

PHILIPS

Whitepaper

BlueSeal magnet technology

**Innovation in magnet design:
the hidden engine behind
the progress of MRI in Healthcare**

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Executive summary

Philips is a pioneer in helium-free operations MRI systems. Launching the first BlueSeal MRI system in 2018, Philips has the largest installed base of helium-free operations magnets at over 2200. BlueSeal magnet technology innovates by drastically reducing helium usage, addressing issues related to helium volatility and availability that have affected traditional systems for decades. This is achieved without compromise to image quality or uptime.

The superconducting magnet is the engine behind a clinical MRI system. For the last four decades, liquid helium cryogenics has been a staple of magnet technology¹, faithfully enabling superconductivity for tens of thousands of systems worldwide. There have also been clear trends to reduce the end user burden of challenges associated with these cryogenics.

To address these challenges, Philips has invested in the development of BlueSeal technology for over 20 years. Several approaches, architectures, and prototypes were pursued before a product capable design was chosen. The goal always has been to free MRI from the constraints of helium bath cooling while still delivering phenomenal image quality and uptime.

Philips first launched BlueSeal technology with the release of the 1.5T Ingenia Ambition System. This system reduces helium consumption by 99.5% compared to systems using legacy technology.

Several aspects are discussed to highlight the benefits of BlueSeal, with particular attention given to answering these questions:

- What is a Sealed magnet and how does it work?
- What problems are solved with BlueSeal technology?
- What other approaches are there to eliminate bath cooling, and are they equally effective?
- What attributes make BlueSeal technology readily scalable to higher field strengths?
- What is the history of BlueSeal development?

BlueSeal magnet technology and its benefits

Introduction

Liquid helium has been at the core of MRI magnet technology for over 40 years. With its unique ability to remain in the liquid state of matter at nearly absolute zero temperatures, it can efficiently cool niobium titanium alloys

to create superconductive properties and enable powerful electromagnetics. With increasing volatility, availability, and geo-political instability with respect to liquid helium, a new technology of magnets is needed.

Magnet architecture and requirements

The transition to helium independence represents a paradigm shift in technology, thus requiring careful rethinking of traditional magnet requirements to ensure clinical needs are met. These requirements can be summarized across three critical domains:

Sustainable Cryogen Framework

- Cryogen sealed for life
- No helium refills required
- No quench vent required
- Efficient power consumption

Operational Resilience

- Redundancy to power outages
- Redundancy to chilled water outages
- Heavy duty scan tolerance
- Automated & smart recovery logic
- Uptime without UPS

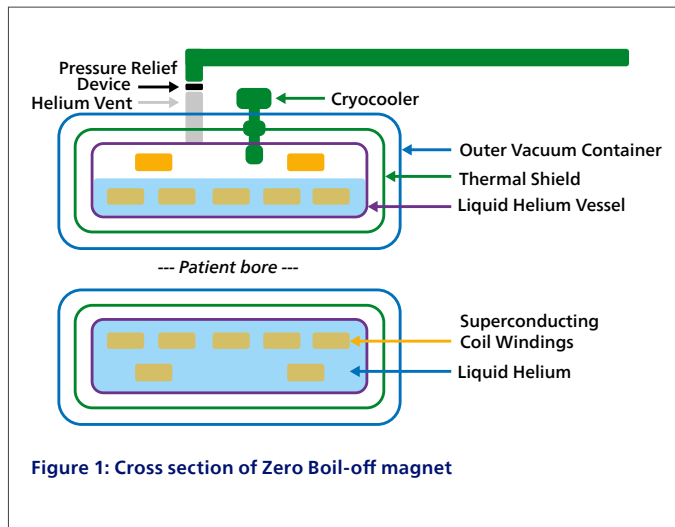
Clinical Utility

- Compact & lightweight
- 1.5T & 3.0T compatibility
- 70cm patient bore
- Best in class image quality

Table 1: Key Requirements

Zero Boil-off magnet architecture – the classical approach

The fundamental cryogenic design of a Zero Boil-off Magnet consists of a liquid helium vessel, typically suspended inside an Outer Vacuum Container. The liquid helium vessel contains the superconducting coil windings which are submerged in hundreds or thousands of liters of liquid helium. A thermal shield is needed to intercept thermal radiation which can still travel through the vacuum space. A two stage Gifford-McMahon cryocooler is used – with one stage cooling the radiation shield and the other stage re-liquifying boiled off helium gas. The magnet also requires a helium pipe to direct the helium out of the exam room during both servicing and in the event of a quench.



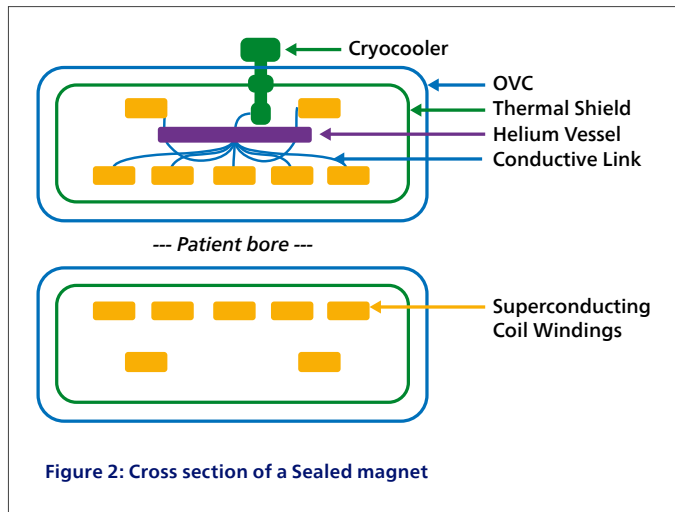
The liquid helium of the ZBO architecture served three functions: (1) maintain the entire vessel at a fixed nominally uniform temperature, (2) thermally couple the superconducting windings to the Cryocooler, and (3) create a thermal heat sink or buffer to absorb energy and limit temperature rise. The large helium inventory allows the system to absorb significant thermal energy, providing critical 'ride through' time during refrigeration interruptions. When more heat is added to the system than what the cryocooler is capable of liquifying, the liquid helium simply boils off, builds pressure, and eventually exits the magnet. However, as long as liquid helium remains in the vessel, the superconducting windings will remain at operating temperatures.

