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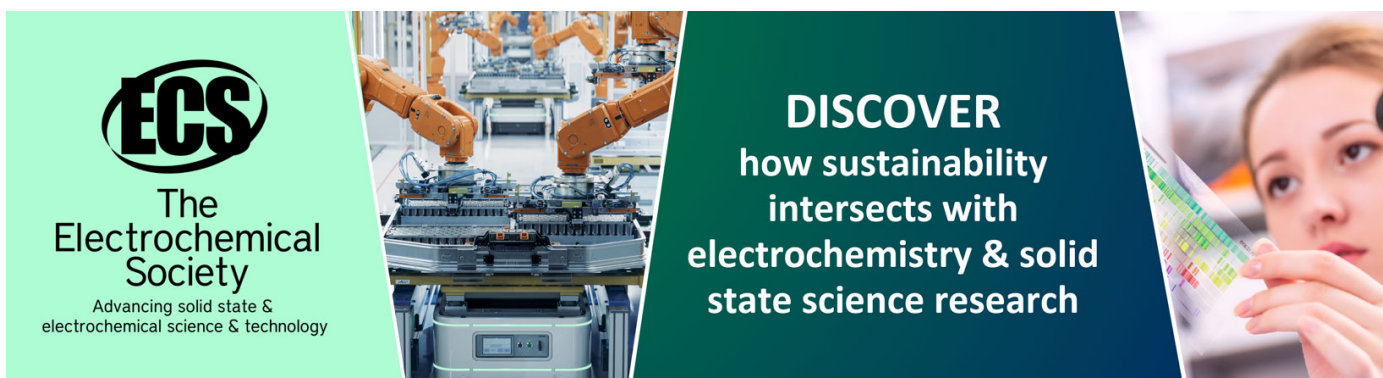
Development of a 20 T 100 mm Cold Bore Superconducting Magnet System

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Development of a 20 T 100 mm Cold Bore Superconducting Magnet System

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Abstract. Oxford Instruments has successfully developed a series of large bore, high field magnet systems, using conventional NbTi and Nb₃Sn low temperature superconductors (LTS). These magnet systems built to date have cold bores ranging from 150 mm to 250 mm diameter with central field from 15 T to 19 T. In this paper, we will introduce the development of a new member of high field and large bore magnet system at Oxford Instruments, with a central field of 20 T and cold bore of 100 mm. The magnet will be integrated with a special low-loss cryostat, generally stainless-steel construction with conductive radiation shields, constructed to minimize eddy currents and reinforced to withstand induced forces in the event of a magnet quench. The key technical challenges which must be met to provide such magnet system will be discussed in this paper.

1. Introduction

Significant development and progress have been seen in continuous-operation (referred to as “DC”) high field superconducting magnets in recent years, which are mostly driven by applications in materials science, NMR, particle accelerators and detectors, Fusion research, etc.

Over the past few years, Oxford Instruments has successfully developed a series of high field and large bore magnet systems, using only low temperature superconductors. The magnet systems built to date have cold bores ranging from 150 mm to 250 mm diameter with central field from 15 T to 19 T. These systems are enabling many new customer applications which are not possible with smaller bore systems. With help of these magnets and with the development of high temperature superconductors (HTS), especially the 2G HTS ReBCO conductor, our customers have successfully made great progress in development of all superconducting magnet systems. Q Wang in Institute of Electrical Engineering China has successfully developed a 27.2 T (12.2 T REBCO coil plus 15 T/160 mm bore Oxford Instruments magnet) all superconducting magnet in November 2017 [1], and his teams continues to develop a 30 T magnet (15 T REBCO coil plus current 15 T/160 mm bore magnet) [2]. H Weijers in NHMFL-Tallahassee has successfully developed a 32 T (17 T REBCO coil plus 15 T/250 mm bore Oxford Instruments magnet) magnet in December 2017 [3]-[5]. Table 1 lists typical high field and large bore magnet systems delivered or in-development by Oxford Instruments.

In this paper, the development of a new member of high field and large bore magnet system, for low temperature Scanning Tunneling Microscopy (STM), is presented, featuring a central field of 20 T and cold bore of 100 mm incorporating a large low loss cryostat. The design challenges in producing the system, such as stress/strain control, quench energy management, the large interaction force between coils and eddy current force on cryostat during magnet quench will be discussed.



Table 1. Oxford Instruments typical high field and large bore magnets.

