

KVASIR: A backscattering instrument optimised for hard condensed matter.

Sylvain Petit,¹ Kim Lefmann,² and Pascale Deen^{3,2}

¹Laboratoire Léon Brillouin, CEA, CNRS, Université Paris-Saclay, France

²Niels Bohr Institute, University of Copenhagen, Denmark

³European Spallation Source ERIC, Lund, Sweden

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I. EXECUTIVE SUMMARY

We present the science case and instrument concept for KVASIR, a novel backscattering indirect time-of-flight neutron spectrometer, proposed for the European Spallation Source (ESS). The instrument is conceived to deliver new capability by opening up a novel window on the low-energy dynamics of quantum, functional and energy materials. KVASIR will access low-lying excitations in millimeter-sized single crystals that underpin many emerging and transformative technologies. Guided by comprehensive ray-tracing simulations, the instrument has been optimised to deliver outstanding resolution in energy and momentum transfer, with $\Delta E = 5.7 \mu\text{eV}$ and $\Delta Q = 0.03 \text{ \AA}^{-1}$ (FWHM). KVASIR preserves the space required for complex sample environment and full polarisation analysis enabling controlled perturbations of materials and the unambiguous separation of intertwined degrees of freedom. By combining unprecedented spectral resolution and with access to extreme conditions (temperature, pressure, E, B fields, laser irradiation), KVASIR will establish a unique platform for inelastic neutron scattering studies of single-crystal hard condensed matter. KVASIR will thereby drive discoveries in emergent quantum phenomena as well as next-generation functional and energy materials.

II. BROAD SCIENTIFIC CASE AND SOCIETAL RELEVANCE

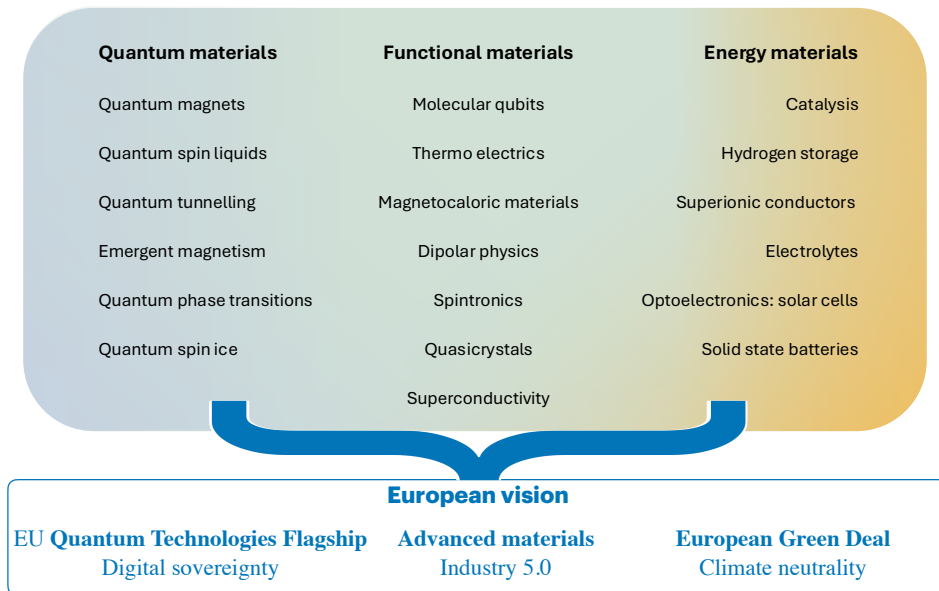


Figure 1. Scientific focus areas of the KVASIR instrument and corresponding high-level strategic priorities and policy initiatives of the European Union (EU).

The science case of KVASIR is focussed on three scientific pillars: quantum, functional and energy materials. These topics underpin many emerging technologies that address major societal challenges, including clean energy, efficient electronics, and advanced computing. Their societal relevance comes from how they improve efficiency, sustainability, and performance of key technologies. The remarkable properties of these materials often arise from complex interactions between spin, charge, orbital, and lattice degrees of freedom, which give rise to collective excitations in the μeV – meV energy range. Understanding these low-energy excitations is therefore essential to reveal the microscopic mechanisms governing their behaviour. Control over electronic,