Cryocooler	A standalone mechanical refrigerator designed to reach and maintain cryogenic temperatures.
Outer Vacuum Container	The primary vacuum vessel that provides thermal insulation and houses the suspended superconducting magnet system.
Thermal Shield	A high-conductivity radiation barrier, usually metallic, positioned between the OVC and the cold mass to intercept ambient thermal radiation.
Zero Boil-off (ZBO)	A cryogenic management strategy that uses active refrigeration to re-liquefy vapor, maintaining a constant liquid inventory with no net loss.
Bath Cooling	A cooling method where superconducting coils are directly immersed in a reservoir of liquid cryogen (e.g., liquid helium) to maintain operating temperatures.
Ride Through	The duration a superconducting magnet remains at its operational field strength following a loss of active cryocooler refrigeration.
Heat Pipe	A high-efficiency heat transfer device that utilizes the latent heat of fluid phase changes to transport thermal energy across small temperature gradients.
Thermosiphon	A passive heat exchange loop that relies on natural convection and gravity-driven buoyancy to circulate a cooling fluid without a mechanical pump.
Quench Pipe	A dedicated exhaust conduit designed to safely vent rapidly expanding cryogenic gases from the magnet cryostat to the external atmosphere during a quench event.
Spaceframe	A magnet coil support structural design that minimizes the ability for eddy current formation inside the magnet during imaging.

Table 2: Glossary of Technical Terms

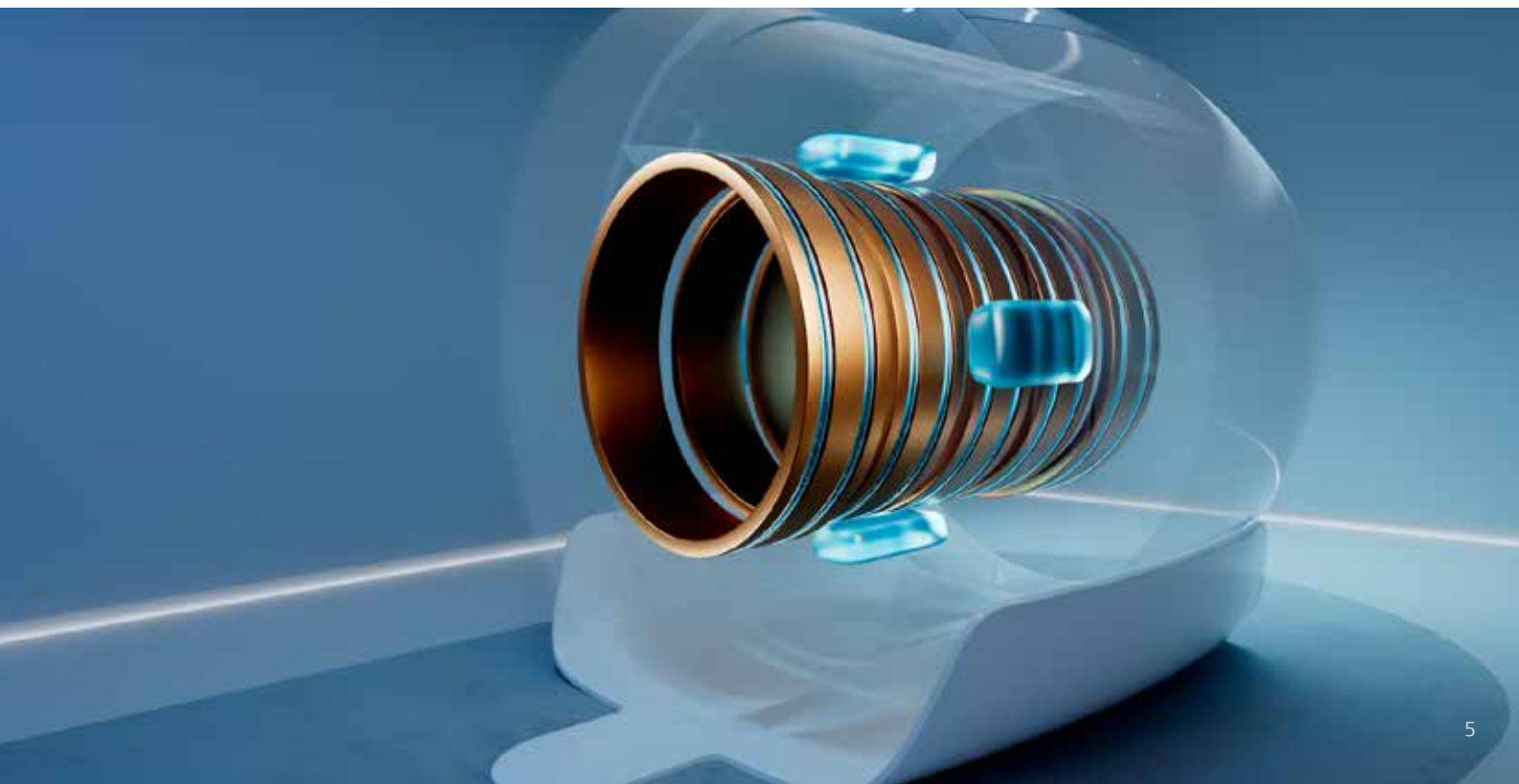
Sealed magnet architecture

The design of a Sealed magnet is defined by the presence of a single, sealed helium volume inside of the magnet. This helium volume is thermally connected to the cryocooler. The superconducting magnet windings, now in vacuum, are thermally connected to the helium volume. The connections can be made with conductive links or fluid links, such as heat pipes or thermosiphons.



