

## Superconducting Spin Precession Magnets For A New Neutron Spectrometer

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The required field shape of optimal Larmor precession magnets to obtain the best possible homogeneity is  $B_0 \cos^2(\pi z/L)$ . In practice this field shape is approximated by 30 superimposed concentric solenoids. The coils are made with an extreme dimensional precision with a typical error of 10  $\mu\text{m}$ . A special winding technique in combination with a relatively thin superconducting wire of 230  $\mu\text{m}$  diameter provided a significant overall accuracy. In this paper the design and construction aspects of the superconducting Larmor precession magnets will be discussed. Results of the magnetic field optimisation as well as preliminary test results of the magnets are presented. However, the ultimate performance will be investigated when the magnets are put into operation in the new neutron Larmor precession spectrometer at the Institut Laue Langevin.

### INTRODUCTION

The energy resolution of a neutron spectrometer can be enhanced with several orders of magnitude by implementing two superconducting Larmor precession magnets. An impression of such a magnet system including flipper coils and correction coils is shown in Figure 1. The optimal field for these precession magnets is the  $\cos^2$  field shape [1]. After passing a polariser the magnetic moments of the neutrons are aligned perpendicularly to the magnetic field vector by means of the flipper coil (F) before entering the magnet system (M1) after which precession starts. Correction coils (C) are implemented to reduce the field at the positions of the flipper coils to an acceptable level for optimal performance of the flippers. At the exit of the magnet precession is stopped by means of a second flipper coil. After reflection at the sample the beam passes a similar magnet system (M2) before it will be detected by a spin analyser. If the integral for all possible path positions of the diverging beam are equal, then the number of precession turns in such a system is directly related to the energy of the neutron [2]. In that case energy exchange during reflection on the sample results in a signal from the spin analyser that is directly related to the difference in Larmor precessions prior and after the collision with the sample.

The desired line integral of the precession field is 1 Tm with a maximum relative inhomogeneity ( $\Delta|B|/|B|$ ) of  $10^{-6}$ . This value of the line integral is achieved in a magnet with a length of 1.41 m and an inner diameter of 80 mm which is defined by the neutron beam diameter (40 mm) and the minimum cryostat wall thickness. This diameter is kept as small as possible to reduce the stray field. The main coils provide a basic line integral homogeneity of about  $10^{-3}$ . In order to obtain the required homogeneity of  $10^{-6}$ , 2 spiral in-beam correction coils (S) are added to the magnet system.

Additionally two identical guiding solenoids are placed around the mid-plane of the precession magnet. They are used during experiments with a very small number of precessions. In such a case the  $\cos^2$  field value at the ends is very weak so that background fields may cause depolarization. The generated fields of both solenoids are equal but the direction is opposite. The net precession caused by the guiding coils is zero but depolarization due to background fields is now excluded.

### SUPERCONDUCTING COIL SYSTEM.

The high homogeneity requirements of the precession magnetic field set high demands on the dimensions of the coil former. Deviations in straightness and diameter do have consequences for a proper operation of the magnet system. The coil former is manufactured from Al 5083. A double helical groove (thread) is cut

in the coil former to achieve very accurate positioning of the superconducting coils. The coil former itself is the inner wall of the helium vessel as can be seen in Figure 2.

#### The Neutron Larmor Precession Magnet.

The required  $\cos^2$  field distribution is generated by a coil system which consists of 30 superimposed concentric solenoids [2]. Due to the double helical grooves in the coil former, 2 coils can be wound in 1 layer. The optimum lengths of the individual subcoils are calculated by minimizing the difference between the field profile of the practical coil system and the ideal  $\cos^2$  field shape. As a consequence of the grooves in the coil former and the grooves formed by the adjacent turns in all the other layers to obtain the required dimensional accuracy, all the coils are wound in the same direction which means that after completion of the windings the coils have to be connected in series through so called return-wires. However, these return-wires generate field too that interfere with the main field. Calculations show that, to minimise this interference, the return-wires must make 1 turn around the coil former. Additionally the generated field of a certain return-wire must be compensated by the field of another return-wire with about the same length and positioned at the opposite side of the coil. The actual joints are located around the mid-plane of the precession magnet.