magnetic, structural and optical degrees of freedom at the atomic scale are widely envisaged to further revolutionise future technologies. Inelastic neutron scattering provides a unique probe of such excitations due to its sensitivity to magnetic correlations and its ability to resolve both energy and momentum transfer. However, many phenomena of interest occur at very low energy scales and require instruments combining extremely high energy resolution with precise momentum resolution under extreme sample environments. In several recent high-impact studies of quantum, functional, and energy materials, the lowest-energy response is reported to appear as a broadened elastic line, or is accessible only at the cost of severely reduced intensity and long counting times. These works highlight a systematic limitation of existing cold time-of-flight spectrometers in resolving weak low-lying excitations due to flux and insufficient energy resolution. Turning to conventional backscattering spectrometers to improve energy resolution down to the μeV range is possible, but this would have a major impact on the Q resolution and on the available space for sample environments. Therefore, many such measurements lie at or beyond the limits of existing instrumentation. The high brightness of ESS enables KVASIR to address an important gap in neutron instrumentation worldwide. The capabilities of KVASIR will enable unprecedented studies of low-energy excitations in materials that underpin key European priorities in quantum technologies, advanced functional materials and sustainable energy systems, see Fig. 1. In recent years, a wealth of discoveries in these classes of materials have elucidated rich dynamical behaviour in the μeV to sub-meV energy regime within three related topics:

Quantum materials are broadly defined as a diverse and rapidly expanding class of systems in which many-particle quantum effects play a central role in determining their physical properties. These include low-dimensional systems, where reduced dimensionality enhances quantum fluctuations; quantum spin liquids, which exhibit long-range quantum entanglement and fractionalised excitations; and molecular nanomagnets, where quantum behaviour can be engineered at the molecular scale [1–6]. In single-crystal systems, strong correlations, reduced dimensionality, and topological effects give rise to a rich landscape of emergent phenomena that cannot be understood within a classical framework or even with conventional single-electron quantum physics (*e.g.* band theory). By hosting these collective quantum phenomena, quantum materials provide a rich platform for exploring new states of matter and for making fundamental discoveries in condensed matter physics. In addition, their unusual properties offer promising opportunities for future technologies, including quantum information processing, spin-based electronics, and advanced sensing. Single-crystal inelastic neutron scattering (INS) is the most direct and powerful technique for probing the dynamical properties of quantum materials, and it has played a central role in shaping our modern understanding of exotic quantum phases by directly revealing their elementary excitations.

Functional materials harbour a coupling between macroscopic degrees of freedom, such as magnetisation and electric polarisation, and beyond these to include lattice, charge, orbital, and spin degrees of freedom, leading to complex multifunctional behaviour [7–11]. In order to understand, and thus utilise functional materials, it is important to understand properties such as electrical conductivity, magnetic and spin transport, strong electron correlations and quantum coherence in addition to their optical response. Recent years have seen major advances in materials with novel magnetic textures, where the magnetisation field hosts topological defects such as windings. These structures offer promising routes toward new electronic device concepts. Of particular interest are topological solitons, exemplified by two-dimensional skyrmions and merons, and their three-dimensional counterparts, hopfions [8, 12, 13], that are expected to drive new spintronic capabilities. A second very novel example is that of altermagnetism. Altermagnetism is a magnetic order characterised by zero net magnetisation but momentum-dependent spin splitting arising from the crystal symmetry. It is expected that altermagnetism will enable spin-dependent electronic functionality with very fast switching and readout capabilities [14] thereby revolutionising spintronic materials.

Energy materials are materials designed to generate, store, convert, or transport energy efficiently. Key properties include ionic conductivity, chemical energy storage, thermal-to-electric conversion, hydrogen absorption, and catalytic activity [15–21]. Examples of such materials encompass battery materials, thermoelectrics, hydrogen storage systems, optoelectronic materials used in solar cells, and superconductors for lossless power transmission. Together, these systems provide a versatile platform for addressing fundamental questions in condensed matter physics while offering promising pathways toward sustainable energy technologies. However, the majority of studies investigating local structure and dynamics in energy-relevant materials, such as solid-state ionic conductors, rely on powder inelastic neutron scattering. Consequently, important crystallographic dependencies are averaged out and lost. A detailed understanding of low-energy dynamics—including overdamped and anharmonic vibrational modes, their directional dependence, and their coupling to even lower-energy processes such as ion diffusion—is essential for optimising energy materials. Studies of single-crystal samples of for example solid-state ionic conductors where neutron scattering investigations remain scarce, will significantly advance the understanding and development of these technologically important materials.