The cryocooler will cool down both the helium vessel and the superconducting windings. If the cryocooler stops working, the helium vessel will slowly begin to warm up, keeping the superconducting windings below the critical temperature. Since there is a fixed mass of helium inside of a fixed volume of the vessel, the density of helium will stay constant. As the magnet cools down, the pressure inside the vessel will decrease. There is sufficient density in the system such that 7 liters of liquid helium will be generated at operating temperatures. Phase change of the liquid helium is the mechanism that provides heat capacity, or the ability to resist changes in temperature, to the system.

The primary engineering challenge is a heat transfer problem. Large surfaces and masses must be kept at near absolute zero temperatures, and heat must be precisely managed. At the required operating temperatures, there is little margin for error.



What problems are solved with BlueSeal Technology?

Problem 1: Liquid helium price volatility and sustainability

Over the last decade, liquid helium pricing and availability have been challenging. Rising geopolitical tensions and infrastructure problems have put increasing pressure on helium's supply as exemplified by shutdowns in the US and Qatar, and fires in Russian facilities². Historical sudden price increases due to supply shocks have reached 20% to 30%³. Helium is consumed globally faster than it is created in the earth's crust.

Therefore, conservation of helium is an important topic, and one where the MRI industry plays a major role.

BlueSeal magnets contain 99.5% less helium compared to Zero Boil-off magnets.

Problem 2: Zero Boil-off Magnets aren't always Zero Boil-off

To maintain zero liquid helium loss, the cryocooler in ZBO magnets must remain running. For this to occur, power and typically chilled water must be available for the cryocooler's compressor. In the event of long power outages or utility issues, these magnets will begin to boiloff liquid helium. Helium loss also typically occurs during transport from the factories. A magnet quench, which results from a rapid loss of superconductivity, will cause a ZBO magnet to lose its entire helium reservoir in a matter of seconds.

Helium loss is also expected during routine service actions, such as energizing and discharging the magnet.

BlueSeal magnets never need to be re-filled with liquid helium.

Problem 3: Siting, quench pipes, and magnet mass

For ZBO magnets, quench pipes of large diameters are required to safely exhaust helium gas from the examination room. These quench pipes can be costly and disruptive, especially in existing construction. Additionally, the substantial infrastructure and cost of installing a single quench pipe is exacerbated when installing multiple systems near each other. The quench pipe cost and complexity can become the limiting factor in the number of systems that can be installed within a single building. The liquid helium vessel in the magnet is also a pressure vessel, which requires significant thickness to react to pressure loads, which in turn will increase the mass of

the magnet. The mass of the magnet, including the helium vessel, is an important factor in siting as well, since this significantly increases the weight of an MRI system. This can often limit siting to ground floor which can stretch the area requirement even for new constructions.

BlueSeal magnets do not need a quench pipe and are significantly lighter, opening more siting possibilities.

Problem 4: Complicated magnet service

Specially trained operators are required to deal with the hazards and complexities associated with liquid helium. Furthermore, energizing and discharging the magnet requires specialized equipment to be brought to site. This action needs to be performed in the event magnetic objects become stuck in the bore.

BlueSeal magnets can be energized and discharged by hospital personnel from behind the MRI system console.

Problem 5: Inherent safety risks with cryogenic vessels

There are inherent safety risks associated with ZBO liquid helium vessels. Liquid helium at atmospheric pressure has an expansion ratio of ~750x, meaning that a liquid helium vessel which is completely blocked and warmed up to room temperature would generate pressures well exceeding 70 MPa (10,000 psi). Designing a cryogenic vessel to handle such high pressures is impractical, thus pressure relieving devices are employed.

Therefore, reliable functioning of the pressure relief devices, along with preventing blockages or restrictions in the quench pipe are critical to ensure safety of a ZBO magnet.

BlueSeal magnets have reduced inherent safety risks compared to Zero Boil-off magnets.

Problem 6: Liquid helium availability in the event of a quench

Large quantities of liquid helium are not readily available at every location in the world where many MRI systems are installed. An unintended magnet quench can leave the system non-operational for days or even weeks. The transport of liquid helium to a remote site can be both time-consuming and expensive. If the delay in refilling the magnet takes too long, the magnet can warm up. Cooling the magnet down again takes even more helium, time and cost.

BlueSeal magnets are immune to logistical challenges and costs associated with transporting liquid helium.

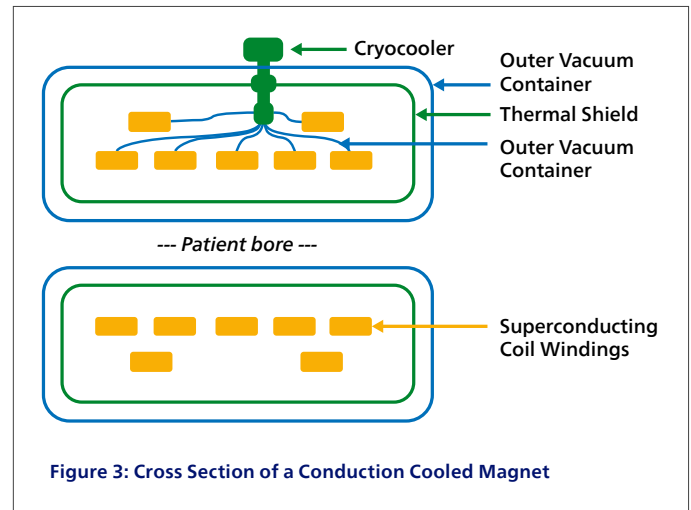
Conclusion 1

Liquid helium bath cooled MRI magnets face escalating cost, supply, logistics, siting, and safety challenges - making alternatives increasingly critical.

