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Panther — the new thermal neutron time-of-flight spectrometer at the ILL

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Abstract. Panther is a new high-flux medium-resolution direct-geometry thermal-neutron time-of-flight spectrometer at the Institut Laue-Langevin (ILL). It is designed for inelastic neutron-scattering measurements of excitations in condensed matter using single crystals, polycrystalline samples, and liquids. Panther uses double focusing graphite or Cu monochromators, a Fermi chopper, and position-sensitive ^{3}He detectors covering 2 steradians of solid angle. A system of disc choppers and an optional sapphire filter are used to reduce the epithermal neutron background. Thermal neutron background is reduced by a radial oscillating collimator, a beam dump, and an elaborate set of Cd shielding inside the evacuated detector tank. The outside of the tank is covered by a 0.3 m thick layer of borated high-density polyethylene to reduce ambient and cosmic background. The design and performance of the instrument in its current status are described, as well as planned developments.

1 Introduction

Neutron time-of-flight (TOF) spectrometers are ideal for studies of excitations in condensed matter. In the thermal energy range, from a few up to about hundred meV, typical science applications are crystal field excitations, spin-waves in magnetically ordered materials, magnetic excitations in quantum and/or frustrated magnets, quantum rotations and translations of small molecules in confinement, phonon dispersion relations and density of states, vibrational spectroscopy in the low-energy range, diffusion and relaxation processes in fuel cells, thermoelectric materials, and other energy-related applications. For powder samples, an overview of the excitations can be obtained in a short time, typically a couple of hours on a high-flux spectrometer. With the generalization of large-area highly pixelated detectors on TOF spectrometers, single crystals are increasingly being studied, giving very detailed information on the excitations in four dimensions, provided the sample is rotated during the measurements. Such experiments require longer measuring times, typically a couple of days.

Panther is a completely new thermal neutron TOF spectrometer at the ILL. It replaces IN4C, which was constructed in the mid nineties [1]. Panther uses the same "hybrid" TOF principle with a focusing monochromator and a Fermi chopper operating in time focusing mode. For thermal neutrons, focusing optics using a monochromator is advantageous compared to current supermirror guides in terms of flux. The instrument uses one incoming energy at a time, since the high pulse repetition rate allowed on a continuous neutron source (typically 250–1000 Hz on Panther) is not suitable for so-called repetition-rate multiplication. The main improvements compared to IN4C are that Panther has a huge array of position-sensitive 10-bar ^{3}He detectors allowing single-crystal experiments, a longer secondary flight path to improve resolution, optimized Bragg optics, a larger sample area allowing more complex sample environment, and improved background protection. The incoming energy E_i can be varied between 7.5 and about 150 meV, with the highest flux in the range 15–76 meV. At E_i = 19 meV, the flux of monochromatic and pulsed neutrons at the sample position is 5×10^5 n/cm^2/s. The energy resolution varies between 3.8 and 5.7% of the incoming energy for the pyrolytic graphite monochromator, depending on the monochromator take-off angle. The instrument will accommodate a set of five new background choppers operating as a discrete tunable velocity selector. Longitudinal XYZ polarization analysis is also planned.

The design of the Panther spectrometer started in late 2014 when funding was granted from the ILL Endurance program. The IN4C instrument was dismantled in October 2018, after which the floor for Panther was prepared, 200 mm lower than on IN4C to allow for a larger vertical detector coverage. In April 2019, the 8 ton heavy detector tank swung around the whole reactor suspended from the main crane to arrive at its final position. Commissioning started in February 2020 with the graphite monochromator. The first user experiment took place in September 2020 on a powder sample. Regular user operation for powder samples started in early 2021, in parallel with the commissioning of the Cu monochromator and the single-crystal option. The first single-crystal user experiment took place in May 2021, and became routine shortly after.

This paper is organized as follows. The Panther instrument and its different components are described in Section 2. Section 3 discusses the performance and the first user experiments, while planned developments are outlined in Section 4.

