Conceptual Design of a Portable, Solid-Nitrogen-Cooled 0.5-T/560-mm Point-of-Care MRI Magnet

Dongkeun Park, Juan Bascuñán, Wooseung Lee, and Yukikazu Iwasa

Abstract— **We describe the conceptual design of a portable, liquid-helium-free, all-REBCO, 0.5-T/560-mm point-of-care magnetic resonance imaging (MRI) magnet. It is free from an external power supply and a refrigeration system during operation. In our portable MRI magnet, we use a detachable "cryocirculator" that circulates, in a closed circuit, cold working fluid, and most importantly for portability, it can be readily coupled to or decoupled from the magnet, in contrast, a conventional cryocooler is mechanically attached to the magnet. Another unique feature of our system is a volume of solid nitrogen (SN2) in the cold chamber that adds enough thermal mass to the magnet in the 30–36-K operating temperature range, enabling it to maintain its field over a period of, for this system, ≥10 hours, plenty enough for this portable MRI system, uncoupled from its cryocirculator, to perform its mission before it needs recooling.**

Index Terms—**Detachable Cryocirculator, Portable MRI, Quasi-Persistent Operation, REBCO Magnet, Solid Nitrogen Cooling.**

I. Introduction

MAGNETIC resonance imaging (MRI) is a widely used medical diagnostic tool that provides excellent soft tissue contrast, and multiparametric anatomic and functional information on the central nervous system. Nearly 50% of MR scans are of the head to diagnose ailments, injuries, and diseases. Some cases of stroke, hemorrhage, and concussion are acutely life threatening and require immediate care. Early management improves outcome at prehospital, emergency room, or intensive care unit. Although standard superconducting MRI scanners with fields of 1.5 T and higher is an established tool for diagnose and treatment planning for these patients, it is very difficult to make an MRI scanner with portability and ruggedness for use as a point-of-care (POC) device. The primary reason is the magnets most typically cooled with liquid helium and permanently connected with a venting system in case of magnet quenches and a cryocooler system for helium recondensing. Lower-field scanners adopting permanent magnets have been finding important niche applications, for example, in bedside and intrasurgical/interventional situations [1]–[3]. Although some of these scanners are compact, "portable" and easy-to-operate and suitable for certain applications, they have a serious limitation: they employ portable size permanent magnets with very low fields and therefore suffer from low image quality which would not be considered for diagnostic use. In this paper, we introduce the concept of a portable superconducting head MRI magnet with a field that has been shown to be capable of diagnostic image quality. Diagnostic quality portable head MRIs might revolutionize POC diagnostics, e.g., in triaging traumatic brain and other injuries at sports events, concerts, disasters and battlefields.

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II. Portable Diagnostic 0.5-T Head MRI

It has been shown that diagnostic image quality is capable with a modest field between 0.35 and 0.6 T [4], and for a number of applications 0.5 T is diagnostically equivalent to 1.5 T [5]. Siemens has developed a 0.55 T interventional scanner that shows high performance when coupled with a modern console, comparable to older 1.5-T scanners [6]. Synaptive employs a 0.5-T head dry superconducting magnet for its interventional/intrasurgical scanner. A notable finding in the Siemens and Synaptive scanners is that because of their modestly lower field, the safety risks associated with scanning patients with medical implants are manageable. However, all of these magnets require liquid helium and/or cold heads, and are therefore tethered to compressors, cooling water and high electrical power sources. They cannot be adapted to mobile POC applications. Permanent magnet technology also can in principle achieve very modest field strengths approaching those of current clinical scanners but their weight precludes transport. We believe that an entire window of possibilities in POC scanners can open with our proposed truly mobile compact superconducting head MRI magnet of diagnostic quality untethered to a refrigeration system and a magnet power supply for an extended period sufficient to carry out its mission. The portable MRI magnet we present in this paper is based on the concept of using a quasi-persistent mode high-temperature superconducting (HTS) REBCO magnet (Section III) and a volume of solid nitrogen (SN2) in the cold chamber that adds enough thermal mass to the magnet, thus enabling it to maintain its field for a period time, uncoupled from a detachable cryocirculator (Section IV).

