Aspects of superconducting magnet design for neutron scattering sample environments

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Abstract. The majority of superconducting magnets for neutron scattering experiments take the form of split pairs with magnetic field vector in the vertical plane. Sample environment access is along the vertical magnetic axis whilst neutron access is in the horizontal plane. Split pair superconducting magnets present significantly more challenges in terms of design than the simpler solenoid type arrangement and the addition of requirements for neutron access further complicates the situation. Many of the requirements of split pair magnets for neutron scattering are conflicting and often compromises have to be made. Presented here are some of the more important design criteria and the ways in which these are met in practical magnet designs. Topics covered range from the choice of superconducting material through to the control of magnetic flux density profiles and mechanical aspects of the magnet former providing the neutron access between the coils. Most of the information presented is based on recent or current production magnets manufactured by Oxford Instruments for a range of neutron related applications.

1. Introduction
Although simple solenoid geometry magnets are employed in neutron scattering experiments the majority take the form of split pair solenoids. The greater proportions of these are orientated with field vector and sample environment access in the vertical direction whilst neutron access is in the horizontal plane.

The ‘split pair solenoid’ configuration takes its name from the fact that the windings are circularly symmetric but split into two regions in the axial direction arranged either side of a central gap. Conventionally the solenoid part of the name is dropped and such magnet arrangements are simply known as ‘split pairs’.

Many of the requirements of split pair magnets for neutron scattering are conflicting and often compromises have to be made. Presented here are some of aspects of split pair superconducting magnet design and engineering from basic operating parameters to mechanical design and control of flux density profiles.

Data is taken from magnets designed by Oxford Instruments to meet a wide range of individual requirements for laboratories around the world. A typical magnet system for neutron scattering is shown in figure 1 whilst figure 2 shows a section through the magnet and lower portion of the cryostat.
2. Superconducting materials

The main commercial superconductors are Niobium Titanium (NbTi) and Niobium Tin (Nb3Sn). The first is a ductile alloy and conductors including this material are easily handled and wound into coil form. The latter is a brittle intermetallic compound which is normally formed from constituent components by high temperature reaction in the as-wound form in a process known as “wind and react”. Both conductor types contain high conductivity normal metal to act as stabilisation and to provide a normal current path in the case where the superconductor passes into the normal regime in the event known as a “quench”. The normal stabilisation material is copper.

Engineering current density is defined as the critical current divided by the total area of the conductor. In high field magnets the two materials are employed in various sizes of conductor at positions within the magnet to suit the local conditions.

In general the flux density within the magnet windings falls with increasing radius and the conductor sizes are graded by size to achieve similar critical current operating fractions throughout the magnet. Critical current is measured by testing short lengths of conductor at various flux densities. For a standard conductor the curve generated is known as the short sample curve and a magnet is designed to operate at a certain fraction of this.

3. Principal Specifications and Magnet Operating Parameters

3.1. Flux Density Homogeneity

In a solenoid magnet it is relatively simple to produce flux density uniformity or homogeneity over the required sample volume down to the PPM level. In split pairs the geometry constraints applied by the neutron aperture make the creation of very uniform flux density much more difficult. There are
configurations of split pair windings that allow for higher uniformities but in general, over typical neutron scattering sample sizes, the homogeneity is normally limited to the range 0.1 to 5%.

3.2. Operating Flux Density
The available current density for a given conductor decreases with increasing flux density (as shown in the figure above). The flux density seen by the superconductor at the inside of the magnet windings is greater than the operating central value.

This is particularly so in split pair magnets where the ratio can be large. In the example shown in figure 4 the ratio is almost 1.6 giving a maximum flux density of 14.3 tesla for a central value of 9 tesla

3.3. Forces and Stresses
For circular symmetric windings it is normal to describe the Lorentz forces in two directions; axial and radial.

Radial components of flux density react with the current flowing in the conductor to produce axially directed forces. The radial flux density generally has a maximum value at the ends of the windings resulting in axial forces directed towards the mid-plane. For simple solenoids this is not generally a serious issue as the associated axial stress is well within the compressive strength of the winding. In a split pair however these forces have to be reacted by the components that form the gap between the windings. There are also issues related to the interfaces between winding blocks and plates that form the sides of the gap.

Axial components of flux density react with the current flowing in the conductor to produce radially directed forces. These forces, over the majority of the windings, are outwardly directed resulting in the conductor being placed in tension and producing winding stress in the hoop direction. After the available current density limited by the peak flux density, this parameter is generally the next most important limiting factor. Gradients in the hoop stress distribution may also present problems as these result in radially directed stresses which, if positive in direction, tend to pull the winding apart.

4. Split pair magnets for neutron studies
The main purpose of the “split” in split pair magnets is to give access normal to the magnet axis. For many applications involving the use of split pair magnets access through the central region may be satisfied by simple holes through the spacer. In the case of magnets for neutron studies the access aperture requirements are generally greater and it is normal to use either rings of aluminium alloy between the two halves of the magnet to provide a “window” transparent to neutrons or wedge shaped openings between the coils. The axial forces outlined in the previous section clearly have to be reacted between the two sets of windings by the components that make up the space between them to provide the required support to maintain mechanical integrity with minimal distortion.
In the aluminium alloy ring type arrangement the available opening angle can be close to 360º with only a single dark angle of 10 to 20º being required to allow cryogenic and electrical connections between the two halves.

The thickness of the rings depends on the magnetic forces and the mechanical properties of the aluminium alloy employed. The magnetic forces are not only dependant on the central flux density but also to some extent on the geometry of the coils.

The mechanical properties of aluminium alloys are composition dependent with only a restricted number of types being suitable for neutron transmission and having suitable mechanical properties. A typical example of such a magnet is shown in figure 5.

In the wedge shaped opening approach it is clear that the rigidity of the former plates that form the sides of the openings has to be significantly greater than in the window ring case outlined above.

As with the ring case approximate calculations may be made using appropriate formulae to determine stresses and local distortions but only finite element analysis can provide the detail required to allow optimised design. Figure 6 shows a typical wedge aperture type magnet assembly.

5. **Summary**
The number of variables involved with a split pair is greater than for simple solenoids due to the added access through the mid-plane. As described this leads to increased complexity of superconducting split pair magnets for neutron scattering.

The number of potential specification variables is large and magnets of this type tend to be specifically designed for each application. For instance the size of the neutron aperture (height, vertical divergence angles and horizontal angle) has a very large impact on the other magnet parameters such as available flux density, homogeneity and magnet size / cost.

The mechanical aspects of split pair magnets for neutron scattering studies are important if the overall magnet is to be stable and reliable in operation.

The exploitation of the latest developments in superconductor design, together with robust magnet manufacturing techniques, makes possible high flux density magnets for neutron scattering studies of up to 16 tesla. The number of competing parameters makes defining the range of apertures and divergences difficult however in general higher flux densities require smaller neutron apertures and divergences to keep the magnet within reasonable size and cost.