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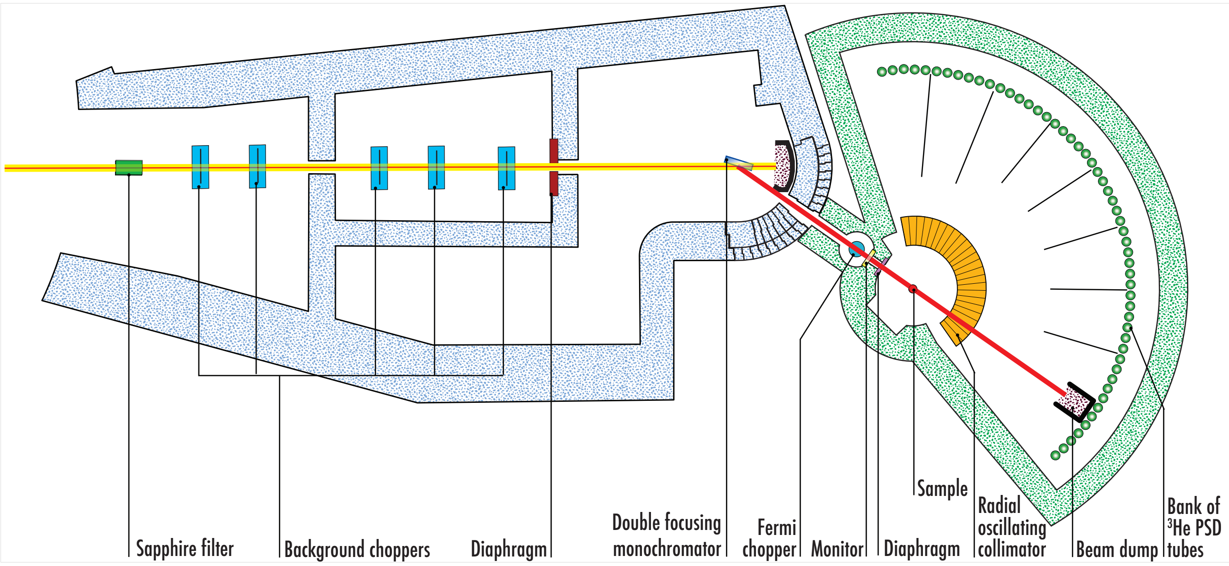

Figure 1. Schematic plan of Panther.

2 Instrument description

A schematic plan of Panther is shown in Fig. 1. The first part of the instrument is enclosed in a heavy concrete casemate, and contains a filter, background choppers, diaphragms, and two monochromators. The detector tank rests on rails in the floor and can rotate around a vertical axis centered at the monochromator in order to change incoming energy. The first part of the mobile detector tank contains a Fermi chopper, a beam monitor, and a set of four independent slits used to adjust the beam size. The sample space is part of the evacuated detector tank, with no windows between the two parts. Typical distances are given in Table 1. The different components will now be described in the order they are intercepted by the neutron beam.

Table 1. Distances L on Panther. The source is taken as the nose (entrance) of the beam tube inside the heavy-water moderator.

Elements	L (m)
Source — Monochromator	12.1
Monochromator — Sample	2.5
Fermi chopper — Sample	0.8
Sample — Detector	2.5

2.1 Beam tube and filter

Panther is installed on the H12 thermal neutron horizontal radial beam tube in the reactor hall, viewing the ambient-temperature heavy-water moderator of the ILL 57-MW high-flux reactor. The beam tube has a circular cross-section of 100 mm diameter and a divergence of 1.27°, both horizontally and vertically.

The first optical element is a single crystal sapphire filter of length 90 mm along the beam, which by Bragg scattering quite efficiently removes high-energy neutrons. The transmission is between 70 and 80% for incoming neutron energies below about 60 meV but drops rapidly below 50% at higher energies. It can be translated out of the beam by remote control.