A multifilamentary NbTi wire of  $\varnothing 230 \mu\text{m}$  is selected to build up the 30 superimposed coils to achieve the current density for a field integral of 1 Tm. The main specification of the conductor is as follows: 138 x 121 filaments of  $0.8 \mu\text{m}$  in a Cu matrix, Cu fraction 73%, twist 6 mm, bare diameter 0.200 mm and a critical current 32 A at 2 T.

#### The Guiding Field Coils.

The guiding field coil system consists of 2 solenoids positioned symmetrically with respect to the centre of the Larmor precession magnet. The superconductor used for the main coils is also used for these solenoids. Both coils are wound on top of the Larmor precession magnet. The outer radius of the windings from the mid-plane to the coil ends is reduced from 43.200 mm to 40.232 mm. Both coils of the guide field system are wound clock wise and they have an equal number of turns. For magnet systems M1 and M2 the numbers are 1410 and 1402 respectively. The pitch of these turns is  $500 \mu\text{m}$ .

#### Calculated Magnetic Fields.

The disturbance field generated by the return-wires is minimised by finding the best possible positions for these wires. The best configuration of the coils and the return-wires with minimal deviation of the primary model is worked out. The program simulates a neutron passing through the magnet system and calculates the total field and the components on its path in given points. These are positioned on a straight line and the line integral of the field  $\int B dl$  can be calculated by integrating the total field component along the path. 200 points are taken on a path from  $z = -1 \text{ m}$  to  $z = +1 \text{ m}$ . The disturbing field of the return-wires is calculated by modelling the wire as 15 straight pieces on a radius of  $0.0415 \text{ m}$  of which the field can be calculated. The  $\int B dl$  is determined for different path positions to study the homogeneity of the magnet.

In Table 1 the calculated line integrals for the magnets M1 and M2 are compared with the values obtained from the ideal  $\cos^2$  field shape. The given integrals of the precession magnets are average values of the  $\int B dl$  calculations at different angles of the path in the magnetic field. The effect of the return-wires is included. The deviation with respect to the average value as function of the angle position is shown in Figure 3. The average values of the M1 and M2 line integrals are used to determine the (in)homogeneity factor  $\eta$ . This factor is defined as:

$$\eta = \left[ \frac{\int B dl_{(r)}}{\int B dl_{(r=0)}} - 1 \right] \cdot 10^6. \quad (1)$$

Calculated values of  $\eta$  for different radii are collected in Table 1. It can be seen that  $\eta$  is proportional with the square of the radius. To reduce the homogeneity factor  $\eta$  further to less than 1, in-beam correction coils have to be implemented. The disturbances due to the return-wires as defined by

$$\Delta = \left[ \left( \frac{\int B dl_{\text{undisturbed}(r)}}{\int B dl_{\text{undisturbed}(r)}} \right) / \left( \frac{\int B dl_{\text{disturbed}(r)}}{\int B dl_{\text{disturbed}(r=0)}} \right) - 1 \right] \cdot 10^6, \quad (2)$$

are also collected in Table 1. It shows that this contribution is smaller than 0.5 ppm.

Table 1. Line integrals and inhomogeneity factor of both Larmor precession magnets M1 and M2.

Radius [m]	Model		Magnet M1		Magnet M2		
	$\int Bdl$ [mT*m/A]	$\int Bdl$ [mT*m/A]	$\eta$ [ppm]	$\Delta$ [ppm]	$\int Bdl$ [mT*m/A]	$\eta$ [ppm]	$\Delta$ [ppm]
0	59.529116	59.5291367	0	0	59.5290374	0	0
0.005	59.531659	59.5316313	42	-.4980			
0.010	59.539228	59.5392449	170	.0052	59.5391537	170	.0056
0.015	59.551843	59.5519238	383	.0127			
0.020	59.569704	59.5697576	682	.0284	59.5696600	682	.0272