A growing number of recent studies using inelastic cold neutron scattering are targeting excitations in a range of energy and wave vector, pressure, or temperature that require pushing instruments to the limits of their current performances. The experiments that are successful today, which have managed to overcome problems related to available flux or instrument resolution, are making headlines. However, they must become routine thanks to the instruments of tomorrow. We are therefore motivated to build a new generation of

high-flux, ultra-high-resolution instruments with adequate momentum transfer, often under extreme conditions of temperature, pressure, and applied electric and magnetic fields. KVASIR is designed to overcome this difficulty and will provide unseen spatial and dynamic precision for a broad community of hard condensed matter physics and inorganic chemistry.

A. Particular scientific examples

In this section we highlight three recent high impact scientific examples within quantum, functional and energy materials. All three examples illustrate the limit of what is routinely possible today.

1. Quantum materials

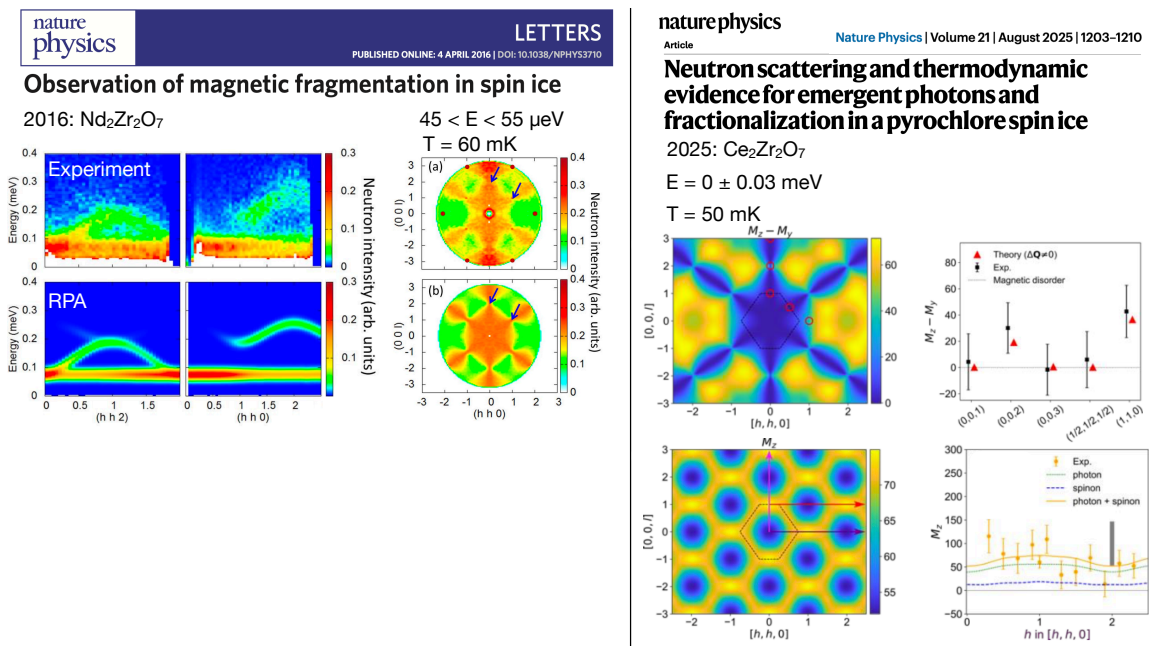


Figure 2. (left) $S(\mathbf{Q}, \omega)$ and $S(\mathbf{Q}, \omega = 50 \mu\text{eV})$ of $\text{Nd}_2\text{Zr}_2\text{O}_7$ at 60 mK with comparative dynamical structure factor calculated in the RPA approximation for the pseudo spin 1/2 model [22]. (right) Theoretical predictions of the polarisation dependence of magnetic $S(\mathbf{Q})$ at $E = 0 \pm 0.03$ meV for $\text{Ce}_2\text{Zr}_2\text{O}_7$ in the $[h, h, l]$ scattering plane with a comparison between the theoretical calculation for the spin space anisotropy suggested compared to magnetic disorder (for $M_z - M_y$) and contributions from spinons, photons, and their total in the M_z [23].

