Polarised Neutron Developments in NMI3

Eddy Lelièvre-Berna[1] and Alexander Ioffe[2]
[1]Institut Laue Langevin, Grenoble
[2]Forschungszentrum Jülich

NMI3 included two Joint Research Activities related to neutron polarisation: Neutron Spin Filters (NSF) and Polarised Neutron Techniques (PNT) – both highly international projects.

Neutron Spin Filters

NSF was coordinated by Eddy Lelièvre-Berna (ILL) with partners from ISIS, Jülich, CEA Grenoble, FRM-II and HZB (formerly HMI), and observers from LENS (Indiana), NIST, SNS, KEK and Michigan University. This project has improved the production of polarised ^3He gas using both the spin-exchange (SEOP) and metastability-exchange (MEOP) optical-pumping techniques. It has also spread the exploitation of spin filters through improved containers and new magnetostatic cavities necessary for the slow decay of the ^3He polarisation.

At the beginning of the project, ISIS and Jülich were producing polarised ^3He using the SEOP technique and ILL was starting its MEOP station. From the collaboration established with the observers, we have learned how to replace conventional lasers with external cavity diode lasers and develop many diagnostic techniques. Motivated by these results, ILL decided to launch a SEOP programme and collaborated with ISIS and Jülich. Over three years, the maximum ^3He polarisation achieved in these European facilities has risen from 32% to more than 70%. Together with partners and observers an experiment at the ILL was launched to understand the limits of the SEOP technique when it is used to polarise the gas continuously in a neutron beam: it has been discovered that the ^3He polarisation decreases with increasing neutron flux. This will have great impact on future developments.

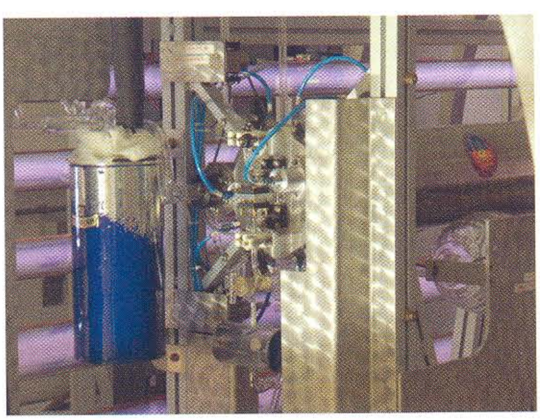

Figure 1. The MEOP station at ILL, achieving 80% ^3He polarisation.

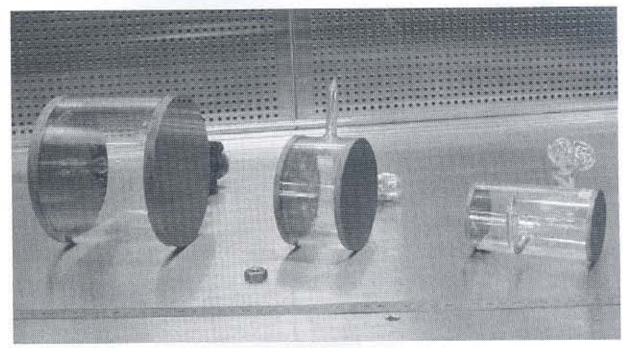

Figure 2. A selection of polarised ^3He cells from ILL with single-crystalline Si windows.

In parallel, ILL has built a set of electronics, tested new optical elements and worked on the electrodes used to polarise the ^3He gas with the MEOP technique. This has led to huge improvements: the gas is now polarised twice as fast as before and the maximum polarisation available on a neutron beam has risen from 68% to 80% (Fig. 1). As a result the number of ILL instruments using spin filters on a regular basis increased from 2 to almost 10 and ISIS and ANSTO are purchasing a MEOP station at ILL.