### Construction Details

All coils are wound in the same direction. The first layer on the coil former is of an insulated copper wire ( $\varnothing 217 \mu\text{m}$ ). Including this layer, the inner diameter of the coil system becomes 80 mm. The first layer of copper wire ensures the electrical insulation between the coils and the coil former and mechanically uncouples the windings from the aluminium coil former. No adhesive is used between the coil former, the copper layer and the first superconducting layer to avoid premature quenching and training. All other coils are wet wound with epoxy resin to obtain a rigid winding package. After positioning and connecting the return-wires, the joints are soldered and connected to heat drains. The current leads are twisted to reduce error fields. Finally the coils are covered with a layer of glass-cloth and STYCAST 2850 FT. A summary of the main parameters of both precession magnets is listed in Table 2.

The magnets are quench protected and overvoltage is prohibited by means of anti-parallel wired cold diodes limiting the voltage across the magnets in both forward and reverse direction to 10 V at 4 K.

Table 2. Main parameters of both magnetic systems.

	Precession magnets		Guiding field magnet	
	M1	M2	M1	M2
Number of coils / layers	30 / 15		2 / 1	
Number of turns	47456		2 x 1410	2 x 1402
Length of 1° coil [m]	1.41474	1.41475		
Inner / Outer radius [m]	0.03997 / 0.04297		0.04000 / 0.04299	
Inhomogeneity	6.8x10 <sup>-4</sup>			
Maximum current [A]	25			
Magnetic field in centre [T/A]	0.0742447	0.0742437		
Self-inductance [H]	14.0		0.0357	

### TEST RESULTS OF THE MAGNETS.

After winding the 30 coils measurements are performed to determine the total bending of the precession magnets. The magnets are supported at both ends and bending is measured on top of the magnets with an accuracy of 3  $\mu\text{m}$ . Figure 4 shows the total bending of magnet M2 as a function of the z-position for different angle positions. Positioning the magnet in the cryostat with the angle position of 270° on top will cause a magnet bending in the neutron spectrometer of 40  $\mu\text{m}$  maximum.

After cool down the Larmor precession magnet to liquid helium temperature the magnet current is ramped up to a maximum of 25 A with a ramp rate of 0.714 A/s. This ramp rate is limited due to the maximum voltage across the magnet allowed by the protection diodes and the self induction of the magnet. In order to determine the maximum temperature in the magnet after a quench, a normal zone is initiated by activating a spot heater at different coil currents. At the maximum coil current of 25 A a hot spot temperature is registered of 150°C maximum.

Measurements of the magnetic field profile are useless, because no instruments with a satisfactory accuracy are known. The final homogeneity can only be determined by testing the magnet with neutron beams.

### CONCLUSIONS.

Two superconducting Larmor precession magnets with a  $\cos^2$  field shape are successfully designed and built. The field shape is obtained by 30 superimposed solenoids wound in 15 layers by which all dimensions of coils and connecting wires are optimised to provide the best possible performance.

Due to this optimisation a maximum deviation in the line integral  $\int Bdl$  between the precession magnets and the primary model of 1.3 ppm is achieved. The deviation of the line integral  $\int Bdl$  with respect to the average at a radius  $R = 0.020$  m is calculated to be 1.2 ppm. This deviation is even less than 0.4 ppm at a radius  $R = 0.010$  m.

The homogeneity factor of the magnets achieved is 680 ppm within a radius of 0.020 m. In order to reduce this value to less than 1 ppm in-beam correction coils have to be implemented.

With the manufacturing of both magnets the magnet development program for the new spectrometer enters the next step of testing the ultimate performance with neutron beams. As far as could be measured without neutrons, both magnet systems operate accordingly to the system specifications and design values.

REFERENCES

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- 2 Kate, H.H.J. ten, Hartmann, R.A., Zeyen, C.M.E., Haken, B ten, and Klundert, L.J.M. van de., Construction of optimized superconducting spin precession magnets for neutron spectroscopy. *ASC-88* (1988) August 21-25.