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TABLE I
KEY PARAMETERS OF FIRST-CUT DESIGN OF AN UNSHIELDED ALL-REBCO HEAD MAGNET WITH 560-MM RT BORE

Parameters for Right 3 Coils		Coil 1	Coil 2	Coil 3
Conductor composite (width; thickness)	[mm]		3.5; 0.1 (use of 3-mm width REBCO tape)	
Winding ID $2a_1$; OD $2a_2$	[mm]	630.02; 637.22	630.00; 638.40	630.00; 647.20
Axial extent b_1; b_2	[mm]	29.84; 71.84	143.99; 192.99	347.0; 410.00
Turns/layer; layers		12; 36	14; 42	18; 86
Tape length	[m]	860	1,173	3,106
Continuous tape length/spool (# of spool)	[m]	440 (2)	597 (2)	528 (6)
Total tape length required (half; all coils)	[m]		5,242; 10,484	
Number of joints (see Fig. 1b)			21	
Operating current, I_{op}	[A]		102.3	
Designed *B0* field @ I_{op}	[T]		0.5	
Operating temperature, T_{op}	[K]		30–35 (maximum up to 40)	
Maximum B @ I_{op}	[T]	0.9	1.1	2.0
Total inductance (all coils)	[H]		10.41 (stored energy at I_{op} = 54.5 kJ)	
Homogeneity @ 26 cm DSV	[ppm]		9.4 (peak-to-peak); 0.56 (V_{rms})	
@ 26 cm × 20 cm DEV	[ppm]		2.6 (peak-to-peak); 0.28 (V_{rms})	
5-Gauss fringe field radius (unshielded)	[m]		4.1 (axial); 3.2 (radial)	

III. ALL-REBCO MRI MAGNET DESIGN

A. *First-Cut Unshielded Magnet Design*

The key design specifications of our portable head magnet are: 1) 0.5-T center field with a φ560-mm room-temperature (RT) bore; 2) field homogeneity of <1 ppm (V_{rms}, the root mean square value in a volume) over 26-cm diameter of spherical volume (DSV); 3) persistent-mode operation with a field decay rate of <200 Hz/hr and; 4) maximum operating temperature up to 40 K for the magnet in a volume of SN2, enabling the magnet to operate without relying on a cooling source, LHe or a cryocooler. Among several magnet-grade HTS conductors, we select REBCO tape because it is the most suitable for operation in the 40-K temperature range with high enough current densities, which make this magnet compact and minimize conductor length, and availability in unit length (up to 600 m or longer) required for this magnet.

Table I shows the magnet parameters based on our 1st-cut all-REBCO 6-coil magnet. Note that it shows a half of the mid-plane symmetric magnet. We designed the magnet to generate 0.5 T with a peak-to-peak homogeneities of 9.4 ppm and a V_{rms} homogeneity of 0.56 ppm in 26-cm DSV, adequate for head scanning. The magnet would be wound with a 3-mm wide 65-μm thick REBCO conductor of which critical current, I_C, at 40 K (max. Top) and 2 T (max. field in the coils) is well above an operating current, I_{op} of 102 A, but we used 3.5 mm × 0.1 mm dimension that may include spacers and shunts for the 1st-design. Figure 1a shows a schematic drawing of the coil configuration and a 26-cm DSV. However, there will be field errors in the as-built magnet because of manufacturing tolerance and screening-current induced field (SCF) from magnetized REBCO conductors. First, the SCF can be reduced by our proven method, temperature-controlled charging sequence [19]. The remained errors may be readily wiped out by ferromagnetic and RT shims. In this conceptual design paper, the proposed magnet is not intended to have additional shielding

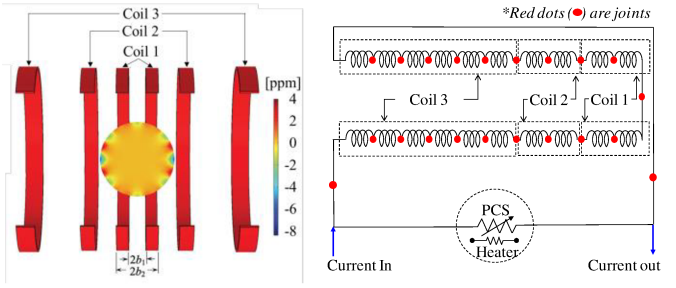

Fig. 1. A 6-coil REBCO head MRI magnet: (a) a drawing of coil configuration and homogeneity in 26-cm DSV with a vertical homogeneity color codes in ppm at right; (b) a circuit diagram (red dots represent joints, here a total of 21). Note that each of Coils 1–3 consists of two identical coil.

options such as active shielding coils that increases outer diameter of the magnet system and/or passive shielding with ferromagnetic materials that significantly increases a total weight.