2.2 Background choppers and heavy slit

For the first years of operation, Panther uses the two old background choppers from IN4C. They consist of steel discs of thickness 100 mm along the beam and diameters of 600 and 640 mm, respectively. The maximum speed is 5000 rpm (83.33 Hz), and to match the higher speed of the Fermi chopper, each disc has eight 60-mm wide openings. In order to reduce the high epithermal neutron flux and gamma radiation in the white beam, the two choppers operate in so-called “static closed” mode, which implies that when one is open, the other is closed. This imposes a phase angle between the two choppers of about 22.5°. The second background chopper is translated along the beam to allow the wanted incoming energy to pass through the chopper system and to block neutrons that otherwise would be reflected as higher and lower orders by the monochromator. The translation covers a distance of 1.5 m, a design criteria from IN4C, which is not sufficiently long for the longer flight distances of Panther. This means that higher- and lower-order contamination is a severe problem for certain incoming energies. This will be solved with the installation of the new background choppers, described in Section 4.1.

A diaphragm (“heavy slit”) made from steel of thickness 160 mm along the beam is placed between the background choppers and the monochromator in the casemate. It allows to adapt the beam size both horizontally and vertically to fully illuminate the monochromator and to reduce background.

2.3 Monochromators

There are two monochromators available on Panther. They are mounted on a turntable that brings one of them into the white beam. One monochromator is made of highly oriented pyrolytic graphite (PG), and uses the (002), (004), or (006) Bragg reflection. The graphite plates are 2 mm thick and the mosaic is 0.5–0.6°. The second monochromator uses the (220) Bragg reflection of Cu, but the crystals are cut and aligned such that the (331) Bragg reflection also can be used in non-specular geometry. The crystals are 8 mm thick and the mosaic is 0.35–0.50°. Both monochromators have variable horizontal and variable vertical focusing, used to maximize the flux at the sample position or to produce a less divergent beam for single-crystal measurements. Each monochromator consists of crystal pieces of size 20×20 mm^2 glued onto $^{10}B_4C$ support plates to reduce background. The pieces are mounted in 15 columns and 11 rows and aligned in both horizontal and vertical directions to better than 0.1° and 0.05° with respect to each other for the PG and Cu monochromators, respectively. The total height of the monochromator is 230 mm and the width is 315 mm.

The incoming energy is selected by choosing the PG or Cu monochromator and adjusting its Bragg angle and the take-off angle. The latter is designed to vary between 35 and 70 degrees, and the whole secondary spectrometer (weighting about 40 tons) turns around the monochromator axis. The monochromatic beam leaves the casemate via a system of vertically translated shielding blocks. The incoming energies available, see Table 2, are currently more restricted than the design values because of a misplaced monochromator protection, but also due to the higher- and lower-order contamination related to the use of the old IN4C background choppers as discussed above. Incoming energies above 150 meV are not yet commissioned.

Table 2. Incoming neutron energies for the different monochromators on Panther.

Mono-chromator	E_i (meV) Current	Design
PG(002)	7.5–19	5.5–20
PG(004)	30–76	22–80
PG(006)	67.5–112	50–180
Cu(220)	52–130	38–138
Cu(331)	123–150	91–330

2.4 Fermi chopper

A Fermi chopper is placed 0.8 m in front of the sample and chops the neutron beam in short pulses. It is equipped with magnetic bearings and the maximum rotation speed is 30000 rpm (500 Hz). The chopper is normally operated in time focusing mode to optimize the energy resolution, in which case typical speeds are 8000–18400 rpm. It has a straight slit package and produces thus two neutron bursts per revolution. Typical pulse-repetition rates are 250–1000 Hz, much higher than on pulsed spallation neutron sources. The slit package is 23 mm long, 32 mm wide, and has a divergence of 1.5 degrees (FWHM). It consists of a sandwich of 0.6 mm thick aluminium slits with high neutron transmission and 0.1 mm thick neutron-absorbing slats consisting of $^{10}B_4C$-epoxy.