^3He polarisation decreases over time and this raises a number of difficulties for exploiting spin filters on neutron beams. From the experience gained by the laboratories in the USA, the partners have changed their 'recipes' and now regularly produce cells with very long relaxation times, i.e. greater than 200 hours (Fig. 2). HZB has shown that magnetic fields have a big impact on the lifetime of the gas in the containers and this has helped people understand some of the irregularities encountered during experiments. Nowadays cells are demagnetised regularly and this has solved a number of problems.

Due to difficulties in transporting the polarised gas to the instruments, the ILL has developed a magnetostatic cavity – 'magic box' – which is easy to handle and which screens the stray magnetic fields that might be encountered during transport. After this successful development, they have added a radiofrequency coil to the cavity that enables flipping of the ^{3}He polarisation. Scientists are now much more encouraged to use spin filters due to this simplification in practical use: twelve copies of this box have been produced and distributed to the partners and observers.

The progress made with the MEOP technique has enabled the production of large quantities of polarised gas and ILL has built large cells covering large solid angles with the aim of improving the efficiency of polarised instruments. Using finite-element calculations, they have also successfully built an apparatus producing a magnetic field that can be rotated on the instrument while maintaining the field homogeneity and therefore the ^{3}He polarisation. In addition, for instruments using high magnetic fields, a special magnetostatic cavity made from superconducting and soft-magnetic materials able to host a ^{3}He container in front of a cryomagnet was developed and successfully tested. A further step in the exploitation of filters has been accomplished by demonstrating that a filter could be maintained at a constant polarisation by repolarising small quantities of gas in pulsed mode using a special magnetic capillary.

The exchange of information between the US observers and the European partners was central for developing the SEOP technique and improving the preparation of containers in Europe. Today, the world's leading technique for polarising ^{3}He remains MEOP in Europe, but the SEOP community is making big progress and the European facilities have acquired most of the knowledge which has been developed in the USA.

With the increase in number of instruments taking advantage of the spin filters, the quantity of polarised gas produced for scheduled experiments has been multiplied by 3 at ILL. In most cases, the use of spin filters has improved the performance of instruments: better flux and/or resolution, less background, easier data analysis and therefore new possibilities arise: for example the investigation of magnetic

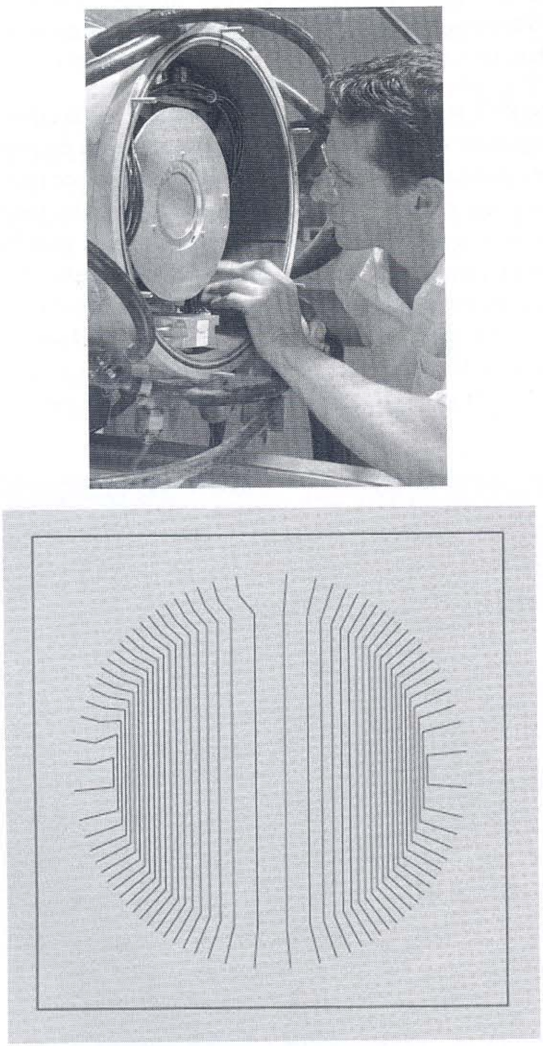

Figure 3. New Fresnel coils developed by the PNT project being installed by Claude Gomez on IN15 at the ILL. The inset shows the design. (Picture courtesy of ILL).

nano-scale samples on powder diffractometers and the exploitation of polarised beams at spallation sources. The major challenge for many of the facilities is now to convert their spin-filter development programmes into regular service activities for users.

