

CONSTRUCTION OF OPTIMIZED SUPERCONDUCTING SPIN PRESSION  
MAGNETS FOR NEUTRON SPECTROSCOPY

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Abstract

This paper deals with the design and constructive aspects of the superconducting magnet system for a new high resolution neutron spin echo spectrometer to be installed at ILL. The principle solution of the field shape of optimal precession magnets we found is  $B_0 \cos^2(\pi z/L)$ . In the practical precession magnets this field shape is approximated by 30 superimposed concentric solenoids with a bore of 80 mm. The required field integral of 1 Tm providing  $10^4$  precession turns, is achieved in a magnet with a length of about 1.5 meter. The field in the centre is 1.5 T maximum. The relative line integral inhomogeneity of about  $10^{-3}$  obtained with such a coil, is improved further to less than  $10^{-6}$  by 2 in-beam correction coils. The advanced homogeneity level means that after 10000 precession turns the precession angle remains still well defined without using tedious correction procedures. The developed advanced magnet system i.e. this new spectrometer will open new fields of Larmor precession spectroscopy.

Introduction

The energy resolution of a classical triple-axis neutron spectroscope can be enhanced by several orders of magnitude by adding a neutron spin-echo method using the Larmor precession technique<sup>1</sup>. In practice this means that a special magnet system which provides the Larmor precessions to the neutron spins, has to be implemented in the classical spectrometer.

In 1986 ILL started in cooperation with the University of Twente a development programme to design and construct a superconducting magnet system for a new neutron Larmor precession spectrometer to be installed at ILL. Recently the collaboration was extended with SBT Grenoble for the design and construction of the cryogenic part of the system including a stand-alone helium cooler providing a 4.5 K bath of liquid helium in the cryostats of both magnets.

Larmor spin precession spectroscopy

Neutron Larmor Precession Spectroscopy use the particle spins as an energy indicator. The technique is based on the condition that neutrons having the same energy, have the same number of precessions while travelling through a certain precession field. The energy loss due to the interaction of neutrons and a sample is related to the difference in the number of Larmor precessions as determined by two precession magnets, one before and one after the sample. As a consequence, this technique requires that for all neutrons in a diverging beam the path integral of the modulus of the magnetic field is a constant. To fulfil this requirement in a practical precession magnet is a main task in the developments.

The basic neutron Larmor precession spin-echo spectrometer arrangement is shown in Fig. 1. The beam coming from a neutron source successively passes a polarizer, a spin flipping coil, a first precession coil, a second flipper, reflects at the sample to be studied, passes through the third flipper, the second precession coil and the fourth flipper, and finally arrives at the analyzer and detector.

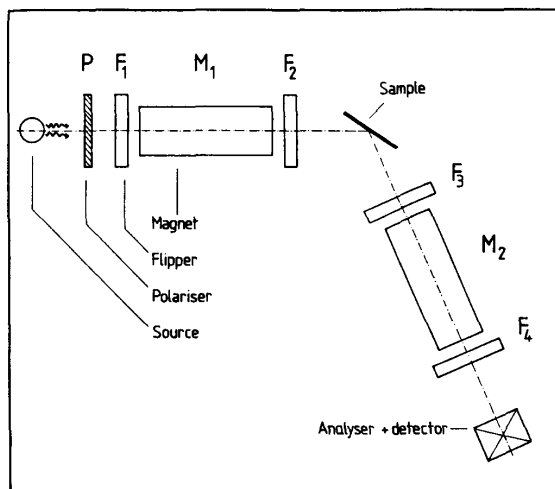


Figure 1. Neutron spin-echo spectrometer arrangement showing both Larmor precession coils and the spin flipping coils.