2.5 Sample area

A ^{10}B beam monitor, inherited from IN4C and operating at 220 V, is mounted after the Fermi chopper close to the entrance to the sample area. Its efficiency and maximal count rate are not adapted for single crystal measurements, and a replacement is foreseen, see Section 4.3.

A set of four independent 2-mm thick sintered $^{10}B_4C$ slits are mounted between the beam monitor and the entrance to the sample area to adapt the beam size to the sample and sample environment. They are positioned with a precision of 0.1 mm by piezoelectric motors and equipped with linear encoders. The nominal sample height is 40 mm and the width is 20 mm.

The sample space has a diameter of 800 mm and is directly connected to the evacuated detector tank without any windows. A motorized elevator allows easy vertical positioning of various standard sample environments from the ILL. Changing the sample environment (from cryostat to furnace, e.g.) requires to break the vacuum of the detector tank. It takes about 50 minutes of pumping to reach a pressure below 0.1 mbar, sufficient for starting measurements. Panther has an orange cryostat specifically designed for the instrument with a 70-mm bore, thinned down aluminum windows with a total thickness in the beam of 1.4 mm, a Gd screen inside the calorimeter, and additional Cd and B_4C shielding on the outside of the cryostat to reduce parasitic scattering. The operation temperature is 1.5–300 K. The cryostat was refurbished in 2021 with a new variable temperature insert equipped with a quadruple heat-exchanger and a 150-W heater for rapid temperature changes. This has reduced cooling-down and heating-up times by a factor of 2–3. It now takes about 50 minutes to cool a typical sample from 300 to 100 K, another 40 minutes down to 1.5 K, and about 20 minutes to warm it up to 100 K again.

A radial oscillating collimator (ROC) is installed in the detector tank just outside the sample area. This positioning implies that the ROC can be used with all sample environments, including large-diameter cryomagnets, high-pressure cells etc., for which background suppression is of outmost importance. The collimator consists of stretched kapton foils of thickness 12.5 μm coated with 85 μm thick Gd_2O_3 layers. The foils are 0.587 m high and 0.2 m long (along the scattered beam), and start outside the sample area at a distance of 0.434 m from the sample center. The angular separation between collimator septa is $2\alpha = 1.25°$, which gives a viewing angle of ±0.69°. This means that a detector sees a region of ±30 mm around the sample. The collimator oscillates over an angle of 1.62° with constant speed at a frequency of 0.02 Hz.

2.6 Detectors and detector tank

Panther has a huge array of position-sensitive detectors located 2.5 m from the sample. They provide a continuous coverage of horizontal angles from -16 to +136 degrees and vertical angles from -13 to +30°, with a total solid angle of 2.0 Sr. The vertical coverage is asymmetric because the beam tube elevation over the reactor floor is quite small. The smallest useful scattering angle depends in principle on the incoming neutron energy and the focusing of the monochromator. In practice, it is about 5 degrees for the whole energy range with the monochromator doubly focused for maximum flux on the sample position. The detector tubes are mounted vertically inside the evacuated detector tank and have an active length of 2.04 m and an outer diameter of 22 mm. The tube walls are made from stainless steel (304L) of 0.4 mm thickness. Neighboring tubes are separated by a gap of 0.6 mm, where 0.5-mm thick Cd spacers reduce cross-talk between tubes. The Cd spacers extend 9 mm beyond the detector surface towards the sample position. The angular separation between tubes is $\Delta\gamma = 0.518°$. The 288 detector tubes are arranged in 9 banks with 32 tubes each. Neighboring banks are separated by a gap of $\Delta\gamma$, corresponding exactly to the dimensions of one tube. In this gap are placed vanes made of Al sheets clad with 0.5 mm thick Cd on each side to reduce parasitic scattering between detector banks. The length of the vanes towards the sample center varies between 0.8 and 1.2 m. The tubes in a bank are interconnected and share a common gas volume, with a partial ^{3}He pressure of 10 bars and an operating high voltage of 2200 V. The detectors are position sensitive with 256 pixels along the tubes. The positions of the pixels have been calibrated using neutrons and a specific Cd mask. An absorbing beam dump is placed in front of the detectors (or pixels) that are in the line of the direct monochromatic beam to avoid saturation.

