MAGNETOM Free.Max: from Concept to Product, a Brief History of the DryCool Magnet Development

Simon Calvert, CEng FIMechE

Head of Product Innovation & Chief Technology Officer, Siemens Healthineers, Oxford, UK

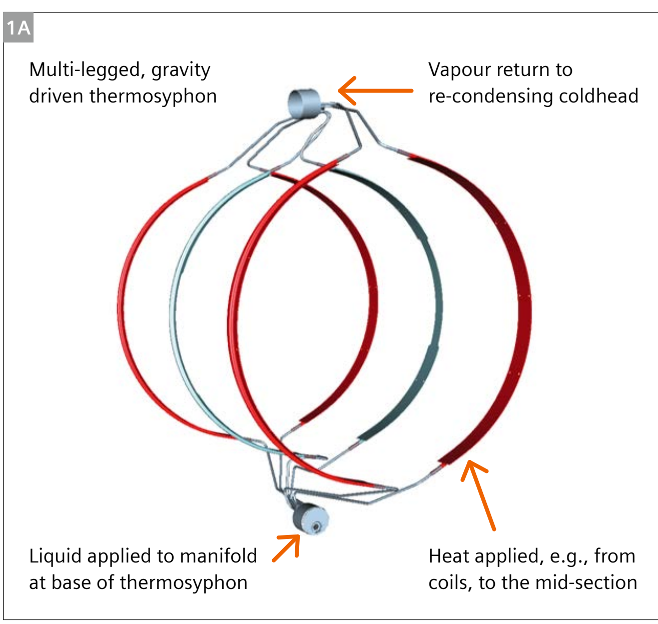
Introduction

Our new DryCool magnet is a key enabling element of our ground-breaking MAGNETOM Free.Max MRI system. The development and production program for the new generation magnet has lasted four years but was preceded by a research program lasting seven years, focussed on completely transforming and deploying new superconducting MRI magnet technologies. The program included developing new magnet coil technology and structural concepts as well as realising a dramatic reduction in our dependency on increasingly expensive, and sometimes scarce, liquid helium coolant. The highly innovative technologies used in the DryCool magnet are complimentary, and deliver a robust, reliable, and lightweight "plug and play" magnet solution to you.

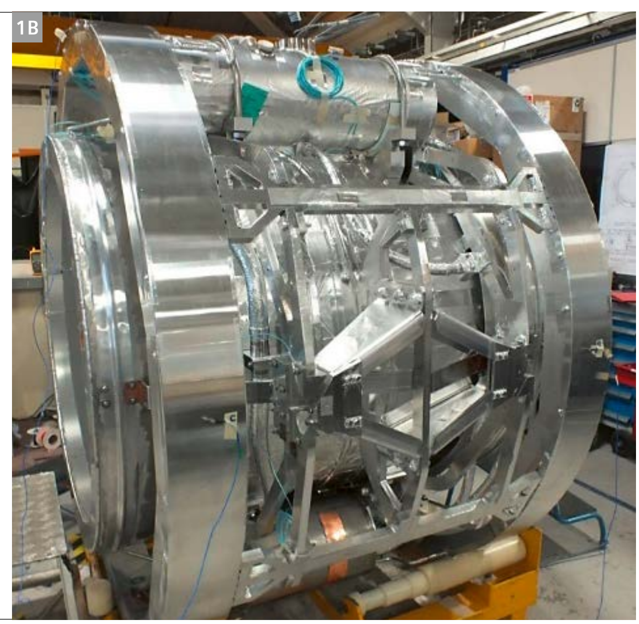
1.5T Minimum Helium Inventory (MHI) research program (2008–2015)

In 2008 we started a program to transform our magnet technology and to reduce our dependency on helium. A key requirement for conduction-cooled superconducting magnets is to minimize the mass of the cold parts of

1A



1B



1 1.5 Tesla demonstrator showing the cryogenic concept and the superconducting magnet structure. **(1B)** 4K mass during build.

