wanted to design a 47 T magnet using 28 MW, one would design a number of combinations of inserts and outserts that meet the requirements, using one's own design standards. One would see a curve similar to the one shown above. The team might then try to determine which magnet along the curve would be cheapest and/or lowest risk to build. This process was used for the MagLab II project with the resulting choice being shown in figure 12 and table 1.

Upgrades are presently underway in Hefei and Grenoble. Hefei presently uses 26.7 MW [85]. The power supplies and chilled water system are now being upgraded from 28 MW to 42 MW [86, 87]. The Hefei lab expects to reach 48 T in 2026 [88]. Similarly, the Grenoble lab is upgrading their power supplies and chilled water system and is considering upgrading the 43 T hybrid to 46 T at some point.

In 1996 John Miller suggested that a 60 T hybrid magnet might be developed using LTS and resistive magnet technology [1]. In 2005 the Committee on Opportunities at High Magnetic Fields that had been appointed by the US Mational Academy of Science issued a report recommending that a 60 T hybrid magnet be developed [89]. Shortly afterwards, a 55 T concept was presented based on an LTS and resistive technology [90]. Since then three additional papers have been published that include 60 T concepts but also require the use the HTS materials [91–93] In addition, an abstract was accepted for a poster to be presented at the 27th International Conference on Magnet Technology in Fukuoka Japan about a conceptual design study on future higher field hybrids that included a 14 T, 1.8 meter warm bore outsert, but the paper was not presented.

Figure 13 shows the field and warm bore of the LTS part of these potential hybrid outserts along with the same parameters for the largest hybrids that presently exist or are under construction. The Tallahassee and Grenoble versions include HTS coils of larger size than had been realized at the times those papers were published. Details of the Hefei design are not yet public. If we look at the Grenoble IV star in figure 13, we see

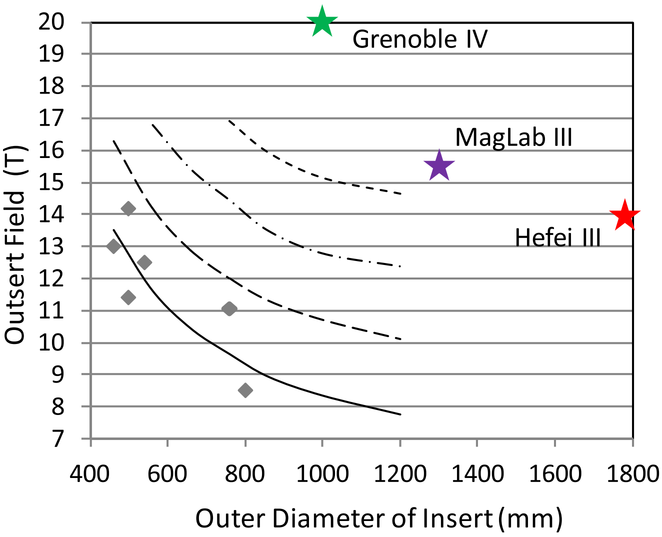

Figure 13. Field and bore of potential LTS coils of higher field hybrids being considered in Tallahassee, Grenoble, and Hefei compared with the largest existing hybrid outserts today.

that it is 20 T in ∼90 cm bore. In comparison, the existing hybrid with the largest bore is Grenoble II which only provide 8.5 T in 80 cm. This new Grenoble IV concept provides 2.4 times the field in a bore 1.12 time larger. The new magnet is clearly more demanding than any of the existing magnets. Determining which of the three proposed designs (Grenoble IV, MagLab III or Hefei III) is the best approach is a matter of some debate. Obviously, the three labs have chosen different configurations.

10. Summary

The first resistive-SC hybrid magnets were completed over 50 years ago. The first generation of successful systems (mostly 1973–1984) typically used rectangular NbTi conductors that were pancake-wound and stacked to form ventilated windings at 4.2 K with liquid helium in direct contact with every turn of the coil. Two exceptions were adiabatic coils in Sendai, Japan and Hefei, China. The second generation of hybrids reached fields in the 30–35 T range (1985–1991) and included either NbTi operating at 1.8 K or Nb_3Sn operating at 4.2 K. They also frequently required more sophisticated reinforcement than the earlier generation but continued to use ventilated windings. The third generation of magnets (completed since 1994) typically operate beyond 35 T and store more than 25 MJ of energy. Reinforcement of these systems is more sophisticated than earlier generations and only the first one in Tsukuba uses ventilated windings. Of the rest, five are CICC, one was Rutherford cable, and one being tested is RCOCC. A new trend, cryogen-free systems, has been demonstrated twice in Sendai, reflecting the increasing cost of liquid helium in this millennium. It is interesting how the perception of required cooling power has varied with time, ranging from fully cryostable up to dry magnets cooled by cryocoolers. Unfortunately, there is not much data available on reliability of these magnets. That is, the rate at which they can be charged to full field and the frequency of quenches is not publicly available.

In December 1999 the Tallahassee hybrid served its first user at record field. This magnet has been operating reliably at 45 T since January 2001 and was only matched by the lab in Hefei, China in the summer of 2022. Presently the lab in Grenoble, France is testing a hybrid using a novel RCOCC approach operating at 1.8 K that is supposed to operate at 43 T. (Interestingly, both the Hefei and Grenoble labs have power supply upgrades nearing completion that should allow the resistive coils of their hybrid to be upgraded to higher field.) The lab in Nijmegen, The Netherlands is also finishing assembly of a magnet intended to reach 46 T.

Moving forward, a recommendation was issued in 2005 by a committee appointed by the US National Academies of Science (NAS) to develop a 60 T hybrid magnet system [89] that was reiterated in 2013 by a different NAS committee [94]. When the first of these reports was issued, there had not yet been a magnet using HTS materials put into service at field higher than had been attained by LTS magnets, yet it was clear to some in the field that a 60 T hybrid would require HTS materials [90]. Since then, REBCO conductor has been used for several very high field magnets with small bores and is being used by fusion companies for ∼20 T magnets at a much larger scale [95]. A 60 T hybrid seems to be nearing feasibility and three groups have proposed very large systems including HTS materials to reach this goal [92, 93]. It seems likely construction of such a system will be initiated in the near future.

Data availability statement

No new data were created or analysed in this study.

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