The detector tank is made of Al alloy plates welded together to form a vacuum-tight (<0.01 mbar) and non-magnetic skin, reinforced by an array of Al profiles to ensure the mechanical strength of the structure. It is covered by 1-mm thick Cd sheets glued to the inside of the tank to reduce parasitic reflections. The outside of the tank is covered on all sides (including top and bottom) by 300-mm thick borated high-density polyethylene (HDPE) to reduce background. Because of the related fire hazard, the instrument zone forms a 500-mm deep pit surrounded by a firewall, which can contain the whole volume of the 21 m^3 (or tons) of HDPE if melted. In addition, all cables in the instrumental area are flame-retardant.

2.7 Data acquisition and reduction

Panther uses the ILL remote control system "nomad" for control of motors, sample environment, and data acquisition. Detected neutron events are stored in a histogram with $288 \times 256 = 73728$ detector pixels and typically 512 time channels. With the current data acquisition system, the histogram method allows higher count rates than so-called event mode. The data are stored in nexus files for

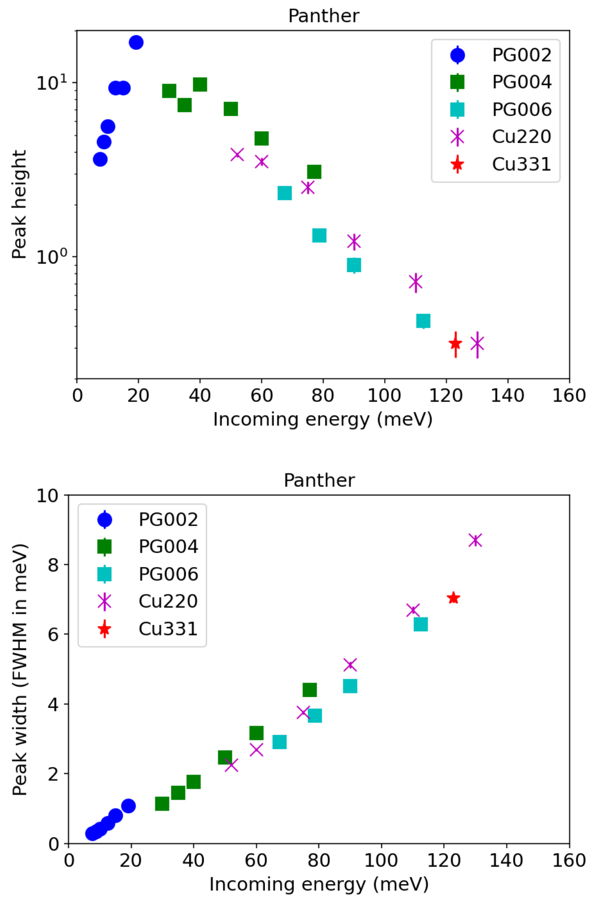

Figure 2. Peak intensity (top) and elastic energy resolution (bottom) on Panther from vanadium measurements.

subsequent data reduction using the ILL branch of mantid [2].

Single-crystal measurements are typically performed by scanning the sample orientation over 353° around a vertical axis in steps of 1°. Such a scan takes one day for a measuring time of four minutes per sample angle, which is sufficient in most cases. The advantages with scanning (nearly) a full turn are that the measurements can start before the exact sample orientation is known and that no time is lost whilst optimizing the angular scanning range. The data are reduced in mantid [2] and analyzed using horace [3], with which the actual sample orientation can be refined and the data can be symmetrized to improve the statistics, thereby compensating for the (too) wide angular scan range.