MAGNETOM Free.Max is currently under development and is not for sale in the U.S. and in other countries. Its future availability cannot be ensured.

the structure. Our focus was to use only the magnet's own refrigerator to cool down to operating temperature, thus avoiding the requirement for complex installation procedures.

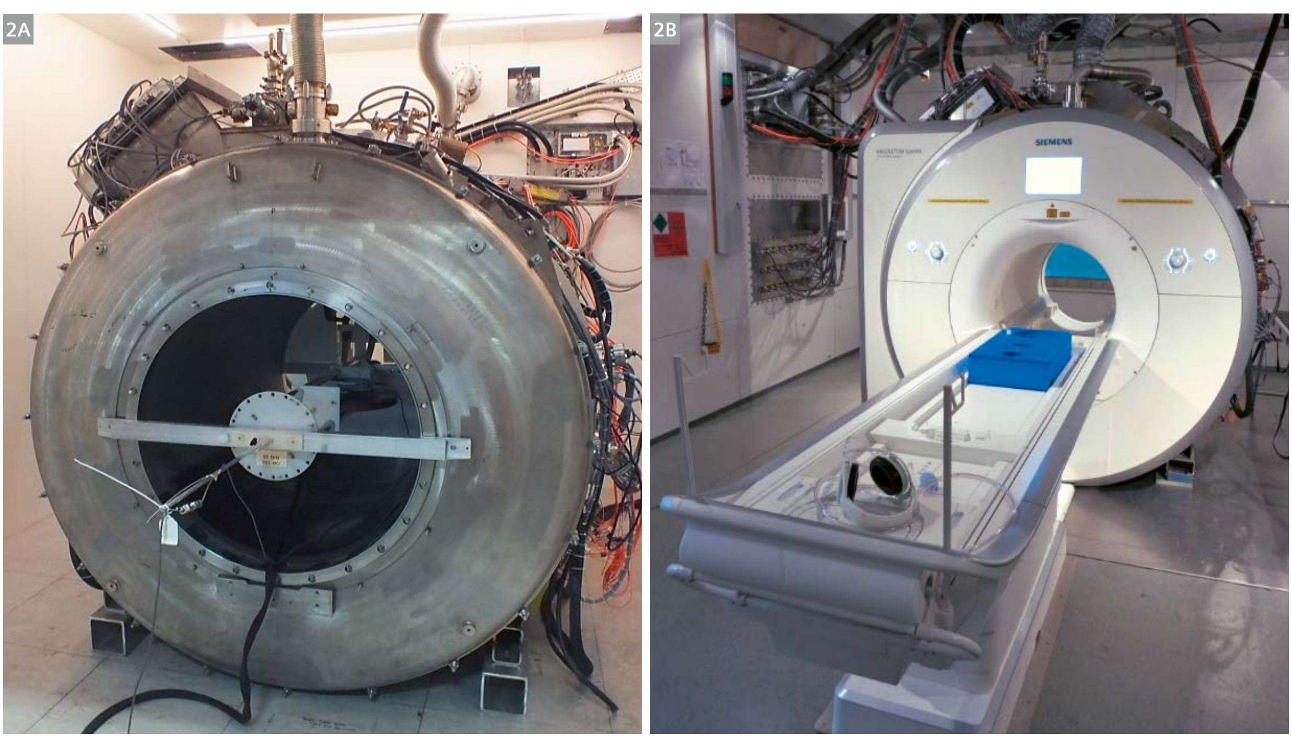
The focus of the research program was to realize a 1.5T "Minimum Helium Inventory" magnet, which could later be integrated into an MRI system for imaging trials. Half scale, pipe-cooled magnets were developed and tested to prove the various technical concepts which were to be used in the 1.5T demonstrator. All tests were successful, and these technologies were then incorporated into the full-size magnet. The demonstrator was not intended to lead directly to a product but was a testbed to evaluate our new ground-breaking technologies. The magnet worked reliably and was also extensively tested in a MAGNETOM Aera MRI system in 2014 where it performed as well as the conventional "wet" magnet. New magnet electronics and software concepts were also developed and evaluated as part of the 1.5T MHI demonstrator program.