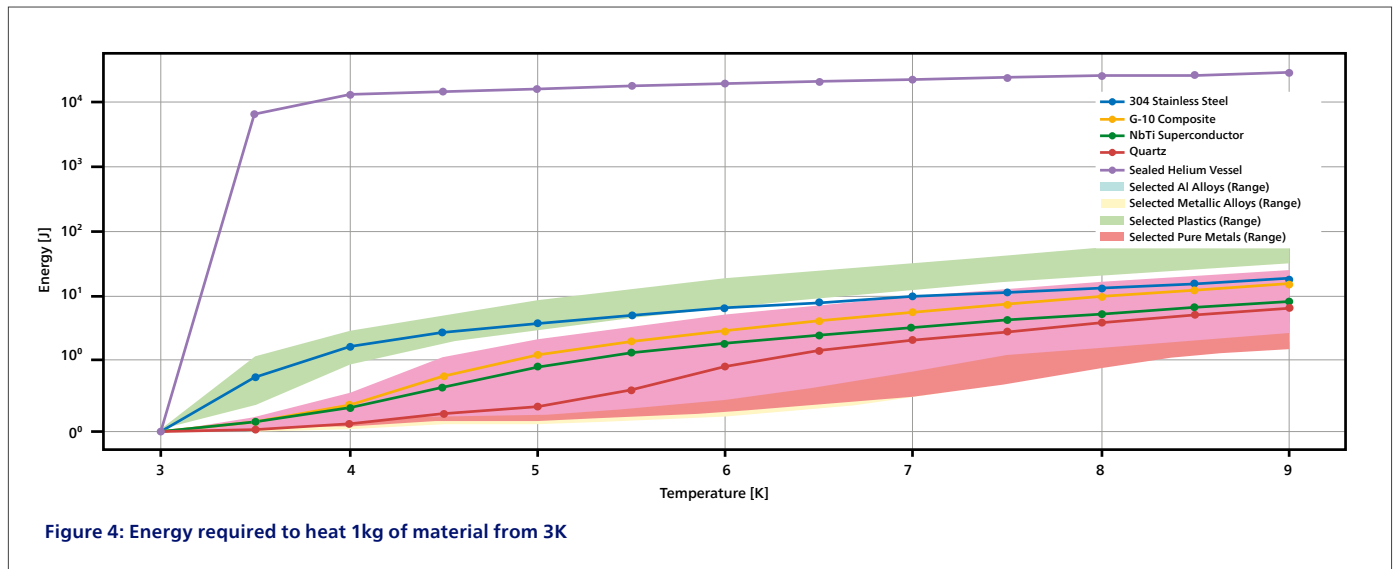
What other approaches are there to eliminating helium bath cooling?

The Conduction Cooled magnet

The Conduction Cooled magnet is perhaps the simplest architecture for a helium-free operations magnet. The liquid helium and liquid helium vessel are replaced with conductive links between the superconducting windings and the cryocooler second stage. The thermal link can be as simple as a copper conductor, or could also be a fluid-based conductor, such as a helium heat pipe or thermosiphon.



While there is appeal in the simplicity of the concept, there is one glaring problem – the lack of heat capacity to perform the critical function of providing a heat buffer.

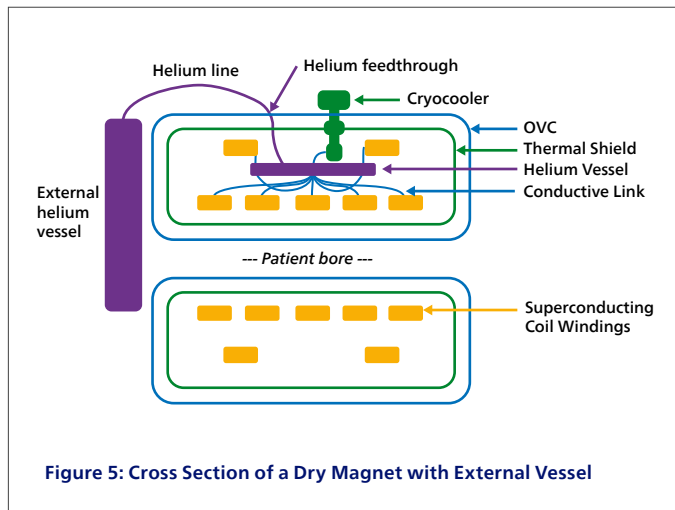


As can be seen from Figure 4, there is very little heat capacity in engineering-class solid materials. Having a low heat capacity and small thermal buffer will result in rapid temperature swings of the magnet in the event the refrigeration stops, which could for example result from power failures or failures within the cryocooler chain, including a chilled water failure.

Even more critically, the superconducting windings will be subjected to temperature swings from gradient coil operation during scanning. This could result in requiring significant limits on gradient amplitudes and slew rates or allowable frequencies and imaging duty cycle, compromising image quality and patient throughput.

The Dry Magnet with External Vessel

In the Dry Magnet with External Vessel architecture, helium gas is charged into two vessels, an external one always kept at room temperature, and an internal vessel which is connected to the cryocooler and will ultimately be cooled down to below 4 Kelvin. If the system charge pressure is sufficiently high and the volume ratio of the internal to external vessels is correctly sized, liquid helium will be generated in the internal vessel. Like the Sealed magnet and Conduction Cooled magnet, the superconducting windings are no longer submerged in liquid helium – they are dry. The windings can be thermally connected to the internal helium vessel either conductively or with closed loop fluid connections.



The external helium vessel needs to be connected to the internal helium tanks through a helium feedthrough which penetrates the Outer Vacuum Container (OVC), ensuring that both the cold vessel (internal) and warm vessel (external) are maintained at the same pressure.

The external vessel acts as an expansion tank. As the magnet gets cold, gas will migrate from the warm helium vessel to the cold vessel. The advantage of this approach is the ability to create liquid in the internal vessel with much lower warm charge pressures, compared to having an internal vessel. Additionally, the cold helium tank can gain additional energy storage from "pushing" helium molecules into the warm tank while it warms; however, the sensible heating of the helium vapor is lost as a result. This architecture cannot be considered truly sealed, as helium is entering and leaving the magnet. Therefore, a risk of contamination of the system exists which could lead to reliability issues. An embodiment of this architecture was investigated by Philips in 2014⁴.

Are the approaches equally effective?

