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Preface

Recent advances in superconducting magnets for MRI and hadron radiotherapy: an introduction to '*Focus on superconducting magnets for hadron therapy and MRI*'

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The '*Focus on superconducting magnets for hadron therapy and MRI*' special issue of *Superconductor Science and Technology* describes superconducting magnets for medical applications. The invention of magnetic resonance imaging (MRI) in the late 1970s has transformed superconductivity from a scientific curiosity to a phenomenon that improves people's lives. Superconductivity benefited MRI by making the modality commercially feasible: over 40 000 superconducting MRI scanners were installed in hospitals worldwide.

Hadron radiotherapy uses heavy ions accelerated by superconducting or conventional magnets. The heavy-ion beams exhibit a very sharp Bragg peak in a patient's body, enabling the concentration of a dose within a tumor while minimizing the dose to the surrounding normal tissues. The first heavy-ion beam radiotherapy facility was built at the Lawrence Berkeley National Laboratory in 1957. Hadron therapy for cancer became an available medical practice since the early 1990s when several facilities were opened worldwide. For example, over 10 000 patients were treated in one of these facilities, the Heavy Ion Medical Accelerator of the National Institute of Radiological Sciences in Chiba, Japan, since it opened in 1994 [1]. Superconducting magnets are being increasingly used in this application for particle accelerators, and for particle beam guidance and focusing on the delivery gantry.

This special issue concentrates on new developments in these applications of superconducting magnets including ultra-high field (UHF) MRI magnets [2, 3], a review of high-temperature superconductivity (HTS) and MgB_2 superconducting materials for use in MRI [4], new MRI architecture for HTS MRI magnets [5–9], and new applications of superconducting magnets in hadron therapy [10]. We envisioned this issue as a topical review: authors were requested to outline system requirements for the magnet, describe scientific challenges, technical and manufacturing trade-offs, and discuss future trends and demands in the MRI magnet technology. Based on this review, we may conclude that mature, well-established low-temperature (LTS) NbTi conductor technology remains the conductor of choice for medical applications in the foreseeable future, especially for commercial whole-body 1.5 and 3 T MRI scanners. Alternative magnet architectures are being considered in other applications, but these still require significant development in both conductor and magnet technology.

Denis Le Bihan and Thierry Schild [2] describe the world's strongest 11.7 T (500 MHz resonance frequency) Iseult MRI magnet. This scanner for the exploration of the human brain is currently under installation at the NeuroSpin center (Saclay, France). The scanner will be able to acquire images at a scale of

100 μm, and to create new approaches to develop new imaging biomarkers for specific neurological and psychiatric disorders. The paper begins with a detailed analysis of the requirements to UHF MRI scanners and magnets that allows for, in addition to the standard MRI procedures, the exploration of the brain's chemistry, metabolism and energy. The Iseult's magnet is the only active shielded 900 mm aperture 500 MHz MRI magnet under construction. This largest MRI magnet, of over 5 m diameter and length, 132 tons in weight and with a stored energy of about 340 MJ, requires multiple non-traditional technical decisions, from driven configuration and pancake wind of the main coils, to specific conductor configuration, quench protection and cryogenic approaches. The 11.7 T magnet is at the limit of the NbTi technology. Multiple manufacturing challenges were successfully resolved at the Alstom (now GE Power) plant in Belfort, France.

The 11.7 T Iseult magnet was designed and built as one-of-a-kind system. Rory Warner (Tesla Engineering Limited, UK) describes small volume production approaches to UHF, 7 T and higher, MRI magnets [3]. Tesla (earlier Magnex Scientific and Agilent) has built and installed over 70 UHF whole-body MRI magnets. The paper outlines major manufacturing challenges and trade-offs. The preferred coil configuration is a compensated solenoid. Many of the UHF MRI magnets currently in operation are passively shielded systems that require 200–870 tons of carbon steel. More recently, actively shielded UHF magnets have been built. This configuration allows for a reduction in weight to less than 50 tons for the 7 T whole-body magnets. Although there are no cryogen costs associated with normal operation, the UHF magnets require over 10 000 l of liquid helium for the cool-down. New methods of cool-down using high-power cryocoolers are being implemented to reduce the helium usage.

Michael Parizh, Yuri Lvovsky (General Electric) and Michael Sumption (Ohio State University) evaluated the potential of HTS and MgB_2 conductors for use in commercial MRI magnets [4]. The eventual market verdict on alternatives to NbTi for MRI application depends on many factors. Benefits to the customer (hospitals, physicians and patients) such as improved scanner performance, patient comfort, reduced acquisition and life cycle cost are the key factors. The authors developed a generic technical specification for superconducting wire for use in MRI that does not depend on a specific magnet configuration. The authors conclude that none of the HTS or MgB_2 conductors meet the minimum specification for commercial MRI magnets at the moment. For some conductors, MRI specifications will be difficult to achieve in principle. For others, cost is a key barrier. In some cases, the prospects for developing an MRI-ready conductor are more favorable, but developments are still needed. The greatest conductor challenges for HTS and MgB_2 include quench performance, insulation, guaranteed properties over 100% of the length in volume production including critical current and *N*-value. It is highly desirable that the same form-fit-and-function conductor is available from multiple vendors.