Simplification and focus on manufacturability

A great deal was learnt from the 1.5T research program, including how to develop a "dry" magnet which was optimized for cost and manufacturability. Much was also learnt about how conduction-cooled magnets interact with the MRI system and, in particular, the gradient system.

DryCool magnet development program (2016–2020)

The DryCool magnet development program was kicked off using the learnings from the 1.5T research program. Here, numerous aspects were considered for a design in order to maximize clinical utility while at the same time minimize the requirements on site infrastructure. The result of this development is a newly designed magnet unlike any Siemens Healthineers has built before. The new DryCool design enabled us to keep the mass low, allowing not only for shorter cool-down times, but also reduce installation costs. This will clearly make it easier to site this magnet at non-traditional sites. Additionally, a new field strength was considered in the DryCool design to allow for greater clinical flexibility. The chosen field strength of 0.55T allows just that. Lower fields show better compatibility when it comes to implants or interventional devices such as catheters. Anatomical regions such as the lung, have been traditionally off-limits for MRI at conventional field stregnths. Lower field strengths can make MRI more versatile in this respect as well. Finally – patients benefit from the DryCool design: with an 80 cm bore, patients will experience an openness in MRI that no other whole body superconducting magnet can offer. All of these elements come into play with the DryCool Magnet design.



2 1.5 Tesla demonstrator during magnet testing and MRI system testing in 2014. **(2A)** Magnet tests in Oxford. **(2B)** System tests in Erlangen.

3 Prototype DryCool 0.55 Tesla magnet

DryCool magnet specification

• Field strength:	0.55 Tesla
• Field temporal stability:	< 0.1 ppm/hour
• 5 gauss contours (from isocentre):	Axial 4.0 m, Radial 2.5 m
• Homogeneity:	See table 1
• Magnet length:	1.48 m
• Magnet warm bore:	1.060 m
• Magnet mass (installed):	1635 kg
• Liquid helium inventory:	0.7 litres (under normal operation)
• Helium boil-off rate:	Zero (under all imaging conditions)
• Cryogenic system:	Sealed helium system, no quench line
• Cooldown time from warm:	< 14 days (using the magnet’s refrigerator)
• Designed acceleration limits:	5g vertical, 2g lateral
• Magnet current leads:	Fixed leads with HTS elements
• Automatic ramp-down:	Yes, if refrigeration is off for a period.
• Auto ramp-up:	Yes. Controlled by the magnet supervisory.
• Remote monitoring of the magnet:	Yes. Diagnostics on magnet and refrigerator.

DryCool magnet features

Advanced superconducting magnet structure with very low mass

The new superconducting magnet structure has a mass of approximately 300 kg. To achieve this exceptionally low mass in a large bore, the actively shielded magnet required the use of several new and innovative technologies. A completely new structural concept was used for the coils and supporting structure which, while very robust, allowed the use of very thin, yet stiff, structures. Since the volume of superconductor in the coil is low, a new ultra-fast quench propagation system was also developed to ensure that the magnet was not damaged if the Emergency Run Down Unit (ERDU) button was pressed. New superconducting joints, superconducting switches and other components were also developed. These components are no longer immersed in liquid helium and so need to be cooled by conduction only. Another key aspect of the magnet structure was to ensure that the coils had very low heating due to interaction with the gradient coil. New and innovative technologies were adopted to ensure that gradient coil-induced heating of the coils was minimized, and subsequent testing showed that the approach adopted was highly effective.

Simplified, manufacturable, and robust DryCool cryogenic system

The 1.5 Tesla demonstrator magnet had a cryogenic system which used pipes encircling the superconducting structure. While quite effective, such a system is complex to manufacture with many joints in the helium system. For the DryCool magnet, we adopted a simpler and more robust approach which was suitable for manufacture in high volumes. The cryogenic package is a separate sub-system which is integrated into the superconducting magnet structure by use of an innovative and highly optimized thermal connection system. This system efficiently removes heat from the coils and supporting structure giving a fast cool-down time, a low base temperature, and excellent tolerance of gradient coil interaction. Even with the most challenging imaging sequences, there is minimal heating of the magnet coils. The cryogenic package contains 0.7 litres liquid helium and is sealed, and so requires no quench pipe. Charging of the helium system is by high pressure gas only and no liquid helium is required. Once charged, and provided with power, the magnet will automatically cool down to operating temperature in less than 14 days. If the magnet arrives at the installation site partially cold, as will often be the case, the cool down time will be shortened.