The following configurations of the three presented architectures will be analyzed:

1. A Conduction Cooled magnet approximated as 1000kg of copper (matrix material of superconducting wire).
2. A Dry Magnet with External Vessel, with pressure and volumes sufficient to make 0.7 liters of liquid at operating temperatures.
3. A fully sealed magnet, with charge pressure and internal volume sufficient to make 7 liters of liquid helium at operating temperatures.



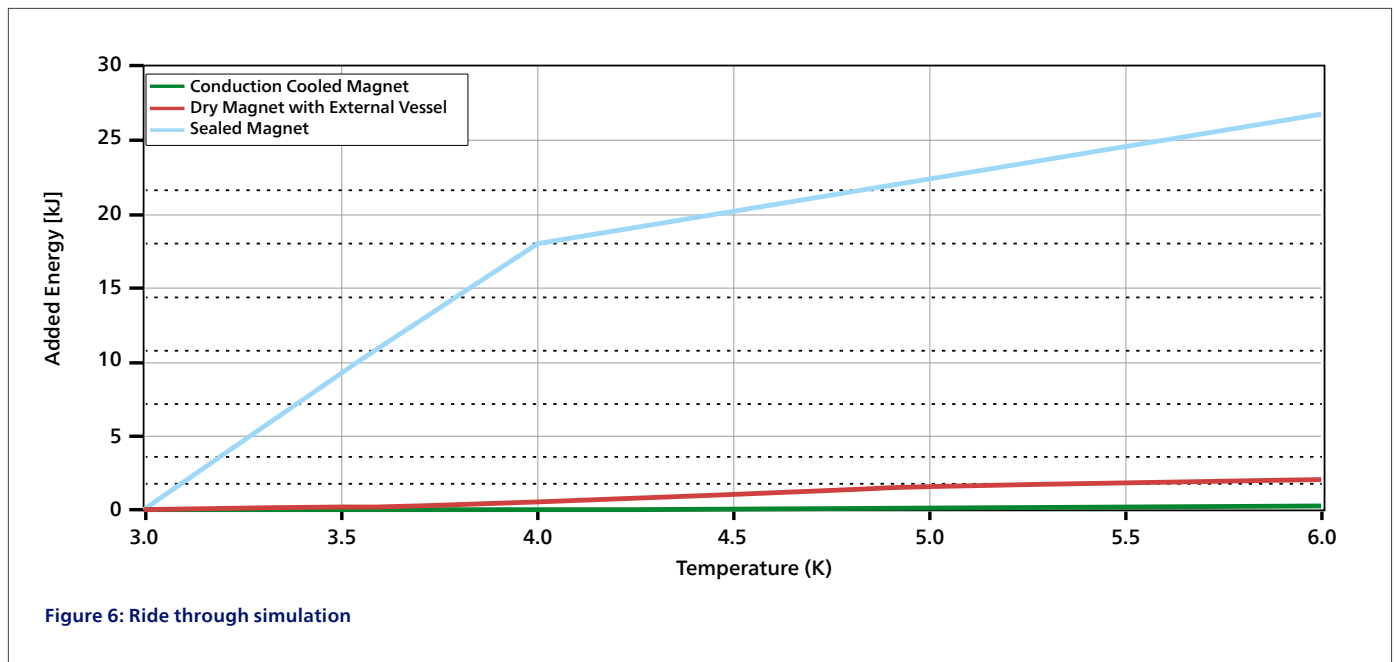
Thermal Ride through

Ride through time, the amount of time that the magnet can stay on field after a refrigeration loss, is an important design parameter for a helium-free operations magnet. Magnets can lose refrigeration for many reasons, with perhaps the two most common being loss of mains power and loss of chilled water for the helium cryo-compressor. Unlike ZBO magnets, refrigeration loss will cause the superconducting windings to rise in temperature. At some point, the superconducting windings will exceed the transition temperature for superconductivity, initiating a quench. In BlueSeal systems, a controlled ramp down is initiated in this scenario thereby avoiding a quench.

Figure 6 demonstrates the significant difference in energy storage between the three example architectures. Clearly the 7 liters Sealed system offers significantly more energy storage. Assuming an average heat load of 1 watt during the ride through, this system achieves over 5 hours of ride through

while staying below 4.5 Kelvin. In comparison, the 0.7 liter Dry Magnet with External Vessel achieves less than 30 minutes over the same temperature range, and the Conduction Cooled magnet is in the order of minutes.

The low ride through times of the Dry Magnet with External Vessel and Conduction Cooled magnet could be compensated with an external generator to prevent loss of refrigeration during a mains power loss. The external generator, however, comes with its own costs and challenges, such as additional burden in siting as well as the maintenance and reliability of the generator itself. Furthermore, an external generator does not compensate for other reasons for refrigeration loss, such as compressor overheating because of chilled water interruption or failure. In these cases, the inherent ride through of the magnet (30 minutes or less for 0.7 liters Dry Magnet with External Vessel) will be observed.



Conclusion 2

BlueSeal magnets provide redundancy to most power outages without the need for a UPS.

Uptime and Redundancy

In addition to the reliability of power, the reliability of chilled water needs to be considered. Chilled water is historically used to cool the cryocooler's compressor. Therefore, the availability of chilled water translates directly to the availability of the cryocooler. Chilled water availability can vary significantly from region to region and installation to installation. BlueSeal's architecture features built-in redundancy against

chilled water failures and is standard on all systems. By closely monitoring compressor diagnostics in real time, the system automatically switches the compressor heat rejection to air cooling mode if the chilled water supply encounters a problem. This ensures that the magnet remains at field strength and within operational range.

Conclusion 3

BlueSeal has designed in redundancy to water chiller failures as standard equipment, enabling high uptime.

Thermal Impact from Scanning

During imaging, heat loads can be imparted into the magnet. This can be due to either stray AC magnetic fields from the gradient coil or mechanical excitation of the cold mass, both of which can result in eddy current generation. The choice of

magnet architecture has an impact on the ability to absorb these heat loads and prevent the temperature from rising to unacceptable levels and possibly leading to limited gradient amplitudes and scan duty cycles or a quench.