For our 0.5-T head magnet with 102-A operating current and the peak field in the coils of 2 T, the hoop stresses (max. 28 MPa by energization without considering screening current effect) and axial forces (max. 26 kN toward midplane in Coil 3) within and between coils are non-issues and readily manageable for our proposed REBCO magnet.

A REBCO magnet typically has much greater stability margin than that of LTS, especially at this higher T_{op} range, i.e., REBCO magnets are not susceptible to quench caused by disturbances that afflict LTS magnets [7]. For protection against overheating, Coils 1-3 are wound with no-insulation (NI) winding technique and thus self-protecting [8]–[10]. Quench-induced stresses and forces in NI coils would not be significant for this relatively low-field (and thus low-stress) magnet. Quench and protection analysis of this NI magnet in accordance with turn-to-turn resistance will be performed in the next detailed design step, out of scope in this paper.

B. *Quasi-Persistent Mode Operation*

To meet the temporal stability of 0.1 ppm/hr, a typical requirement in MRI, for this "persistent"-mode REBCO magnet, *B0* shim coil, to be installed in a gradient coil set, will be used to compensate field-decaying of up to 200 Hz/hr (here at 0.5 T, 9.5 ppm/hr). It is necessary to make a total joint resistance in the circuit as small as possible to reduce the burden imposed on a *B0* shim coil. A layer-winding method will be used in Coils 1–3, i.e., NI layer-wound coils as demonstrated in [10]–[12], to minimize the number of joints. Because of limitation of available continuous length of REBCO tapes (currently, up to 600 m as guaranteed by manufacturers), as shown in Table I and Fig. 1b, we will use 2, 2, and 6 spools to wind Coils 1, 2 and 3, respectively, i.e., a total 20 spools, and thus 21 joints total. Our portable magnet will be operated in a persistent-mode with these 21 joints having very-low (ideally zero by superconducting joints) resistance. Although superconducting joint technologies for REBCO conductors have been reported [13]–[17], these methods, which require long and sophisticated heat treatment with high-temperature and high-pressure, are not highly repeatable and not repairable.

We propose a reliable method to significantly reduce resistance of REBCO joints by soldering a long length of conductors (i.e., increased joint contact area). A long-length joint can be wound on a winding bobbin to make it space-saving and non-inductive [18]. As shown in Fig 2, we have demonstrated this very-low-resistive joint with our 4-mm REBCO tape. A closed-loop sample with a single-turn coil of a φ19-mm, and 1-m long soldered joint was built and tested in liquid nitrogen (LN2). To measure the very low resistance accurately, we use a flux trapped method [18]. The measured joint resistance was 0.55 nΩ. It is known that REBCO-REBCO joint resistance is strongly depending on REBCO-Ag interlayer contact resistance which varies among conductor batches even from the same manufacturer. Low-contact-resistive conductor spools can be selected by pretesting with short joint samples. With 2-m long joints, we can expect to achieve ~0.3 nΩ. With a coil inductance, L of 10.4 H and 21 joints, each of ~0.3 nΩ and thus a total resistance, R_{joint} of ~6 nΩ, a decaying time constant, $\tau = L/R_{joint}$ is computed to be ~1.7×10^9 s, and our 0.5-T magnet can be operated in a quasi-persistent mode with a field decay rate of ~1 μT/hr or 44 Hz/hr, available level for *B0* drift compensation. Moreover, longer (up to 1.2 km) conductors from manufacturers who used to produce such long length REBCO conductors with the greatest quality substrate may be available. Also, by selecting low-contact-resistive REBCO conductors and longer-length, e.g. 5-m long, joints, we may get a total resistance even lower than 1.5 nΩ, i.e., <11 Hz/hr, to reduce a B0 drift compensation effort. Although our proposed long-length joint has higher resistance, and thus must rely on *B0* drift compensation, than superconducting joints [13]–[17], we believe that the process using soldering is much simpler, more well-established, and more repeatable to be practically used in this kind REBCO magnet. Our portable magnet can operate in a temperature range 30–36 K to be described in Section IV, but this temperature change in time can alter the SCF and thus may degrade a little of the field homogeneity and temporal stability. This temperature-change sensitive SCF can be effectively reduced by temperature-controlled charging sequence [19], and then, we may use 1st and 2nd-order RT shims to compensate this small field changes.

