A NEW CHOPPER SPECTROMETER FOR NEUTRON BRILLOUIN SCATTERING AND LOW-ANGLE NEUTRON INELASTIC SCATTERING: PHAROS (PHASE I)

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Abstract

Phase I of PHAROS, the new chopper spectrometer at LANSCE, is described in detail. The main components are a water moderator, a 60-Hz double-bladed T-zero chopper, a 600Hz magnetic-bearing Fermi chopper, a 6m-long vacuum vessel with thin aluminium-alloy vacuum window and a 1.2m^2 array of linear position-sensitive detectors.

1. Introduction

In this article, we describe the design, construction and components of the new high-resolution chopper spectrometer, PHAROS, which is installed on flight path 16 at the Los Alamos spallation neutron source LANSCE. PHAROS is not an acronym, but refers instead to the famous lighthouse[1] of Alexandria, one of the seven wonders of the ancient world. This is in reference to the "lighthouse" effect[2] for Fermi choppers which rotate, along with an acceptance zone, rather like lighthouses and their beams of light[3].

The spectrometer design follows that outlined conceptually by a workshop held in 1987[4]. This specified that the spectrometer should have high incident-energy resolution ($\Delta E_I/E_I = 0.5\%$ FWHM), use incident neutron energies between 100meV and 2eV and have complete continuous detector coverage at a radius of 4m from the sample, between scattering angles of -10° and 140°, but that it should also have the option of extending the low-angle section of the spectrometer to a secondary flight path of 10m. The decision was taken to build the primary spectrometer (incident beam line and choppers) and the 6-m low-angle extension first, as Phase I of the project. The design of the wide-angle spectrometer, Phase II, has been going on concurrently with that of Phase I but is not the subject of this article, except in as far as it has had major consequences for Phase I.

Perhaps the prime example of the potential utility of such a high-resolution low-angle spectrometer is to do "neutron Brillouin scattering", which has been variously defined as "neutron inelastic scattering from acoustic phonons in the first Brillouin zone"[5] and "inelastic neutron scattering at smaller Q-values than is currently customary"[6]. The idea is that one will be able to measure acoustic phonon dispersion curves, along with phonon linewidths and intensities, at small values of the wave-vector Q. This is of particular importance for amorphous materials[7], in which the low-temperature specific heat is not well-understood and where a study of the dispersive excitations may provide crucial information beyond that available from measurements of the density of phonon states. Indeed, such experiments have been attempted on the metallic glass $Mg_{70}Zn_{30}$[8], but the existing spectrometers with sufficient resolution can only reach scattering angles of 3.5° or more. In this case it was only possible to reach the pseudo-zone boundary.

Similar questions arise in the damping of magnetic excitations in amorphous ferromagnets [9] and it has long been recognised[10] that there is a need to follow spin-wave dispersion curves beyond the limits reached on current reactor triple-axis spectrometers. The kinematic constraints imposed by such experiments have been analysed in detail [6] and are quite severe: one needs scattering angles of the order of 1° or less, good resolution and relatively high incident energies. For sound waves, one needs an incident neutron velocity between 1 and $\sqrt{2}$ times the sound velocity of the phonon to be observed. Phase I of PHAROS has been designed expressly for such studies.

However it will also be useful for high-resolution studies of sharp magnetic excitations like crystal-field levels and single-crystal problems in low-dimensional magnetic materials. PHAROS has two potential advantages for the latter. Firstly, the coverage of the available solid angle is almost complete and secondly, the use of position-sensitive detectors means that the vertical divergence in the secondary flight path can be chosen after the experiment is finished, in software. Current practice elsewhere is to mask the detectors with absorbing material. Other design constraints have been that the spectrometer should be completely evacuated, that it should fit into the available floor space at LANSCE on an existing moderator, and that a T-zero chopper should be employed.

2. Source, Collimation and General Layout

The overall characteristics of PHAROS are given in Table 1 and the spectrometer layout is shown in Figure 1. The spectrometer is situated on flight path 16 at LANSCE, with the sample position 20m from the source. It currently views a "high-resolution" water moderator[11] which is heterogeneously poisoned with gadolinium at 1.5cm and has a boron decoupler and liner. It is hoped that this moderator will be replaced with a liquid-methane moderator before too long. A conventional mercury shutter is installed within the bulk shield and the beam is defined with sintered-boron-carbide apertures along its whole length. These are backed up with 35% boron-loaded polyethylene and the fast-neutron beam (which is larger) is defined by fillers made of steel or 5% boron-loaded polyethylene. Following normal practice, the apertures prevent the sample from viewing any filler surfaces. The whole incident flight path is evacuated, except for the spaces immediately before and after the two choppers, where beam monitors are installed, and within the shutter which is helium-filled when open.