3 Performance and user operation

3.1 Flux and resolution

The peak intensity and elastic energy resolution from a vanadium sample are shown in Fig. 2 for different incoming neutron energies and different monochromators. For the pyrolytic graphite monochromator, the energy resolution varies between 3.8 and 5.7% of the incoming energy

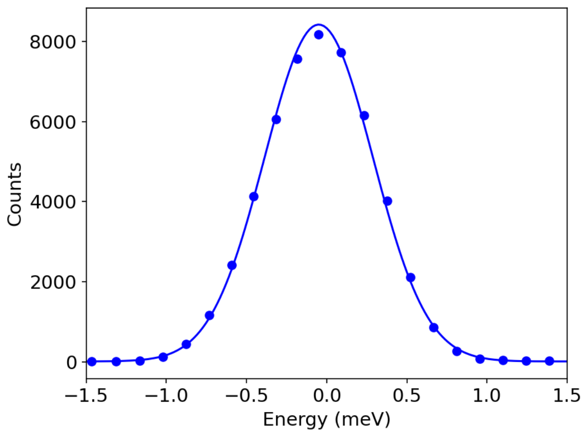

Figure 3. Line shape of the elastic scattering from a vanadium sample at $T = 10$ K and an incoming neutron energy of 15 meV. The line is a fit by a Gaussian plus a flat background.

depending on the monochromator take-off angle. An advantage with "hybrid" spectrometers on continuous neutron sources is that the energy resolution has a nearly Gaussian line shape, as shown in Fig. 3.

3.2 Comparison

All modern high-performance thermal time-of-flight spectrometers have the same detector solid angle within a factor of 1.5. The flux on Panther is 5×10^5 n/cm^2/s for an incoming energy of 19 meV. For a similar incoming energy (E_i = 19–50 meV) and energy resolution ($\Delta E/E_i$ = 3–5.5%), Panther has about 8 times more flux than MERLIN at ISIS [4], and probably a factor of 1.4–2 times more signal than the thermal TOF spectrometers 4SEASONS at JPARC [5] and ARCS at SNS [6].

3.3 User operation

Panther entered the user program of the ILL in 2020, and the average oversubscription factor since then is in the range 3–4. The first official user experiment on a powder sample concerned a crystal-field study of a geometrically frustrated magnet [7] and the first single-crystal experiment was a study of Dirac magnons in a honeycomb ferromagnet [8]. An example of a constant-energy slice from the latter experiment is shown in Fig. 4. The efficient Bragg focusing optics on Panther allows measurements of small samples. Figure 5 shows an example of the quantized energy levels of single ^{3}He atoms trapped inside C_{60} fullerene cages [9]. The measurement time was 1 hour for a mass of ^{3}He of 3.5 mg.

4 Planned developments

The Panther project comprises several parts that are not yet in operation. These planned upgrades are discussed here.

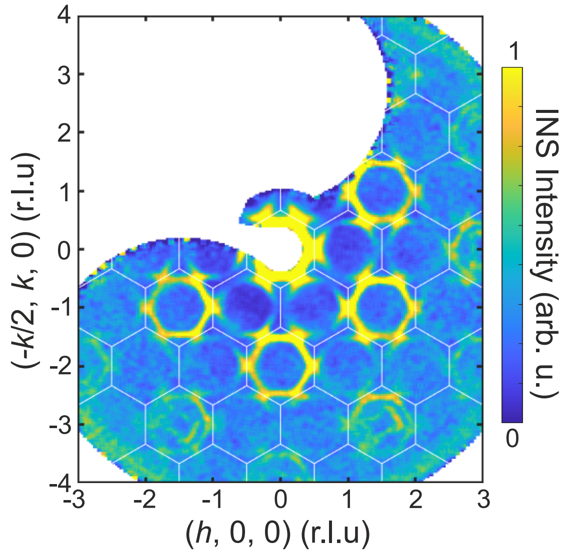

Figure 4. Constant-energy slice of magnon scattering in a honeycomb ferromagnet at $T = 1.7$ K, measured with an incoming energy of 15 meV. The data are integrated over energy transfers between 4 and 5 meV and for values of the perpendicular Q direction between -5 and +5. The white lines show the Brillouin zone boundaries.