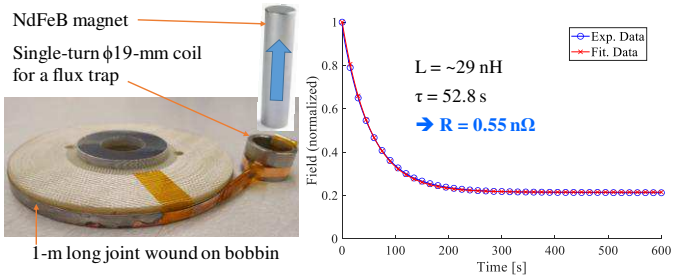

Fig. 2. A preliminary test results on a very-low resistive REBCO-to-REBCO tape joint. (left) a photo of 1-m long joint sample with a single loop coil; and (right) a measured decaying magnetic field along the time constant.

To charge/discharge our closed-loop persistent-mode all-REBCO head magnet, a REBCO persistent-current switch (PCS) is needed. To reduce a joule heating of the PCS during charging, we design the PCS to have ≥3-Ω open resistance at 100 K. With a total copper-and-silver cross section of 0.45 mm^2 and 3-mm width, the same as those of the REBCO tape for the Coils 1–3, the PCS, non-inductively wound with 20-m long tape, has a normal-state resistance of 3 Ω and negligible inductance. Insulated by a Styrofoam container, as the PCS's used in our MgB2+SN2 magnet [20], heating required to make the PCS resistive state will be limited to 1 W.

IV. Detachable Cooling System with Solid Nitrogen

In our portable MRI concept, we use a detachable cryocirculator for magnet cooling. A Cryomech Pulse Tube cryocirculator-based cryogenic system connected to the 0.5-T head magnet is shown in Fig. 3a. In contrast, conventional zero-boil-off liquid-helium-cooled and conduction-cooled MRI magnets must always have a cryocooler attached. For portability, we apply our SN2 cryogenic technology to enable the magnet to operate for ≥10-hr period with its cryocirculator decoupled. A SN2 is an excellent thermal mass enhancer for our REBCO head magnet which operates over the temperature range 30–36 K. We have demonstrated the SN2 cooling for application to NMR/MRI superconducting magnets [21], [22], and recently, some MAGLEV applications have adopted the SN2 cooling concept for cooling-power free during the transit [23]–[25].

The REBCO magnet will be enclosed in a cryostat, whose main features and dimensions are shown, to scale, in Fig. 3b. The cryostat includes cryogen/magnet vessel, radiation shield and vacuum vessel. All common vacuum spaces are filled with multilayer superinsulation (MLI) for an efficient thermal performance, minimizing radiational heat loads. The cryostat is provided with evacuation ports, safety pressure relief, cryogen fill/vent lines with shut off valves and quick connect open/close valves to connect/disconnect the cryocirculator. Two circular series connected heat exchangers are installed,