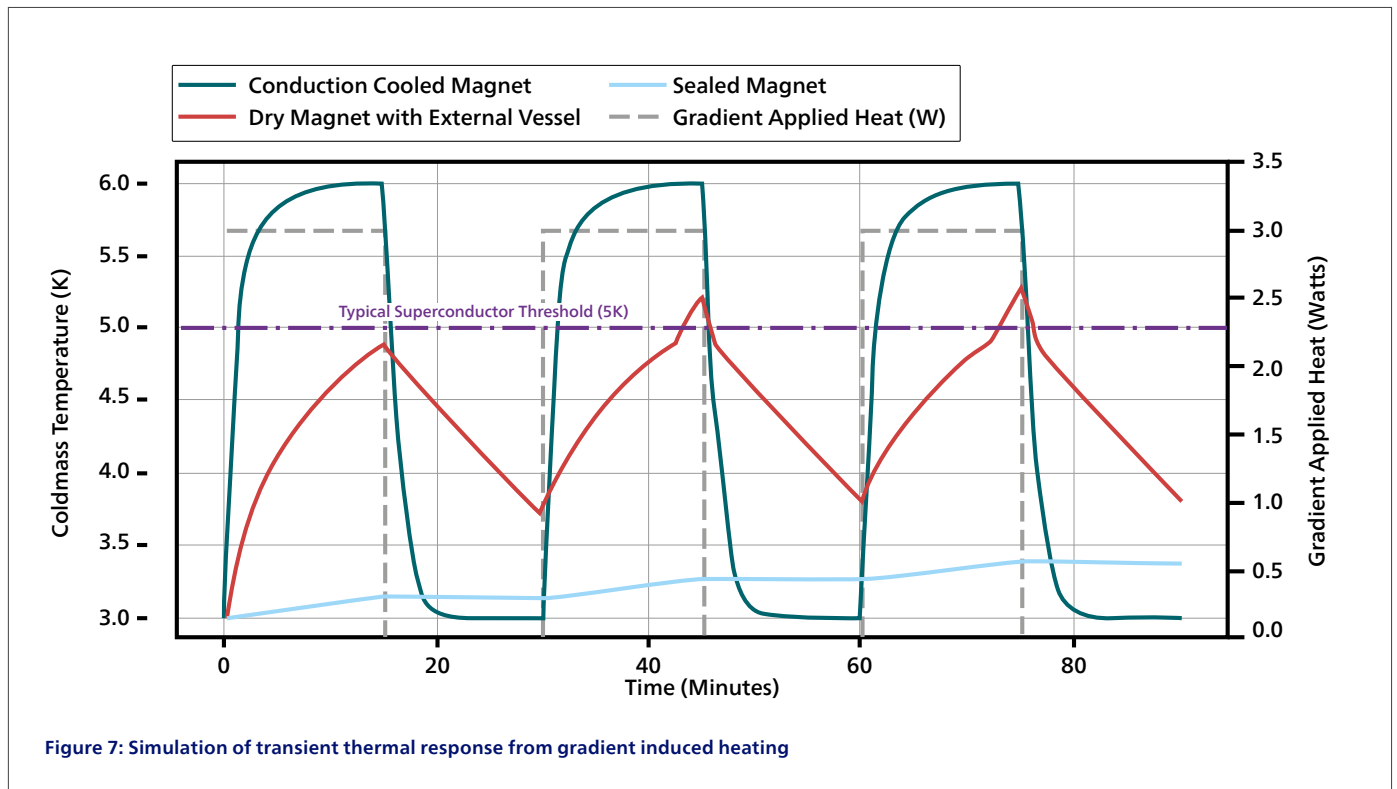


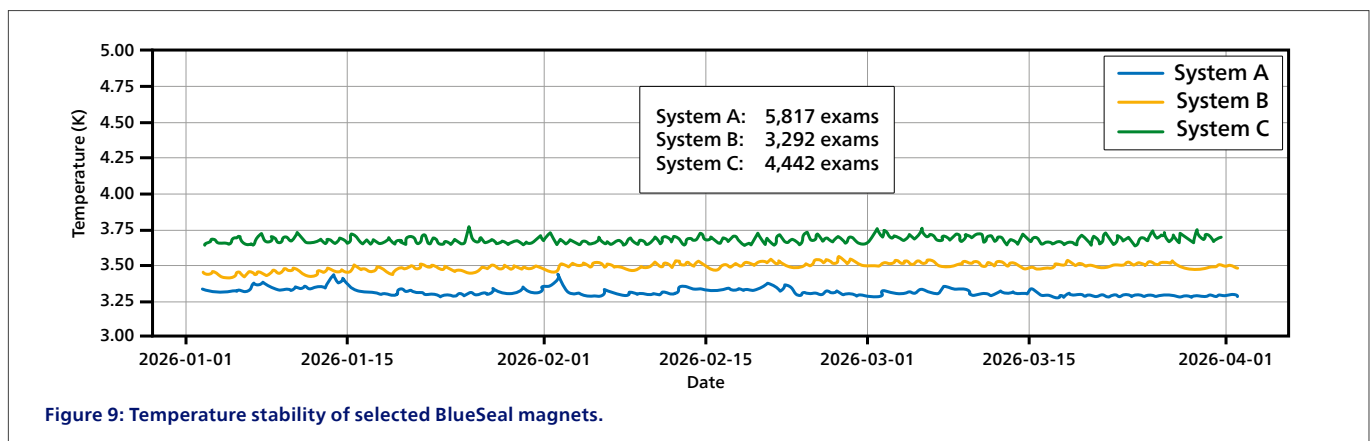
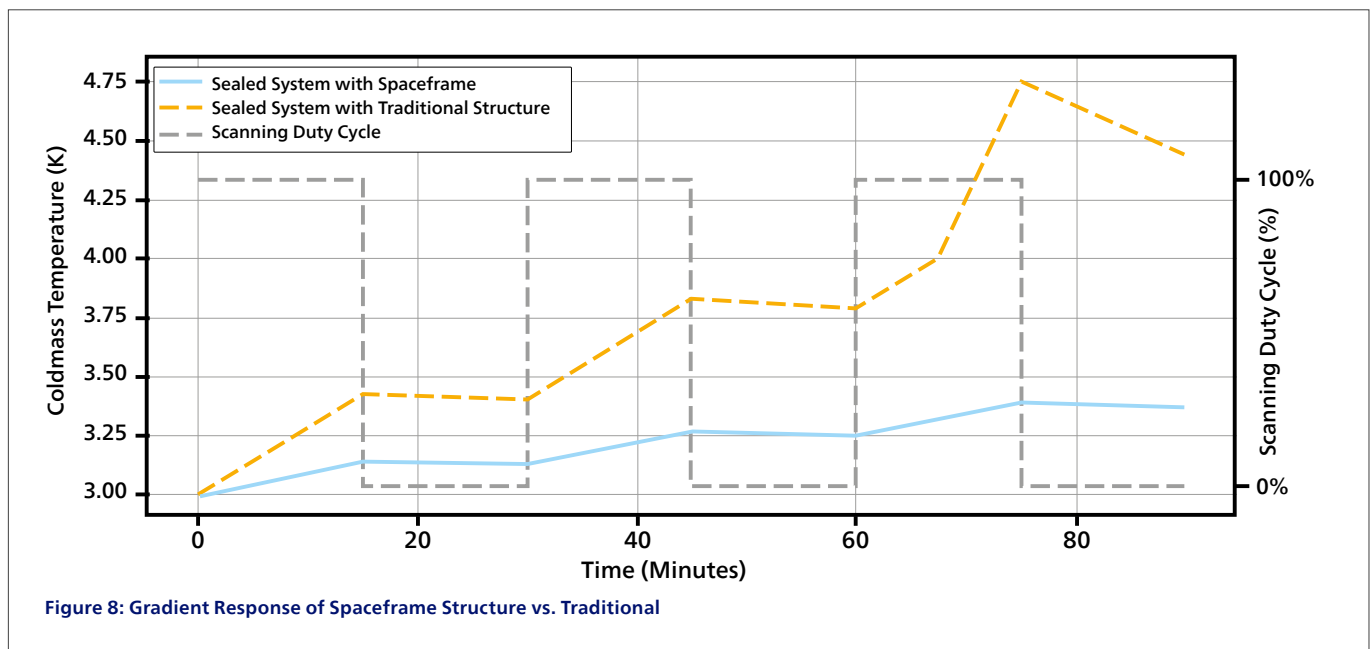
Figure 7: Simulation of transient thermal response from gradient induced heating

Figure 7 shows a simulation of scanning heat loads applied to three different magnet architectures. A scanning heat load of 3 Watts was selected, representing intense but controlled scanning. A 50% duty cycle was selected to simulate 15 minutes of scanning and 15 minutes of recovery.

The simulation shows a dramatic difference between the temperature response of the different magnet architectures. The Conduction Cooled magnet, with very little heat capacity, responds quickly to the heat impulses. Very quickly into the scan the magnet temperature would approach critical levels, requiring scan limitations such as reducing gradient coil power or ramping down to prevent a quench. The Dry Magnet with External Vessel is more resilient to the scan by comparison, but it too lacks enough heat capacity to make it through the two heavy scan cycles simulated.

This architecture also has relatively long recovery times compared to its heat capacity, due to having to re-cool the helium gas from room temperature that was stored in the external tank. Lastly, the Sealed system is most resistant to the applied scanning heat load, with minimal temperature increases and remaining below ramp down or quench temperatures.

The design of the mechanical structure supporting the superconducting coils can either promote or prevent eddy current generation. Philips BlueSeal magnets have redesigned the superconducting coil mechanical support system. The new structure, Spaceframe, uses discrete coil supports to minimize the ability of eddy currents to be formed during imaging. The design enables scanning with high amplitude gradients at high duty cycles.



Conclusion 4

BlueSeal architecture enables compatibility with high gradient performance, high scanning duty cycles and high system stability.