Two crucial mechanical choppers are installed in the incident beam, a *fast, monochromating, Fermi* chopper at 18m from the source and a *T-zero* or *background-suppression* chopper at 14m. These are described in more detail in sections 3 and 4 respectively. In fact the shielding and beam line have been designed in such a way that the fast chopper could be installed at 16m rather than 18m. This might be advantageous for Brillouin scattering experiments if one wanted to work at smaller scattering angles and needed to collimate the incident beam more tightly. The extra length between the chopper and sample would make that task easier. An additional cavity has been provided close to the bulk shield for a second Fermi chopper, if required. Its function would be for *pulse-shaping* the incident time distribution from the moderator, which is highly asymmetric[12]. The chopper would symmetrise the time distribution and the spectrometer resolution could even be tightened in an optimised manner: this is not possible at present because it is not possible to sharpen or degrade the moderator pulse width at high neutron energies to any great extent. We have no immediate plans to do this, not least because the beam cross-section at this distance is larger than our existing rotor size, which is in turn determined by considerations of mechanical strength and safety.

Immediately after the fast chopper, the main vacuum vessel starts. This consists of up to three 2-m long rectangular cross-section steel vessels. The sample is mounted in the first vessel via a 0.74m-diameter standard flange. The detector module can be mounted 5.5m, 3.5m or 1.5m after this, dependent upon whether extra sections of vessel are used. Between the sample position and the fast chopper is a smaller section of vacuum vessel, with good vertical access, which is intended to provide a flexible way of changing the incident-beam collimation: soller collimators or apertures can easily be placed there and an optical-bench rail is provided for this purpose. The internal surfaces of all vacuum vessels are lined with sheets of 1cm-thick boron carbide bonded with 10% epoxy resin. The whole vacuum-vessel assembly is surrounded on all sides, as well as on top and underneath, with 30cm of borated paraffin wax within large custom-designed steel cans. Each section of vacuum vessel can be removed independently of the others, and can be reinstalled reproduceably. This is achieved by mounting each vessel on four self-locating high-precision roller-bearing systems. These permit approximately 20cm of travel parallel to the neutron beam, which allows sufficient clearance to remove any one section by crane. The external shielding is also removeable in a simple way to allow access to all the bolts holding any two vessels together.

The detector module can be mounted on the downstream end of each and any of the vessels and consists of a large thin aluminium-alloy window, with its supports and frame, a short section of get-lost pipe, 56 linear position-sensitive detectors together with two shadow bars used for positional calibration, and a small scintillator beam monitor. The whole assembly is designed to be moved as one piece, though the detectors are mounted in banks of eight. Each detector bank includes 2 preamplifiers for each detector and boron carbide/epoxy resin shielding is built into it, immediately behind the detector. The window is described in more detail in Section 5 and the detectors in Section 6.

After the detector module, there are several sections of evacuated get-lost pipe and the straight-through beam ends up in a large steel/polyethylene beam stop. Again, this is evacuated and the illuminated surface is covered with boron carbide/10% epoxy resin, to reduce the number of neutrons scattered back into the spectrometer. The sections of get-lost pipe are modular and can be assembled to accomodate all possible vacuum-vessel configurations of Phase I and Phase II. The beam stop will not need to be moved when Phase II is installed.