Polarised Neutron Techniques

The JRA for Polarised Neutron Techniques (PNT) was coordinated by Alexander Ioffe (Jülich) with partners from GKSS, ATI (Vienna), ILL, LLB, CEA Grenoble, FRM-II, HZB, TUD, PNPI and BNC and observers from RIKEN (Japan), SNS, ISIS, JINR, LANL, NIST, MPI Stuttgart, Brest University, JAERI, TU Taiwan and ANSTO.

PNT was the largest of the NMI3 JRA and the specific topics are too numerous to be all covered in the space available here, so only a few selected examples will be mentioned. In general terms the project had three main objectives.

(i) To develop and make widely available a new generation of key tools for precise handling of the neutron polarization vector. Measurement of the vector properties of the neutron polarization provides a unique method for recovering the significant directional and phase information that is lost when only the scattered neutron intensity is measured. The changes in the direction of the neutron spin that take place on scattering by a magnetic dipolar field are highly dependent on their relative orientations and can be measured very precisely using neutron polarimeters.

(ii) To develop a new generation of neutron scattering instruments, methods and devices based upon the Larmor labelling. The Larmor precession of the neutron spin in a magnetic field allows the association of a "Larmor clock" with every neutron. This labelling enables the development of novel neutron scattering techniques where the energy (momentum) resolution does not require the initial and final states to be well selected. This decoupling results in an extremely high energy (momentum) resolution that is not achievable in conventional neutron instruments because of intensity losses.

(iii) To develop interdisciplinary contacts and provide hands-on resources that will inform scientists from different scientific fields about the power of polarized neutron-scattering techniques and their applications. These techniques are not 'simple' and therefore require extra effort in education, training and outreach.

One PNT task was to extend the maximum correctable field integral of a 'generic' spin-echo spectrometer, proportionately increasing the maximum accessible Fourier time and hence the energy resolution, thus extending the range of scientific applications in fields from biological membranes to superconductors. The present field integral value for spin echo spectrometers at the ILL and FRM-II is about 0.25 Tm. At NIST there is a correction element working up to 0.45 Tm. However this requires reduced angular coverage equivalent to a 30 × 30 cm^2 detector 3 m from the sample.