Central field (T)	Magnet bore size (mm)	Operation mode	Homogeneity over 10mm DSV	Application	Country	Status
15	160	Driven	0.05%	Outsert	China	Delivered
15.3	250	Driven	0.015%	Outsert	USA	Delivered
18	150	Persistent	0.1%	STM	China	Delivered
19	150	Driven	0.04%	Outsert	Germany	Delivered
12	320	Persistent	0.04%	Dark matter	S Korea	Developing [6]
20	100	Persistent	0.1%	STM	China	Developing

2. System description

This customer system mainly consists of a 20 T central field 100 mm bore magnet, a special low-loss cryostat and a 3rd party UHV dilution refrigeration unit containing the customer self-designed experimental apparatus for STM measurements. The cryostat has special designed high thermal mass on outer radiation shield, which could be pre-cooled with nitrogen, will lengthen liquid helium hold time and minimize vibration to STM experiments.

The 20 T 100 mm bore magnet is designed to have a series of nested concentric solenoids - four Nb₃Sn coils surrounded by two outer coils wound from NbTi conductor. The coils use various grade wires to give the required electromagnetic and mechanical margins during the operation and to minimize the probability of quench damage. Both Rod-Restack Process (RRP) wire and Internal Tin (IT) wire are used to winding these four Nb₃Sn coils. The magnet is designed to be fully self-protected with diodes and energy dissipation resistors.

All coils are assembled to a stainless-steel base flange, which is then bottom loaded, and indium sealed into a low-loss type cryostat. The cryostat is designed with three layers of vapor-cooled radiation shields with 205mm central access neck and three 76mm service necks made from 304 stainless-steel. The service necks provide access for wirings, magnet current leads and exhaust path of helium gas from the system in the event of magnet quench or loss of vacuum. The vapor-cooled radiation shields are constructed to minimize eddy currents and reinforced to withstand induced forces in the event of a magnet quench.

The cryostat is developed according to unfired fusion welded pressure vessels code PD 5500. And the system internal pressure is designed to less than 0.5 barg when magnet quenches, which makes the system is covered by Sound Engineering Practice (SEP) category of Pressure Equipment Directive (PED).

Figure 1 below shows the system in cross-section, Table 2 and Table 3 list some key parameters of the magnet and cryostat, respectively.

3. Typical challenges of the system

Typically for research magnets, the higher the field and the larger the bore, the higher the stored energy density due to the high engineering current density required. The main design challenges are the static stresses when running the magnet to design field, the dynamic stresses generated by inductive coupling between the magnet coils, high hot spot temperature and high resistive voltages during a magnet quench, eddy current damage to other system components due to the large stray field and how fast this collapses in a quench.

This section details a few of the key challenges faced in the design of this 20 T system, and methods to mitigate the risks.

3.1 Stress/strain control

The static mechanical stress and strain inside the coils can greatly affect a magnet's spontaneous quench performance. Careful electromagnetic design is required so that the static stress when running a magnet to design field can be controlled to produce a training free magnet [7]. However, the dynamic stresses in multi-sectioned coils generated by inductive coupling can lead to much higher

stresses than the static stresses seen when operating at design field. Both situations can be modelled satisfactorily with design software developed for these applications. A detailed Finite Element Analysis (FEA) model for coil stress and strain calculation has been developed, in which all materials related to the coil are included, including conductor metal, conductor insulation, impregnation filler, etc.

Table 4 lists a few key stress and strain parameters, normalised to internal design criteria. The data indicate that for this magnet stress and strain are well within the design criteria, which indicates it is training free magnet.

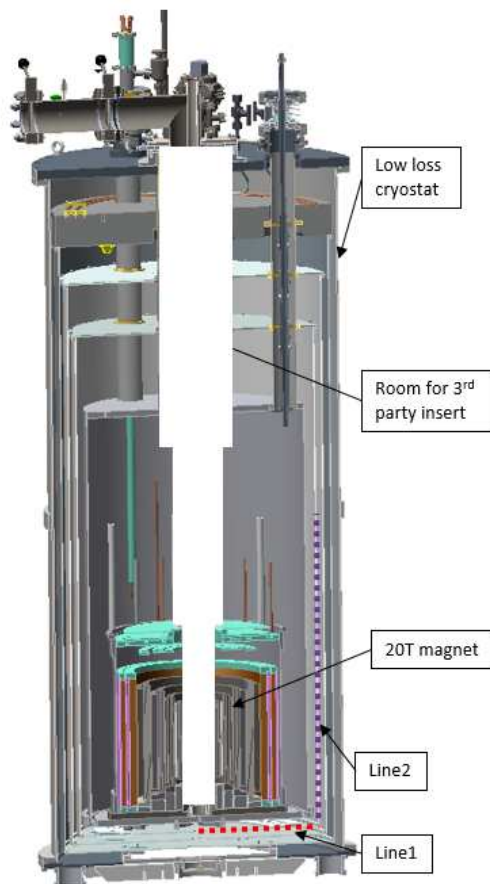


Figure 1 System model cross-section, including magnet and low loss cryostat

Table 2. Magnet main parameters.