Power Consumption

The power consumption associated with a superconducting magnet can be attributed to the cryocooler compressor, which provides pressurized helium gas to the cryocooler. The amount of power needed for the compressor is a function of the refrigeration performance needed of the cryocooler. The refrigeration needs are comparable for the new architectures discussed here when the magnet is at field

in operational status. During energization modes, there are additional demands on the energization system, which must be accounted for in the design of the magnet. A Conduction Cooled magnet will most likely require additional refrigeration, and thus draw more compressor power, due to the limited heat capacity of the system during the energization process.

Conclusion 5

Despite the increased thermal demands, the power consumption of BlueSeal magnets is comparable to ZBO magnets.

What attributes make BlueSeal technology readily scalable to higher field strengths?

The architecture of BlueSeal is designed for scalability to higher field strengths with minimal impact on operational performance. At increased MRI field strengths, higher gradient power is typically demanded, placing greater requirements on the magnet's thermal management. Additionally, processes such as magnet energization require more robust thermal stability at elevated field strengths.

BlueSeal technology's substantial heat capacity effectively addresses these challenges. Spaceframe technology, when scaled to high field strengths, further reduces energy absorption from high gradient power. Finally, redundant power and chilled water systems ensure the magnet upholds the high reliability requirements expected by users of high field strength MRI systems.

Conclusion 6

BlueSeal architecture is readily scalable to higher field strengths.

What is the history of BlueSeal development?