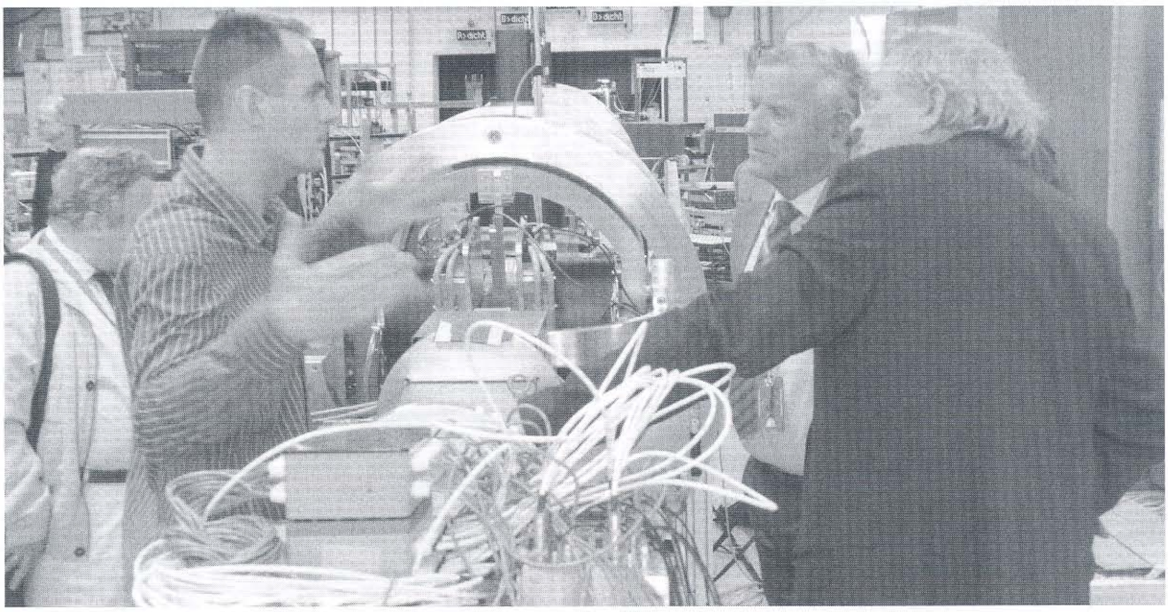

Figure 4. Jeroen Plomp explains the possibilities of Larmor precession to Helmut Rauch and Peter Tindemanns. The beamline components illustrated have been developed at IRI Delft and now transferred to ISIS TS2 and installed on the OFFSPEC reflectometer.

It is also more complicated to realize mechanically with its higher accuracy requirements. The goal within PNT was to a realize field integrals of more than 1Tm, as would be required on a new spectrometer using superconducting main precession coils, but still allowing use of a wide enough neutron beam to obtain reasonable intensity after scattering.

To achieve the design parameters the phase acquired in neutron precession must be the same to within one part in 10^6 for all neutron trajectories hitting the detector. This requires construction of very precise correction elements with the highest current carrying capability; they have to be cooled, mounted on a fixation plate, and to have optimised transmission especially for neutrons with the longest wavelengths. They need to be well understood theoretically so that subsequent modelling can enable an automatic set–up. Beam devices such as flippers and polarisers/analysers will also benefit from these technical and theoretical developments.

A prototype coil has been constructed and tested and a new type of X-Y Fresnel coils has also been developed. The principle is that X and Y components of the radial current can be handled separately, so that $J_R^2 = J_X^2 + J_Y^2$. The element, 80 mm in diameter (see figure), has been prepared using spark erosion and provides significantly better transmission and decreased parasitic small angle scattering.

Spin-echo SANS – SESANS – is becoming a more established neutron-scattering technique and several facilities are considering building an instrument of this type. It is applicable to structures on length scales of microns e.g. in food science, drug delivery systems, colloids and granular materials. The PNT project has developed precession regions with tilted interfaces that work for both monochromatic (using magnetised films) and time-of-flight (using RF-flippers) instruments, tested spin turners and built magnetic field steppers. A major break through has been a test of the technique on magnetic structures. Magnetic scattering causes the spin of the neutron to flip, so with a spin-flipper the nuclear structure can be determined, and without a spin-flipper the magnetic structure.

Similar techniques also have great potential in reflectometry where they can be used to obtain a higher resolution or to measure on bent surfaces. Another application is to measure off-specular reflectivity without collimating the beam. The technical developments within PNT have been applied to construct the spin-echo components for the instrument OFFSPEC that is being built at ISIS TS2.

Other developments within PNT include

- non-cryogenic zero-field polarimeters for diffraction and reflectometry (MUPAD and KLIMPAD);
- polarimetric neutron spin-echo (NSE) techniques;
- the NRSE-TAS method towards neutron energies up to 50 meV and a maximum tilt angle of 70° or simultaneous data acquisition over a large solid angle;
- new alternative NSE techniques;
- an adiabatic broad wavelength spin flipper for $\lambda > 0.4$ Å and
- tests of methods of neutron magnetic spin tomography and dynamical neutron polarization.

The methods that have been employed range from the most modern technical construction and cryogenic techniques to sophisticated analytical calculations, simulations and software development. This includes finite-element based calculations of magnetic field distributions around complicated current distributions carried out using the one of the most powerful CRAY computers in the world. The realisation of polarimetric NSE followed a series of magnetic field calculations which was optimised using genetic algorithms. This pioneering approach opens up new opportunities for the application of evolutionary algorithms in the design of scientific instrument.