Parameter	Values
Main magnet	
Central field	20 T
Magnet bore	100 mm
Operating current	<240 A
Inductance	131 H
Stored energy	3.7 MJ
Field homogeneity over 10mm DSV	<0.1%
Field stability	<10 ppm/hr
Superconductors	Nb ₃ Sn and NbTi
Stray field-5Gs line	5.25 m x 6.62 m
Time to field	< 80 min

Table 3. Cryostat main parameters.

Parameter	Values
Helium capacity	205 L
Static helium boil-off	≤0.35 L/hr
Outer diameter	1010 mm
Height	2260 mm
PED category	SEP
Weight	1000 kg

Table 4. Typical stress and strain of the 20 T magnet main coils relative to design criteria

Stress/strain %	Coil_1	Coil_2	Coil_3	Coil_4	Coil_5	Coil_6
hoop σ	49%	65%	56%	41%	49%	6%
axial σ	4%	11%	16%	19%	35%	57%
hoop ϵ	76%	90%	80%	73%	46%	5%
axial ϵ	49%	59%	67%	82%	68%	68%

3.2 Quench management

For the 20 T, 100 mm bore magnet, the total stored energy is 3.7 MJ; the magnet has a cold mass of 600 kg so if all the energy of the magnet was evenly dissipated in the windings it would reach around 100K.

The problem in these large magnets is ensuring that the energy is dissipated evenly, such that no single section overheats. Quench events typically last seconds, during which large amounts of energy may be transferred through inductive coupling between coils. The last coil to quench can generally have so much energy ‘pumped’ into it that it is strain damaged or develops a high local temperature thereby damaging the coil.

During a quench, the current falls rapidly in the quenched coil and very large currents are coupled into adjacent coils that remain superconducting. There are rapid temperature rises in the coil itself and the adjacent coils when they quench. The stresses set up by differential temperatures and rapidly changing currents lead to the necessity to control the quench and extract energy from the magnet coils in a controlled manner.

The new series of Oxford Instruments magnets do not use active quench management but instead use a tuned passive system utilizing voltages from coil sections to drive patented heaters, able to quench the magnet rapidly. Analyzing the potential quench voltages from many possible quench scenarios allows the operating parameters for the heaters to be defined such that the magnet’s own energy is used to spread the quench to every coil.

Figure 2 and Figure 3 show the current and voltage variations during a typical magnet quench originated from coil 3. Though the current in some coils will rise to approximately 1.4 times of operating current, the transient peak stress and strain are still below 90% of design guidelines. Multiple quenches have been analyzed, considering all potential quench scenarios, to make sure all magnet operating parameters are under acceptable limits.

Figure 4 shows the dynamic hoop stress relative to static hoop stress (stress pump ratio) during a quench originated from coil 6. Utilizing passive quench management, the hoop stress pump ratio is much lower than that of without. The pump ratio of coil 1 is reduced from 1.46 to 1.09 and coil 2 is reduced from 1.37 to 1.19.

3.3 Eddy current force minimization

For these cutting-edge high field large bore magnet systems, the magnets usually are not designed with active shield coils, which means the magnets have high stray field. Figure 5 shows the magnetic field distribution on Line 1 and Line 2 along one of gas-cooled radiation shield, as illustrated in Figure 1. Line 1 is on radiation shield’s bottom plate and Line 2 is on shield’s cylinder can. As magnet current usually drops from full operating current to zero in just a few seconds during a quench, the high eddy current force, due to the extended high stray field, imposes great challenges to cryostat design, as this high eddy current force will easily buckle a poorly designed cryostat. Cryostat design needs, on one hand, to minimize radiation heat load, so it is preferable to use high thermal conductivity material to improve thermal conductance and minimize temperature gradients along the radiation shields. On the other hand, to minimize the eddy current force during quench, it is preferable to use high resistivity material (low thermal conductivity), which is contradictory to thermal design requirements. For this special custom system, to simplify manufacture process and minimize cost, normal medium grade aluminum alloy was used to manufacture the two gas cooled radiation shields, instead of using special composite material glued with high thermal conductivity material.

To fully explore cryostat thermal and electrical response during magnet quench, a detailed multi-physics FEA model has been developed to analyze the transient eddy current force. Figure 6 shows the force density on radiation shields during the magnet fastest quench scenario. As shown in the figure, the radiation shield is sliced into a few sections to minimize overall eddy current force density and reinforced with low electrical conductance material to maintain the mechanical integrity.