The operation of the Larmor precession spectrometer can briefly be explained as follows. The technique is based on the principle that the amount of spin precessions, when a neutron is passing through a magnetic field, is the same for all neutrons with the same velocity, i.e. energy. The equation of motion expressed in terms of the magnetic moment  $\underline{m}$  and the magnetic field  $\underline{B}$  states

$$\frac{\partial \underline{m}}{\partial t} = \gamma (\underline{m} \times \underline{B}), \quad (1)$$

where  $\gamma$  is the gyromagnetic constant ( $\gamma = 1.8 \times 10^8$  radians/sT). In the case of a constant neutron velocity  $v_z$  in the axial (z) direction one finds

$$\frac{\partial \underline{m}}{\partial z} = \gamma/v_z (\underline{m} \times \underline{B}). \quad (2)$$

When  $\underline{m}$  is perpendicular to  $\underline{B}$  and this situation remains during the passage of the magnet, then the total amount of Larmor precession turns  $N$  over a length  $L$  will be proportional to the line integral:

$$N \propto (\gamma/\sqrt{E}) \int^L |\underline{B}| dl. \quad (3)$$

The relation between the number of precession turns and the neutron energy  $E$  is unique provided the line integral  $\int^L |B| dz$  is identical for all neutrons in the beam. If this field is not ideal the equation of motion has to be solved in order to check the relation for all trajectories.

Knowing this one can understand the basic operation. Before and after the sample to be investigated, two identical magnets provide an axial magnetic precession field. The precession is started before entrance of the first magnet by flipping the neutron spin orientation into a plane perpendicular to the coil axis. The neutron spins start to precess and at the end of the magnet they have made  $N_1$  turns. Then the precession is stopped using a second flipper and the neutrons hit the sample and reflect. Similar to the situation in the first magnet, the second precession coil will cause  $N_f$  precession turns by which  $N_f$  is less than  $N_1$  due to the energy loss in the sample.

The final spin analyzer provides a signal proportional to  $1 + \cos[2\pi(N_1 - N_f)]$ , which means that the measured neutron intensity is directly related to  $N_1 - N_f$  and thus to the energy difference  $E_1 - E_f = h\nu$ . So we can recognize the main feature of this technique. It directly gives the excitation energy in the sample instead of  $E_i$  and  $E_f$  separately as is the case of classical neutron spectroscopy. For more details concerning the spectrometer operation the reader is referred to references 1 and 2.

#### Precession magnets with optimum field shape

The proper spectrometer operation requires the presence of adequate precession fields along the neutron beam path. A study of the best suited shape of the precession field was dealt with in a previous publication of the project.<sup>3</sup> Here a brief review will be given. The main requirements concerning the precession field are:

- line integral 1 Tm providing  $10^4$  precession turns required for inelastic neutron spectroscopy,
- trajectory independency within the beam, expressed as a maximum line integral inhomogeneity  $\Delta \int B / \int B$  of  $10^{-6}$  in a beam with a diameter of 40 mm.

The optimum field shape was derived assuming cylinder geometry of the magnet and applying in-beam correction coils to achieve the  $10^{-6}$  inhomogeneity. The line integral of the modulus of the field  $|B|$  can be written in the vicinity of the z-axis as a series expansion like

$$\int^L |B| dz = \int^L B_z(0, z) dz + r^2 A(B_z, \partial B_z / \partial z, \partial^2 B_z / \partial z^2) + \dots \quad (4)$$

By minimizing  $A$ , the optimal field shape was found as

$$B_z(0, z) = B_0 \cos^2 \pi z / L, \quad (5)$$

which is a nice symmetric solution also providing  $B_z \approx 0$  and  $\partial B_z / \partial z = 0$  at the boundary points  $L/2$ , i.e. the magnet ends. We can define an inhomogeneity factor  $\eta$  as  $[\int |B(r, z)| dz - \int B_z(0, z) dz] / \int B_z(0, z) dz$ , which using (5) yields  $1/2 (\pi r / L)^2$  provided the higher order terms in (4) are assumed to be negligible. With the given maximum beam radius of 20 mm we find  $5 \times 10^{-4}$  and  $10^{-3}$  for practical magnet lengths as 2 and 1.4 m respectively. So the required  $10^{-6}$  line integral inhomogeneity can not be obtained using solely the optimum field shape magnet. In-beam correction coils are necessary to reduce the  $r^2$  component further. It appeared that the application of 2 correction coils positioned symmetrically in the main precession

magnet, is sufficient to achieve the  $10^{-6}$  although in a previous paper<sup>3</sup> 8 correction coils were mentioned. These so-called spiral coils exhibit a current density which increases linearly with radius. They are made of thin aluminium films which are almost transparent to neutrons.

#### Design of the Larmor precession magnets

The schematic layout of one precession magnet unit is pictured in Fig. 2. It consists of the main coil  $M_1$  providing the  $\cos^2$  field shape, 2 spiral coils  $S_1$  and  $S_2$ , and the flipper/correction coil combinations  $F_1/C_1$  and  $F_2/C_2$ .