3. Fast Chopper System

The single most important component in the spectrometer is the fast chopper, which acts like the shutter of a camera, in that it opens briefly to transmit radiation (neutrons) and then closes again. The time at which it opens can be chosen by the experimentalist and governs the energy of the incident neutrons E_I:

$$E_I = \frac{m_n L_1^2}{2 t_c^2} \qquad (1)$$

where L_1 is the distance from source to chopper and t_c is the phase of the fast chopper. The chopper is a Fermi chopper[2], which rotates about a vertical axis. It contains a set of absorbing slats that define the beam. While the neutron trajectory is a straight line in the lab frame, it is curved in the frame of reference of the rotor, and therefore the slit package is curved, with a radius of curvature R given by

$$R = v_I / 2\omega \qquad (2)$$

which is energy dependent. As for the slit width, we have chosen to match the pulse width σ_M of the moderator pulse to that of the chopper σ_C, which is due both to the sweep time σ_S across an individual slit and to the sweep time σ_m across the moderator.

$$\sigma_M = \sigma_C = \sqrt{(\sigma_S^2 + \sigma_m^2)} \qquad (3)$$

where

$$\sigma_S = d/(2 \times 2.45 \times \omega\, r) \qquad (4)$$

$$\sigma_m = a_m / (\sqrt{12}\, \omega L_1) \qquad (5)$$

and d is the slot width and r the effective radius of the Fermi chopper and a_m is the width of the moderator. The fast chopper system is based on a commercial squirrel-cage induction motor and magnetic bearing system bought from S2M. A Fermi chopper, with a 5cm x 7.5 cm curved slit package embedded in a 10cm diameter aluminium body is suspended on the active bearings in vacuum. The absorbing slats are 1mm thick boron-fibre/epoxy-resin composite sheets made by Composites Inc. The motor is water-cooled. At present we have three rotors, with matched vacuum vessel/motor/bearing systems, optimised to operate at neutron energies of 100meV, 300meV and 1000meV. Their characteristics are given in Table 2. The chopper system can operate at multiples of 60Hz from 60Hz to 600Hz. Part of the control system is commercial and part is home-built.

Phasing to the accelerator system is achieved in several steps. Power considerations make it favourable to fire the accelerator near the zero-crossing of the mains supply, within a window of ±100μs. On the other hand the inertia of the chopper makes it easiest to spin the chopper at a steady angular velocity. We therefore try to follow the low-frequency fluctuations in the power supply line by accelerating and decelerating the chopper, while the high-frequency fluctuations are accomodated by triggering the accelerator system.

4. T-zero Chopper System

The T-zero chopper is a large paddle-wheel arrangement which places approximately 30cm of inconel in the neutron beam at the time (t-zero) when protons strike the LANSCE target. Its purpose is to stop the high energy neutrons upstream of the spectrometer and thereby reduce the background due to scattering and moderation of these neutrons in the spectrometer and its shielding. Its design is the descendant of previous such choppers at Rutherford Appleton Laboratory and at LANSCE, but it is somewhat larger in diameter. It is symmetrically balanced and runs at 3,600 r.p.m. (60Hz) - that is, the beam is interrupted with a frequency of 120Hz, the fundamental frequency of the LAMPF linac. Therefore we do not have to pay attention to which particular proton pulses are delivered to LANSCE, which can operate at 12, 15, 20 or 24 Hz. It is driven by a shaft-mounted motor and control system supplied by Rexroth Indramat. The full characteristics are given in Table 3.

5. Vacuum window

The vacuum window is a large (1.0 x 1.2 m^2) flat sheet of 1.3 mm thick aluminium-alloy (7075-T6), with a small rectangular hole near the centre to allow the straight-through beam uninterrupted passage on to the beam stop. A window of this size is too large to support the atmospheric load, even at an elevation of more than 2000m, without extra support. This is provided by five 4.7mm-thick ribs, each made of aluminium alloy (6061) but coated on both surfaces with 5 layers of boron fibre-aluminium alloy laminate. They are mounted vertically and are parallel to the detectors, with a depth of 15cm and a length of 1m. Laterally, they occur every 22.3cm, this being the width of a set of 8 detectors, and the ribs are angled such that they all point to a focus at 4m. This is to minimise shadowing of the detectors by the ribs. For this arrangement, the safety factor is not sufficient to allow unrestricted access to the loaded window and we have an interlock system to prevent such access.

6. Detector System

The characteristics of the array of postion-sensitive detectors are given in Table 4. There are 40 full-length detectors, arranged vertically in banks of 8. The arrangement is asymmetric, there being three banks covering left-hand scattering and only two for right-hand scattering. There is a reason for this: when the window/detector module is installed in Phase II, there is necessarily a large flange in the range of angles that would be covered by a third set of detectors for right-hand scattering and we thereby lose continuous coverage. But if the scattering is symmetric about the incident beam, as it will be for all but single crystal experiments, the same information can be obtained from data taken on the left-hand side.