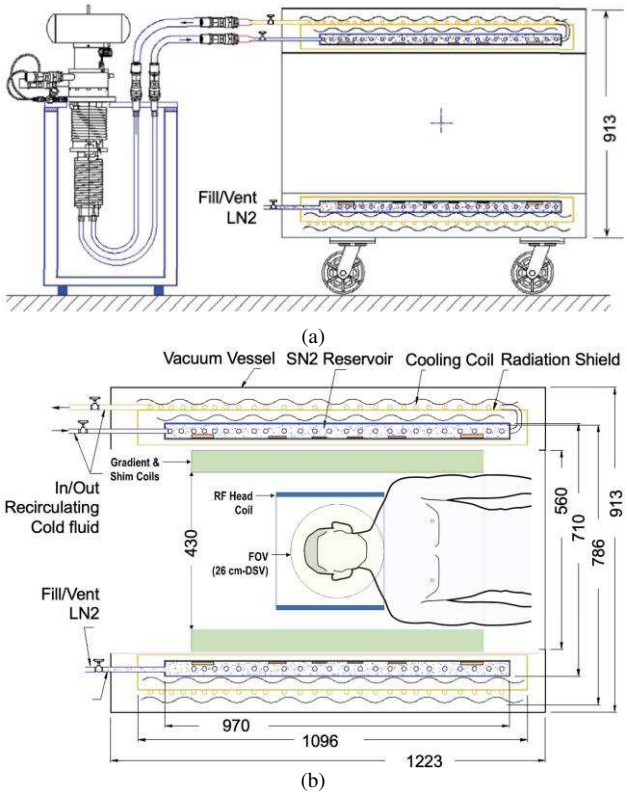

Fig. 3. Drawings of a portable head MRI magnet: (a) a detachable cryocirculator coupled to a magnet system; (b) an overall MRI magnet system with a patient head at the magnet center. Dimensions in mm.

one in the cryogen reservoir, the other around the radiation shield. To minimize heat input, every inlet and outlet design will be thermally optimized, and detachable current leads or a flux pump [26] can be used.

Initially the cryogen/magnet vessel is filled with 84 liters of LN2. The cryocirculator is attached to the cryostat (Fig. 3a) via the quick connect open/close valves and the cold gas from the cryocirculator enters first through the heat exchanger in the cryogen/magnet vessel and then exits after circulating through the radiation shield heat exchanger. Eventually the circulating cold gas will solidify the LN2 to a magnet operating temperature of 30 K and the radiation shield be cooled to around 50 K, at which point the magnet is ready to be energized. Applying SN2 to the shield can also be considered to further reduce a radiational heat input during portable operation. With the magnet at operating temperature and fully energized, the system is now ready to be disconnected from the cryocirculator and to perform point-of-care diagnostics. The volume of SN2 may be reduced to ~70 liters (=70,000 cm^3) at 30 K. With an average volumetric enthalpy density of 1.4 J/cm^3 at 30–35.6 K and a latent heat of 8.3 J/cm^3 by solid phase transition at 35.6 K [7], the SN2 will experience a temperature excursion from 30 K to 36 K under 10 W—roughly estimated heat input while the magnet is decoupled from the cryocirculator—for more than 18 hours. Although this quasi-persistent NI magnet unlikely quenches, the transient behavior of SN2 in any possible fault modes including a magnet quench will be further investigated in the future work.

V. Discussion on Potential Challenges

Here, we present the potential challenges toward a practical portable MRI scanner:

- In the point of care applications, not only during transportation but also during utilization, the fringe field can be easily breached that may cause safety issue. Our magnet design in this paper is unshielded because building an actively shielded REBCO magnet which requires more conductors and adds more construction complexity is out of scope for the first-cut design for proof-of-concept and eventually budget for prototyping. Optimization design study to reduce fringe field radius during transit and operation will be performed as the next step.
- A radio frequency interference (RFI) from an unshielded portable environment can be another challenge. External RF detection and bucking coils and/or a physical shield like a conductive curtain/floor may solve this issue. Our goal is to demonstrate a portable magnet capable of head imaging.
- To date head-dedicated gradient coil studies and prototypes adopt asymmetric design or ultra-short design [27], [28]. However, none of these are the off-the-shelf products, nor optimized between performance (as a 0.5-T head scanner) and portability. A gradient coil cooled by a flowing water and air-heat exchanger can be considered to get rid of a power-consumed external water chiller.

VI. Conclusion

We present the concept of a portable superconducting MRI magnet free from an external power supply and a refrigeration system that can be adapted for POC application. We believe that this concept pioneers a novel MRI magnet technology that promises portability and stronger magnetic field, while eliminating the use of liquid helium, an extremely limited non-renewable resource which has recently suffered severe shocks in supply and cost. Being able to bring the scanner to the patient is not a convenience: it saves lives and reduces morbidity and disability.

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