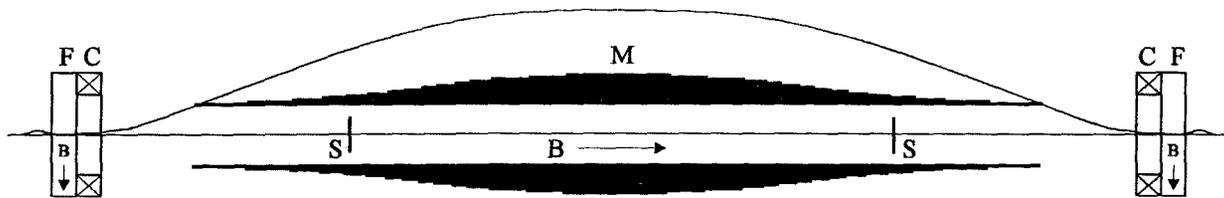


Figure 1. Impression of the magnetic system including Larmor precession coil M, flipper coils F and correction coils C and S.

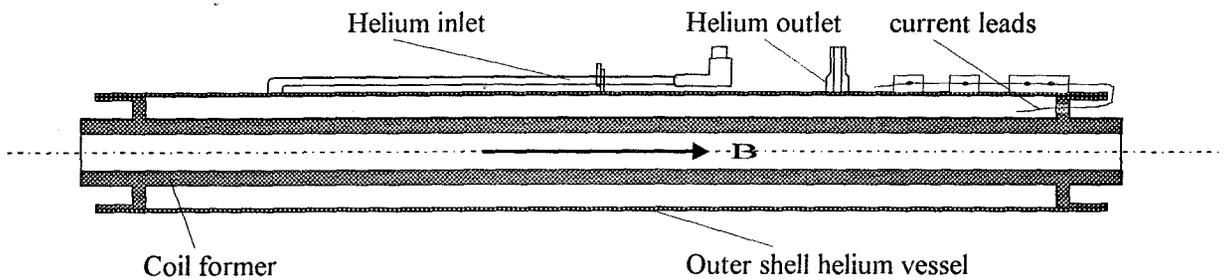


Figure 2. Schematic longitudinal section of the helium cryostat of one Larmor precession magnet.

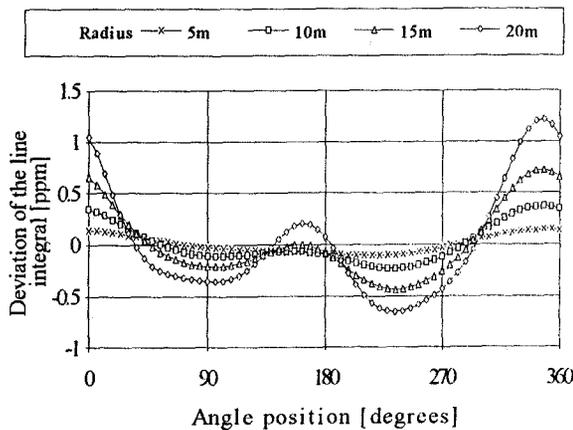


Figure 3. The deviation of the line integral of magnet M1 with respect to its average value as function of the angle position.

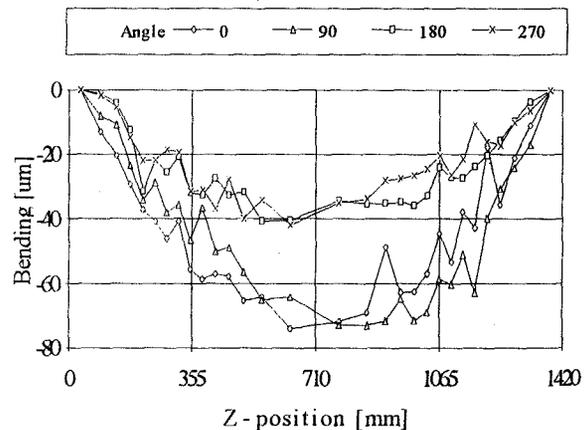


Figure 4. Bending as a function of the z-position with the angle as parameter, measured after winding the 30 coils of magnet M2.