There has been a clear trend in simplifying cryogenics in superconducting MRI magnets since the 1980's:

Year	Cooling	Regular Refills	Quench Refills
1980s	Bath	LHe & LN2	Yes
1990s	Bath	LHe	Yes
2000s	Bath	No	Yes
2018	Sealed	No	No

Table 3: Cryogenic Generations of MRI Magnets

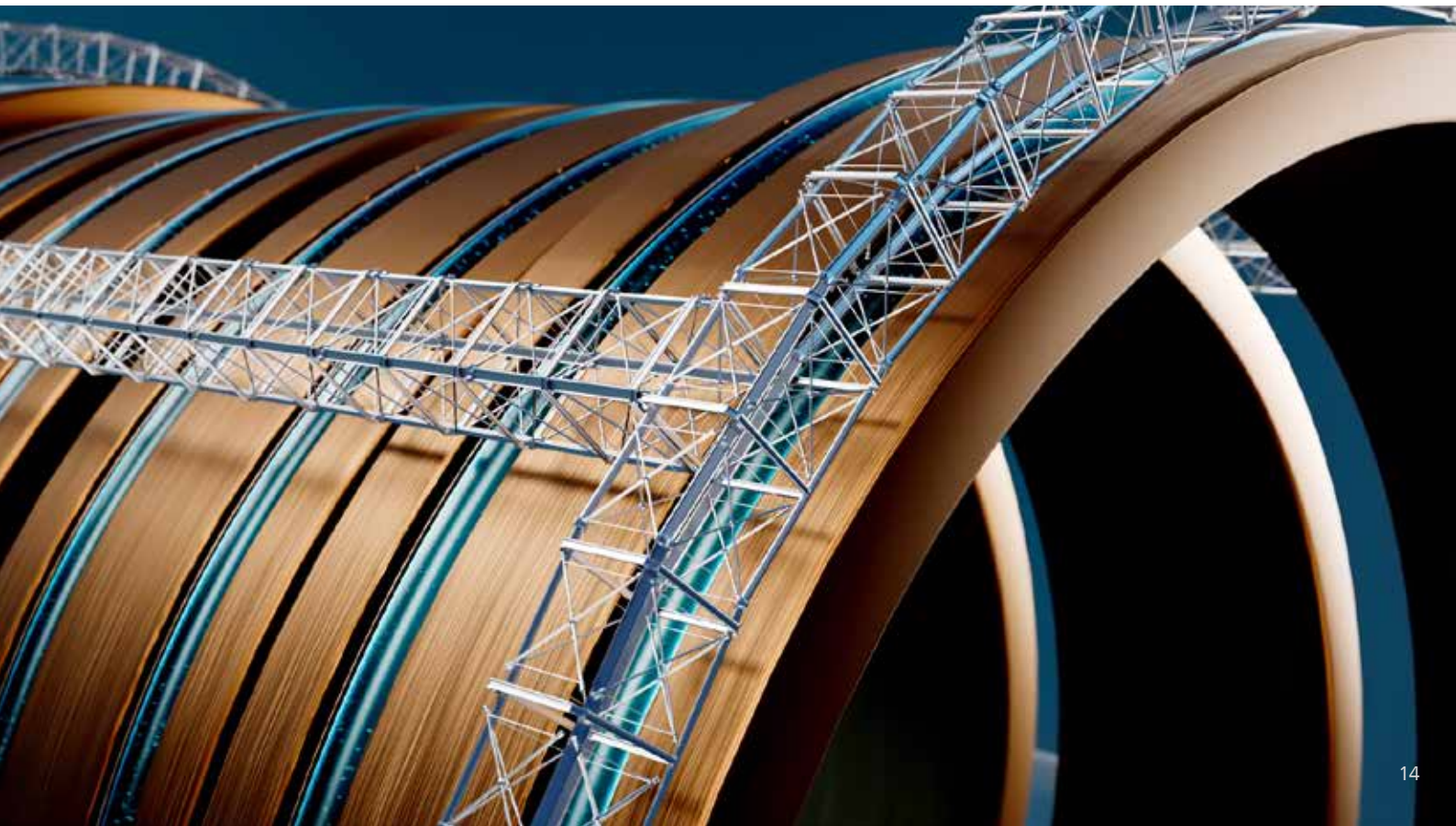
As seen in Table 3, early superconducting magnets for MRI required two cryogens, liquid helium (LHe) and liquid nitrogen (LN2). These two cryogens boiled off over time and had to be refilled at consistent intervals. As technology evolved, liquid nitrogen was able to be eliminated from the design. Eventually regular refills of liquid helium were eliminated with Zero Boil-off designs. Each generation brought cryogenic simplification.

In 2005, Philips began investigating alternatives to bath cooled helium magnets. The development history of BlueSeal magnets is described in the table below.

Year	Activity
2006	1st Dry Coil Experiment
2007	1st Dry Magnet prototype
2010	2nd Dry Magnet prototype
2012	Sealed Technology Advanced Development
2014	First Sealed 60cm prototype
2015	First Sealed 70cm prototype
2016	First Sealed Spaceframe 70cm prototype
2018	1.5T Ingenia Ambition Commercial Launch
2022	First 3T Sealed 70cm prototype

Table 4: Philips BlueSeal Development History

Table 4 illustrates different architecture approaches that were not only investigated theoretically but also built and tested in the laboratory over the last 20 years.



Summary comparison of different magnet architectures

With more than 2200 BlueSeal installations since 2018, there exists solid data on the extent to which the BlueSeal architecture meets the key requirements described earlier. Furthermore, the installed base in Spain and Portugal was

stress tested during a regional power outage in early 2025. All design features to address resilience against power outages performed flawlessly.

	BlueSeal	Dry Magnet + Ext. Vessel	Conduction Cooled	ZBO
Sustainable Cryogen Framework				
Cryogen sealed for life	●	●	○	●
No helium refills required	●	●	●	●
No quench vent required	●	●	●	●
Efficient power consumption	●	●	●	●
Operational Resilience				
Redundancy to power outages	●	●	●	●
Redundancy to chilled water outages	●	●	●	●
Heavy duty scan tolerance	●	●	●	●
Automated & smart recovery logic	●	●	●	●
Uptime without UPS	●	●	●	●
Clinical Utility				
Compact & lightweight	●	●	●	●
1.5T & 3.0T compatibility	●	●	●	●
70cm patient bore	●	●	●	●
Best in class image quality	●	●	●	●

Table 5: Key Feature Comparison

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ⁱ Helium-free operations. 7 liters of helium is permanently enclosed in the cryogenic circuit.