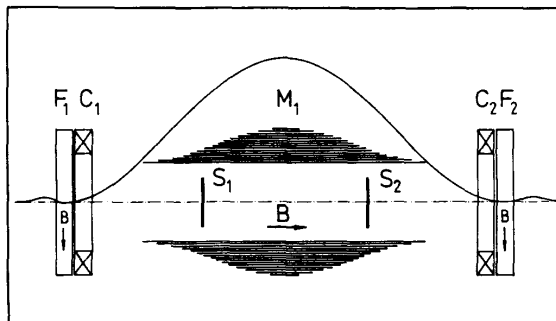


Figure 2. Illustration of one precession magnet unit (drawing not to scale).

Design considerations. During the design of the magnet system the following conditions have to be considered:

- 1) Field integral 1 Tm, which means a magnetic peak field of 1 to 1.5 T in the magnet centre for a practical magnet length between 1.4 and 2 meter. The mentioned peak field and the stationary operation of the magnet system due to the long measuring time to gain a spectrum, oblige to use superconducting windings for the main precession magnets  $M_{1,2}$ .
- 2) Dynamic range of each magnet  $10^4$ , which means a minimum operating field of about 0.1 mT or 1 Gauss.
- 3) A line integral inhomogeneity of  $10^{-6}$  in order to enable inelastic echo polarization measurements by which reference measurements to correct for inhomogeneities are unreliable or whenever they are possible, they are very time consuming.
- 4) The  $10^{-6}$  inhomogeneity should be guaranteed for all particle reflection angles, and field values in the two precession magnets. Therefore, magnet bending due to gravity or Lorentz forces between the coils must be limited.
- 5) The field variations as seen by the neutrons should be much less than the Larmor frequency in order to limit depolarization to the minimum.
- 6) The magnetic stray field at the sample location should be as low as possible but the net field due to all magnets at all reflection angles should enable satisfactory spectrometer operation.
- 7) The magnetic field at the flipper positions must be less than 0.1 mT but the field in the beam from magnet to sample should not change sign.
- 8) The preferred operating current is below 20 A.
- 9) The time stability and the adjustments of the fields, i.e. the magnet currents should be the best as possible.
- 10) Cooling is provided by a liquid helium bath of 4.5 K using a small stand-alone liquefier.
- 11) Quench protection of the coils has to be passive.

**Design strategy.** The first step is to find the current distribution in a practical magnet winding that can provide the  $\cos^2$  field profile. After that the positions and the current densities of the spiral coils are calculated and optimized in order to achieve a field integral inhomogeneity of less than  $10^{-6}$ . Then the flipper coil position is determined and the accompanying correction coil is designed. The following and final step is to check the ultimate operation of the whole spectrometer arrangement by calculating the net magnetic field in the neutron beam throughout the spectrometer and by integrating the equation of motion (1) of the individual spin along this field. For each step the specific computer codes have been developed. At this moment all the numerical tools to design and optimize the magnet system of a Larmor precession spectrometer are available.

#### A practical Larmor precession magnet

The  $\cos^2$  field distribution is generated by a coil system which consists of a large number of symmetric superimposed concentric solenoids, as indicated schematically in Fig. 2. The best suited lengths of the individual subcoils are calculated numerically using a least square routine and minimizing the