Among these materials, quantum spin liquids have attracted considerable interest. This exotic state of matter definitely evades long-range order, yet exhibits large-scale quantum entanglement properties, a feature that has coined the phrase “ultra-quantum”. Frustrated magnets have led to significant discoveries, notably the famous “spin ice” and “quantum spin ice” [24]. The pyrochlore lattice, built from vertice-sharing tetrahedra, plays a central role here. At the classical level, the degenerate configurations of the magnetic ground state are constructed according to a local rule where each tetrahedron must have two incoming and two outgoing spins. These states resonate at the quantum level to form an entangled state, constituting the basis of an emergent gauge structure. A direct consequence is power-law spin-spin correlations, demonstrated by neutron diffraction, with distinct and anisotropic features in reciprocal space, as well as a rich excitation spectrum, including deconfined excitations, spinons, and visons, as well as a collective mode, an emergent “photon”. However, finding examples of this is not easy. $\text{Nd}_2\text{Zr}_2\text{O}_7$, for example, is a classical system, since it exhibits long-range order, yet remains close to a quantum spin ice. This is reflected by a distinctive magnetic excitation spectrum, featuring a flat, non-dispersive gapped mode. Condensation of this mode would indicate the destabilization of the magnetic order in favor of the spin liquid phase. Time-of-flight measurements indicate a gap of approximately $60 \mu\text{eV}$, which is currently measurable, but still requires excellent energy resolution [22]. However, the $\text{Ce}_2\text{B}_2\text{O}_7$ materials, where $B = \text{Sn}, \text{Hf}, \text{or Zr}$, is the best example of these quantum spin liquids, even if the observation of the photon remains elusive, because it is presently too close to the elastic line. The spinon spectrum appears as broad peaks around $50 \mu\text{eV}$, which can only be detected using backscattering techniques, at the limit of today’s current capabilities [23].

2. Functional materials: Novel spintronics

Skyrmions are topologically protected, nanoscale spin textures that are robust to defects and perturbations, making them reliable information carriers. Their small size and low current-driven mobility enable high-density, low-energy data storage and racetrack memory concepts.

Science

Topological magnon band structure of emergent Landau levels in a skyrmion lattice

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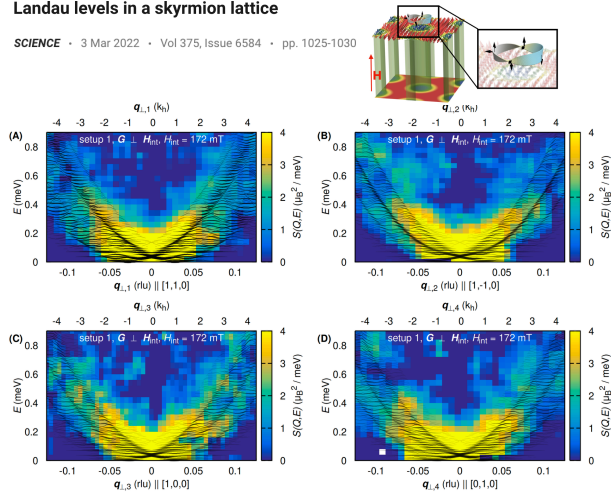


Figure 3. Inelastic neutron scattering to investigate the propagation of magnons in a lattice of skyrmion tubes in manganese silicide MnSi. Contour maps of inelastic data as measured at LET for momentum transfers q_{\perp} along $[110]$, $[1\bar{1}0]$, $[100]$ and $[010]$, respectively. In all panels black lines represent the magnetic response tensor predicted theoretically, where the line-thickness denotes the calculated spectral weight [25].

Their rich dynamics and interactions enable multifunctional applications ranging from magnonic computing to sensors. However, challenges remain in materials optimisation, notably the need for clearer understanding and control of Dzyaloshinskii–Moriya interactions, magnetic anisotropies, and excitation damping. A particular example is the determination of the topological magnon band structure of emergent Landau levels in the skyrmion lattice of MnSi [25]. Studies using MIEZE spin-echo spectroscopy combined with Time-of-Flight and Triple-Axis Spectroscopy have resolved Landau levels in MnSi, proving that the magnon energy is quantized. Fig. 3 shows the scattering profiles, measured using the low energy spectrometer LET (ISIS), of a single crystal of MnSi with the expected theoretical magnetic response superposed on the data.

High energy resolution quasielastic scattering was essential to correlate theoretical prediction with experiment. In particular, the agreement between theoretical prediction and experiment improved considerably when adding a quasi-elastic magnetic contribution of magnetic origin. However, the complexity of the theoretical models far outweighs the details of the experimental data, indicating that improved resolution could be strongly beneficial.

3. Energy materials

Perovskites such as $\text{CH}_3\text{NH}_3\text{PbI}_3$ have emerged as highly efficient materials for solar cells, with power conversion efficiencies increasing from approximately 4% in 2009 to around 20% today. This remarkable progress has largely been driven by advances in single-crystal growth, which have enabled the development of scalable and practical photovoltaic applications.

