A New Member of High Field Large Bore Superconducting Research Magnets Family

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Abstract. Over the last 5 years, Oxford Instruments has successfully developed a series of large bore, high field (hence high stored energy) magnet systems, using conventional NbTi and Nb3Sn low temperature superconductors (LTS). These systems are enabling many new customer applications which have not previously been possible with smaller usable volumes. The magnet systems built to date have cold bores ranging from 150mm to 250mm diameter with central field from 15T to 19T. As well as their use as “outsert” magnets for High Temperature Superconductor (HTS) magnet systems, applications also include Scanning Probe Microscopy (SPM) and dark matter research. In this paper, we will introduce a new member of our high energy magnet system family, with a central field of 12T and cold bore of 320mm incorporating a large field cancellation volume some distance above magnet centre line. We will discuss the challenges which have to be met to provide such magnets, including stress/strain control, quench energy management, coil force and mechanical support.

1. Introduction

Driven by applications in materials science, NMR, particle accelerators and detectors, etc, significant developments have been seen in superconducting high field magnets. With the development of high temperature superconductors (HTS), especially the 2G HTS ReBCO conductor, the magnet field of all-superconducting magnets has been pushed up from ~21 T at 4.2 K [1], generated by combination of NbTi coils and Nb3Sn coils, to 32 T at 4.2K at NHMFL-Tallahassee [2], generated by NbTi coils, Nb3Sn coils and YBCO coils.

Oxford Instruments has designs for superconducting magnets for research applications encompassing a wide range of field strengths. A production magnet with a field of up to 20 T at 4.2 K and 22 T at 2.2 K with 52 mm magnet bore size is available commercially [3]. However, it is often the case that the best choice (referred to as figure-of-merit (FOM)) for a particular experiment is not the highest field; depending on the experiment, it could be the stored energy $B^2V$ (B is the magnet field and V is the field volume), $B^2L$ (L is the length of the field), etc.

To provide the right FOM for the right customer, over the last 5 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. Table 1 lists typical high field and large bore magnet systems developed and delivered in the past few years.
In this paper, the development of a new member of high field and large bore magnet system, for dark matter research, is presented, featuring a central field of 12 T and cold bore of 320 mm incorporating a large field cancellation field volume, situated 750 mm above the magnet centre line. The design challenges in producing the system, such as stress/strain control, quench energy management, the large interaction force between coils, 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 |
|------------------|-----------------------|----------------|---------------------------|-------------|---------|
| 15               | 160                   | Driven         | 0.05%                     | Outsert     | China   |
| 15.3             | 250                   | Driven         | 0.015%                    | Outsert     | USA     |
| 18               | 150                   | Persistent     | 0.1%                      | SPM         | China   |
| 19               | 150                   | Driven         | 0.04%                     | Outsert     | Germany |

2. System description

This customer system mainly consists of a 12 T central field 320 mm bore magnet, a low-loss bucket style Dewar and a 3rd party dilution refrigeration unit.

The 12 T 320 mm bore magnet is designed to have a series of nested concentric solenoids - two Nb3Sn coils surrounded by two outer coils wound from NbTi conductor. The coils use various grades of Bruker-OST wires to give the required electromagnet and mechanical margins during the operation and to minimize the probability of quench damage. The Nb3Sn coils use traditional internal tin superconductors, and the outer coils use normal monolith NbTi superconductors.

Compared with the previous four high-field large-bore systems Oxford Instruments has delivered, this magnet system has a new important feature - a large field cancellation field region (local field below 100 Gauss), 100 mm in diameter and 100 mm in length, situated 750 mm distance above the magnetic field centre. This feature enables the customer to do some field-sensitive measurements close to the magnet, which is not possible in previous systems.

All coils are assembled to a stainless steel base flange, which is then top loaded into a bucket type Dewar with a vapour-cooled radiation shield. It is a 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.

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 12 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. With careful electromagnetic design with appropriate wire grading, and incorporating overbinding if needed, the static stress when running a magnet to design field can be controlled to produce a training free magnet [4]. However, the dynamic stresses in multi-sectioned coils generated by inductive coupling can lead to far higher stresses than the static stresses seen when operating at design field. Both situations can be modelled satisfactorily with internal design software.
A detail 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, over-binding, 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.