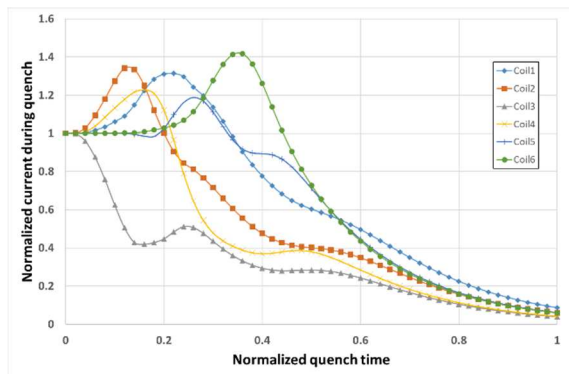


Figure 2. Normalised current variation during quench.

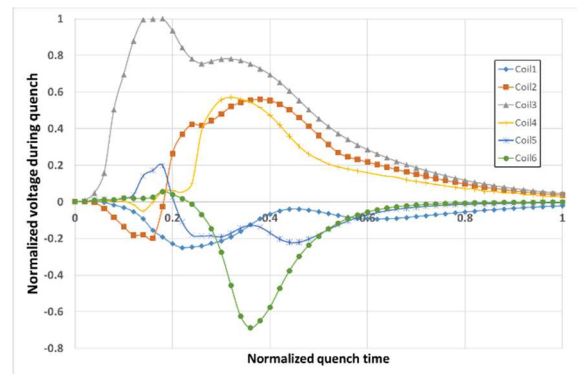


Figure 3. Normalised voltage variation during quench.

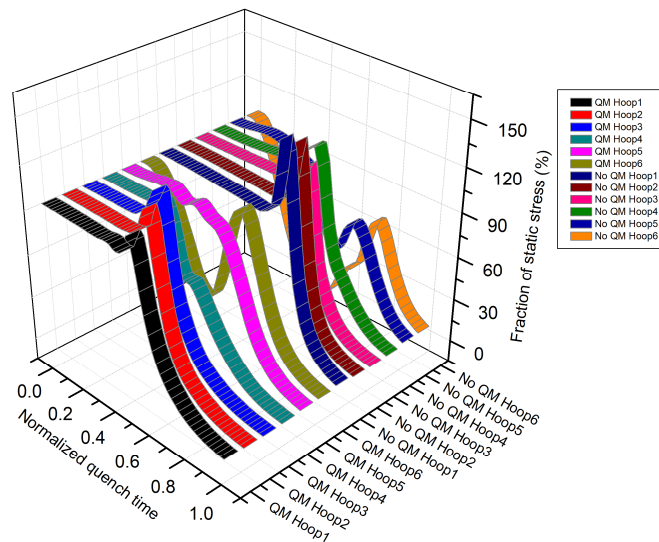


Figure 4. Stress pump during quench with and without quench management

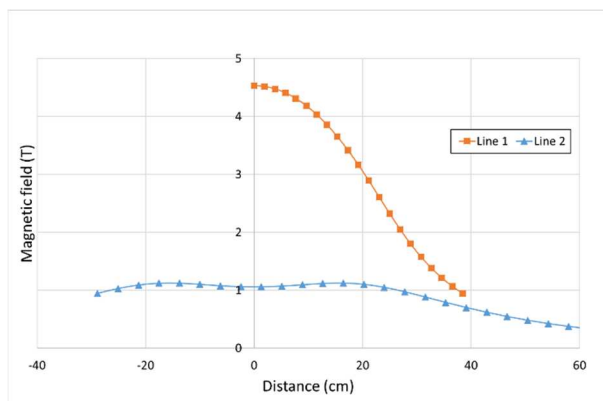


Figure 5. Magnetic field distribution along gas cooled shield

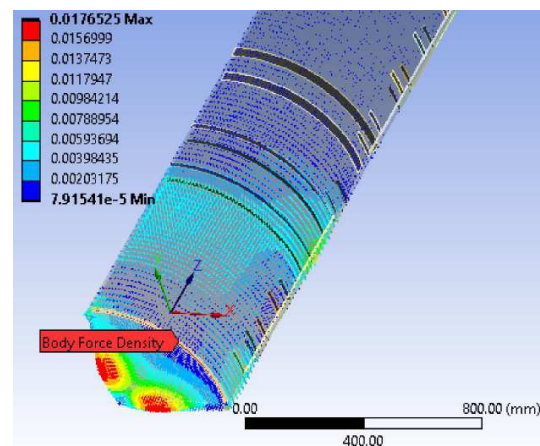


Figure 6. Eddy current force density distribution

4. Summary

A 20T central field, 100 mm cold bore magnet system is under development at Oxford Instruments. Key challenges for this magnet have been outlined and ways to mitigate the risks have been discussed. The majority of magnet design work has been finished. The system is planned to be tested in October 2020.

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