Above and below the get-lost pipe there are shorter sets of detectors mounted in the same way as the other detectors. Indeed, the whole assembly is designed in such a way that a full window (with no get-lost pipe) could be used, along with a full-length detector bank in place of the two short ones and get-lost pipe. This exposes those detectors to the direct beam, even if it is collimated specially for Brillouin scattering experiments. While this is unusual for inelastic scattering spectrometers, it is normal practice on small-angle scattering spectrometers and has been employed on the glass diffractometer[13] at Argonne National Laboratory. Of course, one would then need to place a small beam stop of suitable size in front of the detector, as in small-angle scattering machines. But, in our case it might be possible to use a resonant absorber, as we use monochromatic radiation: the absorption cross-sections are much higher on resonance, as are the ratios of absorption to scattering, so a small amount of material could be quite effective. A port has been provided in the top of the window frame to allow such access.

7. Discussion

It is also worthwhile to compare PHAROS with the ideas prevalent at the time the spectrometer was in its conceptual design stages. For instance, in 1985, Lander and Carpenter[14] proposed a similar spectrometer for a next-generation neutron source. Its principal aim would be for low-Q inelastic magnetic scattering with good resolution and they envisaged a 20-m machine with secondary flight paths of 20m at low angles and 7m for wide angle scattering, together with full polarisation analysis. PHAROS looks very modest in comparison: but it will still cost \$2.5-3.0M, by the time Phase II is complete. Of that, a total of \$1.3M, excluding labour, has been spent on Phase I.

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Table 1. Overall Characteristics of PHAROS (Phase I)

Moderator[11]:	"High-resolution" water Poisoned with Gd at 1.25cm Decoupled and lined with boron Flight path is angled 15° away from the normal to the moderator surface	
Nominal Distances:	Moderator-Sample	20m
	Sample-Detector	1.5, 3.5 or 5.5m
	Moderator- Fast Chopper	18m (16m is also possible)
	Moderator-T-zero Chopper	14m
	Sample-Beam Stop	11.3m
Beam size at sample		5cm x 7.5cm
Available volume for sample environment equipment		0.736m diameter, 0.45m below sample.
Detector area		$1.2m^2$

Table 2. Characteristics of rotors for PHAROS fast choppers

Materials:	
Rotor body	7075-T6 Aluminium Alloy
Absorbing slats	boron fibre - epoxy resin composite 5 ply
Other characteristics	
Distance from source	18m
Speeds	multiples of 60Hz up to 600Hz
Diameter of rotor	10cm
Height of rotor	12.5cm
Beam width	5cm
Beam height	7.5cm
Positional pick-up	magnetic
Phasing error, relative to accelerator system	<1μs FWHM
Veto rate	<0.5%

Rotor	A	B	C
Nominal energy(meV)	100	300	1000
slot width (mm)	3.6	2.1	1.0
radius of curvature (m)	0.58	1.00	1.83
Sweep time across one slot σ_s at 600Hz (μs)	3.93	2.23	1.14

Table 3. Characteristics of PHAROS T-zero chopper

Materials:	
Rotor material	Inconel
Bearings	self-aligning ball bearing with vacuum-rated lubricant
Motor	Indramat brushless AC servomotor
Positional pick-up optical	optical
Other characteristics	
Distance from source	14m
Speed	60Hz
Diameter of rotor	0.7m
Mass of rotor	341kg
Width of active section	11.6cm
height of active section	11cm
Beam width	7.25cm
Beam height	9.0cm
Phasing error, relative to accelerator system	20μs FWHM
Characteristic energies (assuming perfect phasing)	
Neutron energy at which chopper starts to open	37eV
Neutron energy at which chopper is fully open	3.4eV
Neutron energy at which the rotor next intercepts the beam	14.75-17.65meV