4.1 New background choppers

A set of five new background choppers have been designed, manufactured, and delivered. They are expected to substantially reduce the background and also remove higher- and lower-order contamination from the monochromators. The choppers operate like a discrete velocity selector with variable pitch, obtained by spinning them in the same direction at the same speed but with different phases. Because of the large number of choppers, the "static-closed" condition required for the IN4C background choppers is not necessary.

The five identical disc choppers have a diameter of 750 mm and a thickness (along the beam) of 100 mm. They are made from epoxy-loaded carbon fibre, where the fibre volume content varies in the radial direction of the disc to ensure mechanical stability and that the epoxy content is at least 60% in the region of the neutron beam. It is the hydrogen in the epoxy that reduces the epithermal

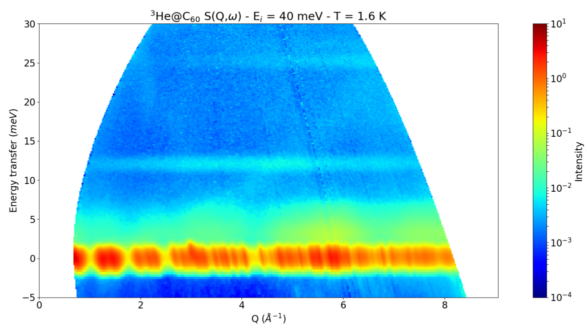

Figure 5. ^{3}He trapped inside C_{60} at $T = 1.6$ K showing quantum transitions at energies of 11 and 24 meV.

neutron flux by scattering. To absorb thermal neutrons, the discs are coated with a layer of $^{10}B_4C$-epoxy on each side, with a thickness corresponding to a 0.18 mm layer of pure $^{10}B_4C$ per side. The non-metallic construction of the discs leads to a reduced weight, only 52 kg per disc, which allows to run them at a relatively high speed of 10000 rpm (166.67 Hz). To match the speed of the Fermi chopper, limited to 30000 rpm, each background chopper has 6 windows of width 105 mm.

Each chopper has its own evacuated ($2 \cdot 10^{-3}$ mbar) and water-cooled housing made from stainless steel to prevent damages to surrounding equipment in case of a disc failure. The inner part of the housings are coated with a (non-enriched) B_4C layer to reduce neutron background. The neutron beam enters and exits the housings through Al windows of thickness 0.4 mm. Each disc is directly driven by an electrical motor, the bearings are non-magnetic, and the cables are radiation-proofed. The ramp rate is 12 rpm/s for both acceleration and deceleration and the phase stability at constant speed is better than 0.01°. The vacuum levels, water temperature and flow rate as well as the motor temperatures and disc vibration levels are monitored by a control system, which automatically shuts down the choppers in case of anomalies, and also provides information on the chopper status to the interlock system of the instrument.

4.2 Increased energy range

Repositioning of the misplaced monochromator protection will remove the penalizing gap in incoming energies between 19 and 30 meV, which corresponds to the maximum of the Maxwellian flux distribution from the heavy-water moderator. Incoming neutron energies beyond 150 meV are expected to become exploitable with the installation of the new background choppers because of their better higher- and lower-order suppression and also since the sapphire filter may not be needed.

4.3 New beam monitor

A high count-rate ^{3}He beam monitor, required for single crystal measurements, is being developed in-house. It is based on the multitube concept with a maximum count rate of about 100 kHz for an efficiency of $3 \cdot 10^{-4}$ for thermal neutrons. Care is taken to assure that the monitor is fully non-magnetic, as required for the future polarized neutron option.

4.4 Sample environment

Temperature changes between 1.5 and 100 K are very quick using the Panther refurbished cryostat. At higher temperatures, between 150 and 300 K, temperature changes are slower, which may hamper measurements of e.g. the temperature-dependence of phonon density of states. To address this issue, the development of a cryoloop as well as a new cryofurnace is envisaged.