Despite these advances, the underlying physics governing thermal and charge transport has remained debated. A key step toward resolving this came from single-crystal inelastic neutron scattering studies [26], which demonstrated that long-wavelength, low-energy acoustic phonon modes, with sub-picosecond lifetimes, play a dominant role in thermal transport. Furthermore, the study revealed that charge and thermal transport are governed by a common mechanism, challenging the conventional view that these processes are independent. In $\text{CH}_3\text{NH}_3\text{PbI}_3$ the methylammonium (CH_3NH_3^+) ions inside the lattice rotate dynamically along particular crystallographic axes and their low lying dynamics are consistent with rotating dipoles. These rotating dipoles interact with charge carriers and phonons thus impacting the mobility within these materials. These studies show that the combination of molecular jumping rotations and

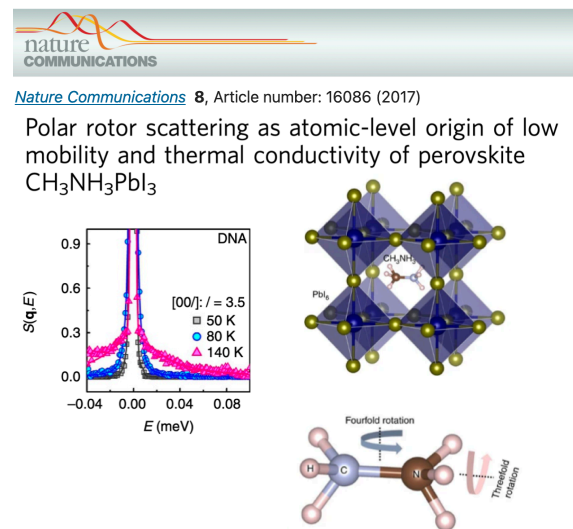


Figure 4. An overview of the temperature dependence of quasielastic scattering from single crystal perovskite $\text{CH}_3\text{NH}_3\text{PbI}_3$ indicating jumping rotational dynamics [26].

phonon excitations in addition to their directionality have to be considered.

This shows that better material design can be guided by anisotropic information, which can only be gained via studies of single crystals. There have been some recent studies, albeit limited in number, that have probed the crystallographic directionality of the dynamics in energy materials with great success. These include the elucidation of the conduction pathways in fast-ion conduction in solid-state materials [27], the liquid like behaviour of a two-dimensional type I superionic conductor [28] and solidlike to liquidlike behavior of Cu diffusion in superionic Cu_2X ($\text{X}=\text{S},\text{Se}$) in which diffusional directionality plays an important role [29]. KVASIR would, in this respect, open up new opportunities in the field of energy materials and will allow for studies of the directionality of low-energy dynamics, such as overdamped and anharmonic vibrational dynamics and its relationship to even lower energy scales.

B. Potential new science

a. Delicate weakly interacting conventional magnetic compounds. The combined excellent energy and Q resolution of an instrument like KVASIR allows one to address the spin wave spectrum of conventional magnets characterized by very weak interactions, hence by a delicate dispersion. Weakly interacting magnetic compounds provide an important testbed for fundamental physics. Weak interactions are highly sensitive to subtle effects, such as quantum behaviours, that may be masked in systems with stronger exchange interactions. Equally, these systems allow one to understand fundamental concepts since they are often easy to manipulate due to the low energy scales. In addition, the low energy scales provide an easy handle to perturb these materials, with low magnetic fields for instance, and thus use them as spintronic materials. An example is Cyanochroite, $\text{K}_2\text{Cu}(\text{SO}_4)_2 \cdot 6\text{H}_2\text{O}$, a Tutton salt with nearly non-interacting $S=1/2$ spins, placed fairly distant apart in the lattice. Large crystals are very easy to grow, see Ref. [30]. Cyanochroite remains a perfect paramagnet down to subkelvin temperatures and therefore serves as calibration sample for ESR, but cyanochroite actually does order magnetically at 29.6 mK according to ac susceptibility and specific heat (references are in the above-cited paper). No one ever considered measuring spin waves in such weakly interacting systems, simply because the magnon band width would be extremely small. An instrument like KVASIR would make it possible.