In a series of publications [5, 6] and several others, the team from HyperTech Research Inc., Case Western and Ohio State Universities introduce an encyclopedia of the MgB_2 whole-body MRI magnet design. In [5], the major design challenges for both 1.5 and 3 T magnets are analyzed including the magnet uniformity and persistence, conductor and winding approach selection, stress analysis in different operating modes, cryogenic configurations, and other factors. Areas that require further technological development are outlined, and include both component development such as superconducting joints and manufacturing methods for volume production. Significant progress was made towards the development of a reliable, low-cost conduction cooled MRI system. In [6], the team considers different quench protection approaches. Quench protection of the large-size, >1 MJ, MgB_2/HTS magnets is one of the most challenging issues in the magnet design. The authors demonstrated that traditional LTS quench protection approach using internal heaters is inadequate for MgB_2 MRI. In [11], the team made the next step outlined in the special issue: analysis of a promising CLIQ technique for a small 0.5 T MgB_2 MRI. It was, perhaps, the first detailed analysis of the CLIQ approach for MgB_2/HTS magnets.

The MIT team lead by Yuki Iwasa describes MgB_2 MRI magnets that are cooled by solid nitrogen and operate at a temperature of 10–13 K [7, 8]. This approach promises cost and reliability advantages over a gas-cooled cryogenic system. Quench protection of the MgB_2 magnet is, perhaps, one of the most challenging areas that requires further development. The other challenges include (1) development of the magnet-grade MgB_2 conductor optimized for MRI while keeping the conductor price-competitive with NbTi, and (2) the MgB_2 magnet cannot be a direct replacement to the NbTi MRI magnet. The MgB_2 magnet may be commercially competitive only if it is free of liquid helium, cryocooled, and operates at a temperature well above 4.2 K. When these and other challenges are addressed, MgB_2 might become a realistic superconductor option for the next generation of marketplace MRI magnets, with initial application in a niche area such as for osteoporosis screening. A possible configuration of such a niche magnet is outlined in [8]. The paper provides a detailed electromagnetic design, approach to the conductor selection, quench protection architecture, pioneering design of the thermal switch, cryogen selection and design of the cryogenic system, and also shares manufacturing and test experience.

The team led by Ben Parkinson (Victoria University of Wellington, New Zealand) designed, built and tested the whole speciality MRI scanner using a cryogen-free HTS MRI magnet [9]. Although these systems cannot be considered as fully optimized or ready for commercial production, in part due to insufficient funding for HTS conductor procurement, the research is of obvious interest to the community. An outstanding trade off analysis of the design and manufacturing alternatives make the paper especially valuable. Discussion of the conductor selection—coated tape versus BSCCO-2223 multifilamentary untwisted wire—has concluded that the screening currents in REBCO tape are significantly higher than ‘modest’ currents in the BSCCO-2223 wire, although the screening currents in the latter are significantly higher than in NbTi magnets. The authors conclude that, in the short term, BSCCO-2223 is advantageous versus coated tape due to a lower cost, longer-length availability and more robust winding technique. The coated conductor might be a conductor of choice in the long-term due to higher current density in no-insulation coils and lower-resistance joints. Evaluation of the coil winding methods—pancake coils versus layer-wound coils as in traditional MRI magnets—results in a conclusion that pancake winding might be advantageous for the smaller-bore, tape conductors available in relatively short lengths. The reader will find valuable details of the cryogenic design that was especially challenging since the unshielded gradient coils were used.

Superconducting magnets for use in hadron therapy facilities promise more compact and lower weight units as compared to conventional copper magnets. These advantages are of critical importance to rotating gantries that direct the hadron beams to target tumors from any of the medically desired angles for cancer therapy [12, 13]. The use of HTS superconductors—including coated conductors—offer a potential for reduction of the system life cycle cost by allowing operation at elevated temperature and more efficient compensation of AC losses. Application of the tape conductors including coated conductors has a known issue: screening currents might significantly degrade the field quality of the magnets (i.e. the special and temporal uniformity of the generated magnetic field), see for example [14, 15]. The screening currents were thoroughly investigated in NMR and MRI scanners. In the present SuST issue, a team of researchers led by Naoyuki Amemiya and Yoshiyuki Iwata carried out, perhaps, the first detailed experimental and theoretical study of screening currents in hadron therapy magnets [10]. The team demonstrated that the screening currents in coated conductors result in up to 1% of the design field deviation and uniformity drift, and they proposed means to compensate the negative effects.

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