The sample space is designed to accommodate the 10 Tesla magnet developed for IN5, although the scientific case for such low fields (compared to the energy range of Panther) is limited. No particular problems are expected in terms of stray fields or magnetic forces, because the sample area is non-magnetic by design and confirmed by measurements using a three-dimensional magnetic field probe. However, possible interferences with the magnetic bearings and the motor drive of the Fermi chopper remain to be investigated.

4.5 Polarized neutrons

A new device has been developed at the ILL to perform wide-angle XYZ polarization analysis using thermal neutrons, the so-called Pastis-3 concept. It has been successfully tested and brought into operation on the thermal triple-axis spectrometer IN20 at the ILL [10]. The device employs two cells containing highly polarized ^{3}He gas: one to polarize the incoming beam and the second to analyze the polarization of the scattered neutrons over a wide angular range, both horizontally and vertically. The ^{3}He filters are incorporated in a mechanical device where a tilted coil design produces a weak magnetic guide field at the sample. Measurements can be performed for three orthogonal directions of the guide field, XYZ, but more general directions can also be measured. The neutron spin is "flipped" in the first ^{3}He cell by an adiabatic fast-passage technique, where an amplitude-modulated radiofrequency signal inverts the polarization of the ^{3}He gas.

A Pastis-3 device designed to operate in the vacuum environment of Panther is being developed. It fits into the 800-mm diameter non-magnetic sample area of Panther. The angular acceptance range is -14 to +112 degrees horizontally and ±10 degrees vertically. The device will allow completely new types of overview measurements using polarized neutrons for both powder samples and single crystals. The main application will be to separate magnetic from nuclear inelastic scattering in a wide range of scattering angles and energies simultaneously. This separation is particularly important in the thermal energy range (5–60 meV), where phonon excitations often overlap with magnetic scattering from spin waves, crystal field excitations, and spinons. In single crystals, it is also possible to separate e.g. longitudinal from transverse magnetic excitations. A third application is to separate coherent from spin-incoherent nuclear inelastic scattering, which is of interest for studies of polymers and soft matter as well as for hydrogen spectroscopy.

5 Summary

Panther is a new inelastic neutron scattering time-of-flight spectrometer at the Institut Laue-Langevin offering a high flux of thermal neutrons in the energy range 7.5–150 meV at medium energy resolution and a large solid angle coverage of position sensitive detectors. It is expected to become a workhorse for studies of excitations in condensed matter using both powder and single crystalline samples with a high scientific productivity. The development of polarized neutrons will open completely new horizons for separating magnetic from nuclear scattering.

Significant contributions to the planning, design, or construction of Panther were made by: Luc Didier, Baptiste Amoudruz, Joseph Pequeno, Ronan Moreau, David Mezerette, Christophe Vitally, Benoît Jarry, Christophe Gillart, Marc David, Jérôme Nucci, Roland Gandelli, Julien Bonnevaux, Bruno Guérard, Jean-François Clergeau, Jean-Claude Buffet, Sylvain Cuccaro, Fabien Lafont, Martin Platz, Patrick Van Esch, Gilles Pastrello, Pierre Courtois, Benoît Mestrallet, Franck Barneaud, Sandrine Michallat, Florian Philit, Paulo Mutti, Franck Cécillon, Julien Blanc Paques, Franck Rey, Thierry Mary, Emmanuel Courraud, Eric Lampasona, Benjamin Sornin, Eddy Lelièvre-Berna, Yohan Memphis, Jean-Philippe Rey, Fabrice Rencurel, Antti Soininen, Gagik Vardanyan, Alain Filhol, Stéphane Fuard, Emmanuel Farhi, Anton Fossum Hylin, Martin Boehm, Bela Farago, Charles D. Dewhurst, Charles Simon, Mark R. Johnson, and Helmut Schober. The first author has profited from discussions with Rob Bewley and Jacques Ollivier. Ursula Bengaard Hansen, Marek Koza, and Stanislav Nikitin are acknowledged for their help with the commissioning.

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