Table 2. Magnet main parameters.

| Parameter                        | Values         |
|----------------------------------|----------------|
| **Main magnet**                  |                |
| Central field                    | 12 T           |
| Magnet bore                      | 320 mm         |
| Operating current                | 266 A          |
| Inductance                       | 161 H          |
| Stored energy over 10mm DSV      | <0.02%         |
| Field homogeneity over 10mm DSV  | <0.02%         |
| Field stability                  | <10 ppm/hr     |
| Time to field                    | < 1 hr         |
| **Cancellation coil**            |                |
| Clear bore                       | 320 mm         |
| Cancellation field               | <100 Gauss     |
| Cancellation region              | Φ 100 mm × Z100 mm |

Table 3. Cryostat main parameters.

| Parameter                  | Values         |
|----------------------------|----------------|
| Helium capacity            | 300 L          |
| Static helium boil-off     | ≤2 L/hr        |
| Outer diameter             | 900 mm         |
| Height                     | 3500 mm        |
| Weight                     | 800 kg         |

Table 4. Typical stress and strain of the 12 T magnet main coils relative to design criteria

| Stress/strain % | Coil_1 | Coil_2 | Coil_3 | Coil_4 |
|-----------------|--------|--------|--------|--------|
| hoop σ          | 54.8%  | 35.6%  | 34.1%  | 5.3%   |
| hoop ε          | 86.0%  | 66.1%  | 38.9%  | 6.2%   |
| axial σ         | 29.7%  | 33.3%  | 66.9%  | 87.9%  |
| axial ε         | 37.8%  | 38.7%  | 34.2%  | 30.4%  |
| radial σ        | 65.8%  | 42.3%  | 12.4%  | 2.7%   |
| radial ε        | 67.6%  | 50.7%  | 12.1%  | 1.9%   |

3.2. Cancellation Coil

Cancellation coils are used to provide a volume of relatively low field close to the magnet axially and generally confined close to the z axis. The complexity of the cancellation coil assembly and its operating parameters are affected by the strength of the magnet, the position and size of the cancelled region and the level to which the field must be cancelled.
Typical uses for field cancellation include reduction of eddy current heating in ultra-low temperature equipment, reduction of electromagnetic coupling between magnets in multi-magnet systems and provision of low field regions to minimise or avoid physical effects on devices such as sensors and detectors.

For solenoidal coils, the off-centre field components along the magnet axis are mainly the first and second orders. Hence cancellation coils are designed to have a primary coil (axially close to magnet centre) to cancel out the first order and two small secondary coils (axially further away from magnet centre) to cancel out the second order. Figure 2 shows plots of magnetic field magnitude and harmonics (absolute values) along the magnet central axis. It can be seen that with first and second orders cancelled, the local magnet field homogeneity decreases from more than 100000 ppm (1.2 T relative to 12 T) to less than 833 ppm (100 Gauss relative to 12 T) at 400 mm away from magnet centre. The magnetic interaction force between the main magnet and cancellation coils is also important. Assuming a dummy coil, with inner diameter of 340 mm and cross section aspect ratio of 1, to have zero central field at its axial centre, the interaction magnetic force would be more than 4000 t at 400 mm axial position, reduced to 7 t at 1000 mm axial position.

![Figure 2](image1.png)  
*Figure 2. Magnetic field magnitude, harmonics and dummy coil magnetic force plot along magnet central axis.*

To match both customer field requirements and internal magnet technology criteria, the cancellation coil field centre is chosen to be at 750 mm away from magnet center. As shown in Figure 3, the designed interaction force between cancellation coils and main magnet is about 3.5 times higher than the maximum achieved force in our standard systems. To reduce the probability of a magnet quench, the cancellation coils are optimized to have low coil end face pressure, about 0.7 times the maximum achieved pressure in standard magnet systems.

![Figure 3](image2.png)  
*Figure 3. Normalised force and pressure comparison with standard magnet systems.*

### 3.3. Quench management
For the 12 T 320 mm bore magnet, the total stored energy is 5.7 MJ; while this is significant the magnet has a cold mass of 800 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 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 magnets do not use active quench management but instead use a tuned passive system utilizing voltages from coil sections to drive patented heaters [5], able to quench the magnet using as little as 20 Volts. Analyzing the potential quench voltages from many possible quench scenarios allowed the operating parameters for the heaters to be defined such that the magnet’s own energy is used to spread the quench to each and every coil within less than one second.

The additional challenge in quench management of this magnet is the protection of the field cancellation coils. The cancellation coils are small and placed some distance apart from the main magnet. When the cancellation coils quench, the rest of the magnet will not necessarily quench because they are thermally and electromagnetically weakly coupled with the main magnet. Therefore the cancellation coils are protected together with a section of the main titanium coil and have diodes across them to divert current from the cancellation coils.

Figure 4 and Figure 5 show the current and voltage variations during a typical magnet quench in some coil sections. Though the current in some coils will rise to approximately 1.8 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. Normalised current variation during quench.](image)

![Figure 5. Normalised voltage variation during quench.](image)

### 4. Summary

A 12T central field, 320 mm cold bore magnet system with a large cancellation volume 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 September 2019.

### References

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