DryCool magnet cryostat

The magnet cryostat is the sub-system that keeps the magnet coils cold and well protected. It has been highly optimized to minimize weight, minimize heat input to the superconducting magnet, and to ensure a high level of robustness during shipment, installation, or in seismic events when on site. Since we intend the DryCool magnet to be shipped to a wide range of locations across the globe, we have designed the cryostat to meet the same specifications as our wet magnets. The magnet can withstand sustained loads of 5g in the vertical direction and 2g in both lateral directions. This very robust specification ensures that the magnet is well protected during shipment to site.

Magnet electronics package and software

Since the DryCool magnet has a small inventory of helium and the heat capacity of most materials at 4 Kelvin is negligible, the tolerance of loss of refrigeration is less than a conventional "wet" magnet. Conventional superconducting magnets typically contain hundreds of litres of liquid helium and this gives a tolerance of refrigeration failure measured in days before magnet ramp-down is required. For the DryCool magnet, we have developed a sophisticated electronics and software system which monitors the magnet and refrigeration system and makes decisions about when to ramp the magnet down to avoid a quench. If the refrigeration system is off for a significant time period, the Magnet Supervisory and Control Unit (MSCU) will execute a magnet ramp down to avoid dissipating the magnet stored energy in the cold mass. The magnet energy is instead dissipated in a passive Run Down Load (RDL). Once the magnet has been run down, and the power and cooling water is available again, the RDL is actively cooled to reduce the temperature so that the magnet can be ramped back to field. The MSCU also monitors many other magnet parameters to determine when the magnet can be automatically ramped back to field. The magnet has an integrated Magnet Power Supply (MPS) which is used to automatically ramp the magnet to its precise current for field, before putting the magnet into persistent mode. The MSCU also monitors many magnet and refrigeration parameters which can be monitored remotely by our service organisation. This allows preventative maintenance to be planned to ensure maximum "uptime" for the magnet and MRI system.

Product Life Cycle (PLC) and Total Cost of Ownership (TCO) savings

One key focus of the development of the DryCool magnet was to minimize Product Lifecycle Cost and Total Cost of Ownership for the customer. The very low magnet mass reduces the shipping costs, and reduces the logistics carbon footprint as, in many cases, sea or road shipments can be used rather than air freight. The low mass also reduces installation costs and allows the magnet to be sited on upper floors. The low mass and small size of the magnet also allows the MAGNETOM Free.Max MRI system to be sited in non-traditional locations such as ER departments and clinics. The lack of a quench pipe further reduces the installation costs and enables the magnet to be sited in locations where quench pipe runs would be too long, or very difficult and expensive to install. The lack of a large helium inventory reduces the magnet purchase price and reduces the servicing costs for the customer. Since the magnet has its own magnet power supply, the customer can, in most cases, ramp the magnet up and down when required without a service visit being required.

Conclusions

The DryCool magnet is a highly innovative development which incorporates many new technologies and concepts. The magnet delivers the first 80 cm patient bore in the industry and is a key enabler for the ground-breaking MAGNETOM Free.Max MRI scanner. The magnet minimizes product life-cylce costs and total cost of ownership and virtually eliminates the complex superconducting magnet servicing procedures. The magnet is enabled for siting outside of traditional imaging suites and will undoubtably help to extend the reach of MR not only into new locations, but also new clinical fields.

Contact

Simon Calvert
Siemens HC Ltd. MR Magnet Technology
SHS DI MR R&D MD
Wharf Road
OX29 4BP Oxford
United Kingdom
simon.calvert@siemens-healthineers.com