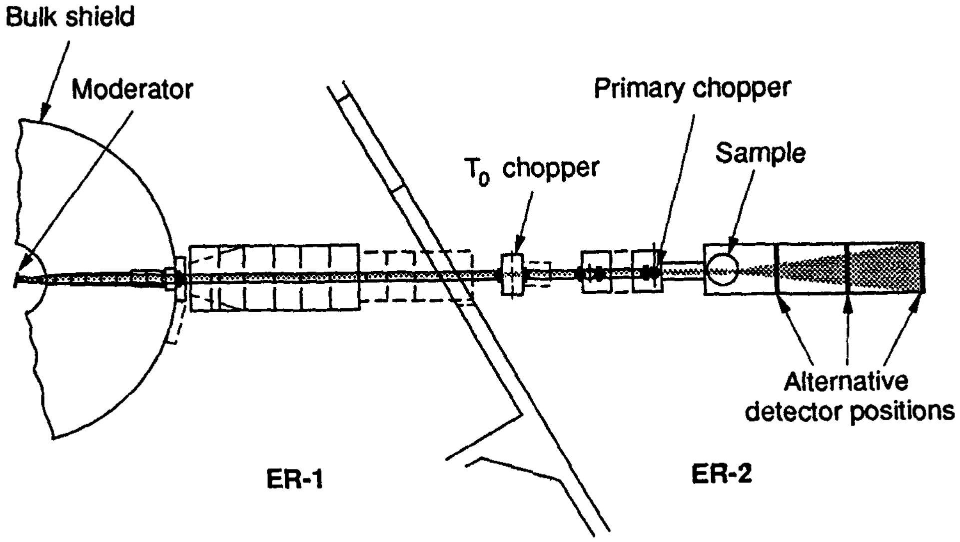
Table 4. Characteristics of PHAROS position-sensitive detectors and electronics

material	10-atmosphere ^{3}He, stainless-steel walled
active length	0.914m (and 0.248 m above/below straight-through beam)
diameter	2.54 cm
manufacturer	Reuter-Stokes
positional resolution	5cm FWHM with present electronics

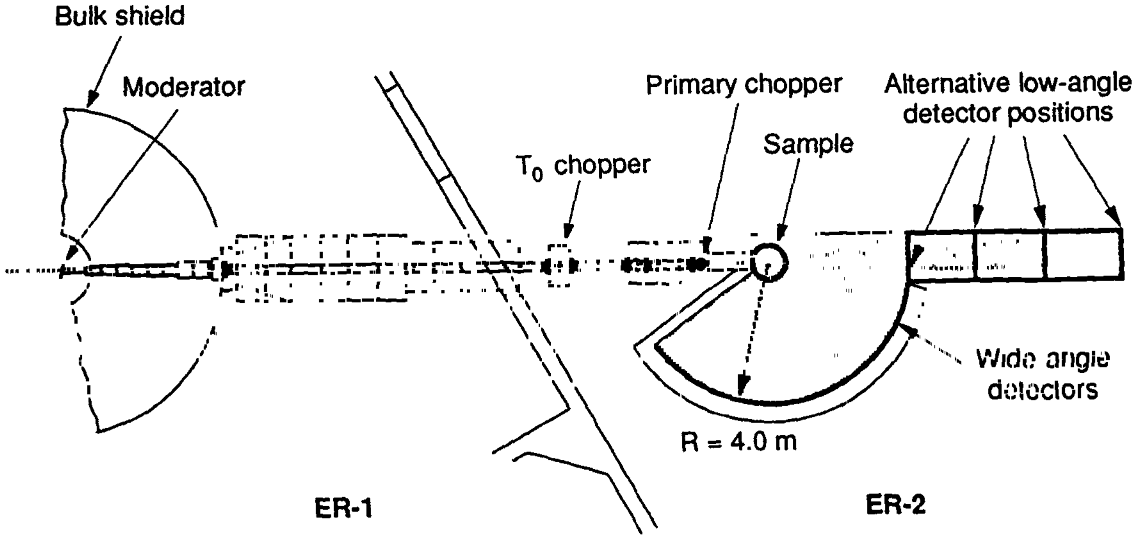
Figure Captions

Figure 1 Schematic diagram of PHAROS: (a) Phase I, with detector positions at 1.5, 3.5 and 5.5m from sample, (b) Phase II, with wide-angle detectors at 4m from sample and low angle detector positions at 4, 6, 8 and 10m.

(a)


Bulk shield
Moderator
T_0 chopper
Primary chopper
Sample
Alternative detector positions
ER-1
ER-2

(b)


Bulk shield
Moderator
T_0 chopper
Primary chopper
Sample
Alternative low-angle detector positions
Wide angle detectors
R = 4.0 m
ER-1
ER-2