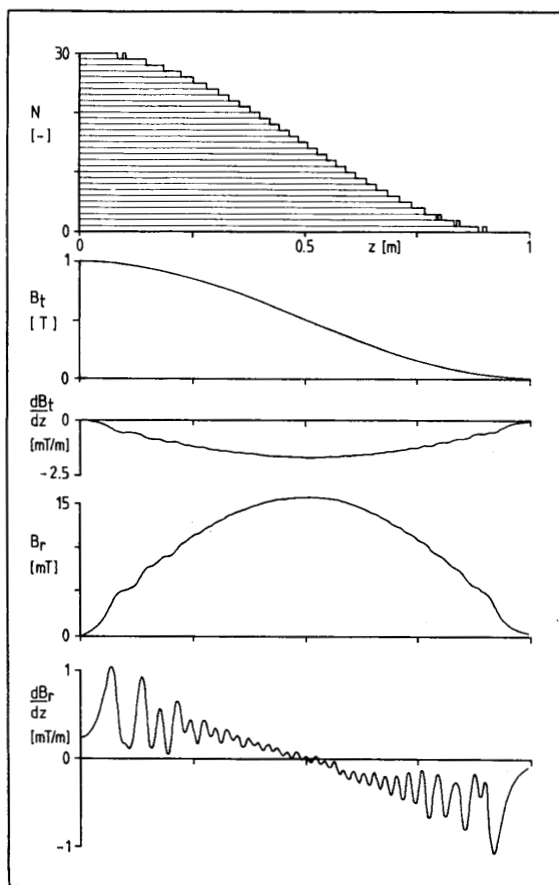


Figure 3. The field profiles  $B$  and  $B_r$  of a precession coil along the axis at the boundary of the neutron beam  $r = 20$  mm, their derivatives  $\partial B/\partial z$  and  $\partial B_r/\partial z$ , and the locations of the coil ends (example of a 2 meter coil system with 30 subcoils in 15 layers).

difference between the field profile of the practical coil and the ideal  $\cos^2$  field shape. The bore of the inner most coil is 80 mm which is the minimum value that guarantees enough space for a coil former, a cryostat wall and a thermal shield. It appeared that 10 subcoils can properly produce the required  $\cos^2$  shape. However, more subcoils are required to suppress sufficiently the wiggles in the  $B_r$  component of the field, especially at the magnet ends where the  $B_r$  component can significantly influence the field profile. As an example, in Fig. 3 the field  $B$  and the  $B_r$  component at the outer beam radius ( $r = 20$  mm) of a 2 meter magnet ( $L = 2$  m in eq. 5) are plotted versus  $z$ , the distance to the magnet centre. Moreover, the  $z$ -derivatives are shown as well as the positions of the individual coil ends. This particular precession coil has 30 subcoils. At four places where normally the  $\partial B_r/\partial z$  changes sign, a few correction windings are used to prohibit this. The result is a gradual and suitable field shape.

#### Magnetic field at the flipper coil

The proper operation of the flipper coils requires a local magnetic field below 0.1 mT. Since the realized field shape in the precession magnet is an approximation of the ideal  $\cos^2$ , the field is not zero at the locations near  $z = L/2$  where the flipper coils are usually located. As a consequence, the magnetic field has to be reduced there by applying small solenoidal correction coils facing the flipper coils. It is obvious to connect these in series with the main coil. The uncorrected and corrected field shape at the flipper location ( $z = 0.8$  m in an  $L = 1.4$  m magnet) is shown in Fig. 4. The field in the flipper can easily be reduced to below the required level over the 20 mm width of the flipper coil.

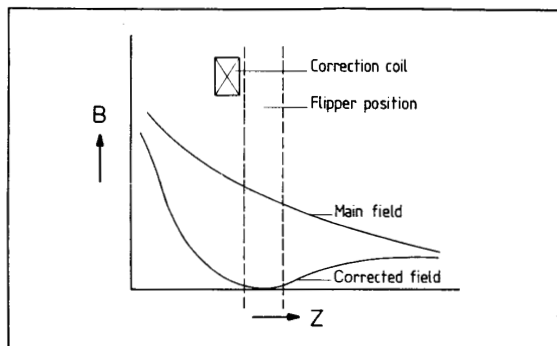


Figure 4. The magnetic field  $B$  at the flipper coil position with and without current in the correction coil (example of a 1.4 meter coil).

#### Selection of the conductor.

There are several reasons to use a relatively thin wire. First the operating current should be small, 20 A maximum, to limit the thermal load of the liquefier since the coils are connected permanently to the power supply. Second, the number of superimposed coils (30) and the current density to achieve 1 Tm, determine a suitable wire diameter when the superconductor should operate efficiently. Third, the accuracy with which the coils can be positioned is the best in the case of a thin wire. Therefore we selected a multifilamentary NbTi wire with a diameter of 230  $\mu\text{m}$ .

The diameter of the NbTi filament in the wire is restricted by the remanent field it produces especially when the main field in the magnet is low. The contribution to the line integral inhomogeneity for the off-axis positions in the neutron beam due to the filament size is calculated to be about  $5 \times 10^{-6}$  for a 100  $\mu\text{m}$  filament. Since the magnitude of the field disturbance due to filament magnetization is linear with the diameter, we suppressed the effect drastically by choosing a filament diameter of 0.8  $\mu\text{m}$ .

#### Coil parameters.

The main parameters of a characteristic precession coil designed along the described lines are listed in Table 1.

Table 1. Main parameters of a characteristic Larmor precession coil.

magnetic length L	=	1.40	m
number of subcoils	=	30	
length of 1 <sup>o</sup> subcoil	=	1.21	m
bore of 1 <sup>o</sup> subcoil	=	80	mm
field integral $\int^L  B  dz$	=	1	Tm
basic inhomogeneity	=	$8.8 \times 10^{-4}$	
inhomogeneity with 2 spiral coils	=	$< 1 \times 10^{-6}$	
nominal operating current	=	18	A
magnetic field in the centre	=	1.4	T
self-inductance	=	14.8	H
stored energy	=	2.4	kJ
number of windings	=	51747	
conductor length	=	13.5	km
type of conductor: NbTi/Cu, diameter 230 $\mu\text{m}$ insulated			
winding technique: wet wound using an epoxy.			

#### Coil winding and demonstration model

The system of subcoils is wound on a cylindrical aluminium former using a winding technique especially developed for this type of coils. It facilitates a very accurate positioning of the subcoils and it yields almost perfectly homogeneous windings. The technique was examined during the production of a 0.25 m superconducting model coil as shown in Fig. 5. The cryogenic test of the model was successful. It achieved its critical current during the first ramp.

The superconducting magnet system is shown schematically in Fig. 6. The helium cryostat with a volume of about 8 L is formed by the coil former itself and an outer thin cylinder which closes the container at both endflanges. The cryostat is surrounded by one radiation shield and suspended in a cylindrical vacuum vessel. The cryogenic parts as heat exchangers, helium piping and in- and outlets are

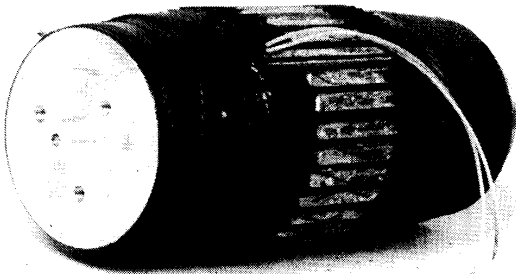


Figure 5. Photograph of the model coil made to test the winding technique. Coil length 250 mm, bore 80 mm.

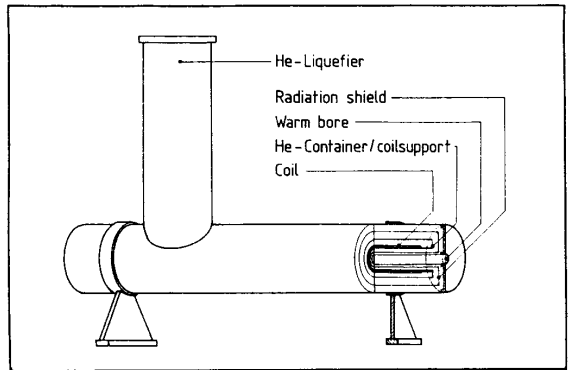


Figure 6. Schematic illustration of a spectrometer precession magnet in its cryostat.

located in a tower on the main vessel. The vacuum vessel and all the other cryogenic parts are made by SBT Grenoble<sup>4</sup> while UT constructs the coil system itself and the helium cryostat.

#### Conclusions

The realization of a new neutron Larmor precession spectrometer featuring a significantly improved resolution, neutron economy and operating performance is en route. All the necessary design tools were developed during the past two years. It has led to a cos<sup>2</sup> field shape in the precession magnets which allows for a shorter and more compact magnet than using other field shapes. The main specifications of the system as the ability of 10<sup>4</sup> precession turns, a field integral of 1 Tm and an inhomogeneity of the field integral of less than 10<sup>-6</sup> in a neutron beam of 40 mm diameter can be realized. The feasibility of the winding technique was proven with the completion of a superconducting model coil.

At this moment the final design values are selected by evaluating the entire spectrometer performance. After this the production of a full-scale prototype will start. The completion of the whole system and the final installation at ILL are foreseen in the autumn of 1989.

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