b. High energy resolution away from the elastic line. While KVASIR will be powerful for the study of low-lying excitations, the spectrometer also holds the potential to study excitations further from the elastic line with excellent resolution; in a similar way to the BIFROST spectrometer [31]. For example, at 5 meV energy transfer and a realistic pulse-shaping chopper (PSC) opening of 100 μs , the energy resolution will be as good as 10 μeV . This could have many strong use cases beyond the low-energy dynamics mentioned in the above. As one example of current interest, altermagnetic splittings are often small and placed close to the zone boundary; at the top of the magnetic band [14]. A relevant example would be the candidate altermagnetic material LiFeP_2O_7 , where the overall magnon bandwidth is supposedly 2-3 meV because the strongest interactions between the Fe moments is mediated along Fe-O...O-Fe super-superexchange pathways [32].

c. Stimulations to drive out-of-equilibrium physics and Time-dependent measurements. Today, most experiments are conducted under thermodynamic equilibrium. However, the capabilities of an instrument such as KVASIR make it possible to conduct studies under non-equilibrium conditions. Although mostly of fundamental interest at first glance, this science is in fact closely linked to societal challenges. One such example of a non-equilibrium phenomenon involves the use of waste heat generated by electronic devices. Thanks to the spin Seebeck effect, a temperature gradient in ferromagnetic or ferrimagnetic materials creates a spin current, which can be converted into an electric voltage. In doing so, low-energy magnons in the magnetic material are excited, and the signature of this excitation is observable via neutron scattering. An pioneering experiment of this type was conducted by injecting a spin current via ultrasound into $\text{Y}_3\text{Fe}_5\text{O}_{12}$ [33]. The nonequilibrium magnon steady state, in the μeV range, was explored using the backscattering technique and manifests as a significant deviation of the effective magnon temperature from the sample temperature. Other types of stimulation, such as laser irradiation [34] or THz radiation, could also induce such a non-equilibrium state. Pump-probe experiments for instance could be another promising development, that will determine real-time dynamics of *e.g.* quantum materials out of equilibrium. Here the pump could be a laser, microwave, an electrical current or a changing electric or magnetic field. The geometry of the KVASIR analyzers and the ESS event mode detection system are ideally suited for such developments, giving time resolutions as good as tens of microseconds.

One should note that studying out of equilibrium phenomena will require theoretical models to extend beyond the Born approximation in equilibrium. As such time-dependent scattering theory will need to be implemented since the interpretation becomes more complex when energy is not strictly conserved. This will be of great benefit for the community when there is a drive to study real materials in operation that include, but are not limited to, spin currents in spintronics materials and temperature gradients in thermoelectric materials. These are all areas that remain to be explored.

d. Smaller samples. It is expected that improved flux on smaller samples on KVASIR will provide great opportunities to study compounds that could previously not be probed since only small sample masses are accessible *e.g.* for materials synthesised via the trial and error method of flux growth, hydrothermal synthe-

sis or high pressure synthesis. It is also of great interest to move towards true functional materials with thin film or superlattice structures. Functional materials and time-dependent phenomena would be a possibility with microwave- or laser-stimulated samples. In addition, as our samples are getting smaller there are greater opportunities to exploit synergies with the X-ray spectroscopy community.

e. Opportunities for polarisation analysis In this proposal we do not focus on the opportunities delivered through the use of polarisation analysis (PA) on an instrument like KVASIR. Nevertheless each scientific case outlined will benefit enormously from polarisation analysis, as described in the SHERPA science case [35], and highlighted in recent scientific meetings such as PACMAN and HIRES. The intention is to deliver this capability but since there are currently significant developments we would like to follow these before deciding on a final configuration.

C. User community

KVASIR has been developed due to a particular scientific need: to obtain good-quality measurements on small single crystals with Q and E resolution that match low lying modes in the μeV regime. To perform such an experiment on a direct geometry spectrometer, typically used to access both high E and Q resolutions, one would need to use a long incident wavelength, $\approx 7 \text{ \AA}$, and a very fast spinning monochromating chopper. This results in a much reduced flux. This is exemplified in Fig. 7(b), which shows the relative peak brightness of the cold moderators at ESS and ILL. The ratio between the brightness, and thus possible flux on sample, at $\lambda = 3 \text{ \AA}$, typically employed to reach $\Delta E = 80 \mu\text{eV}$, and $\lambda = 7 \text{ \AA}$, typically used to achieve $\Delta E = 30 \mu\text{eV}$, is an order of magnitude. Thus the extra resolution in energy has a sharp penalty in flux on such a spectrometer.

Even though the flux penalty is large the current scientific trends drive towards smaller energy scales and higher resolutions for single crystal studies. This has been noted by instrument scientists of cold chopper spectrometers, particularly IN5 at ILL, where a large number of users now request higher wavelengths and tighter resolutions. A similar trend is seen for backscattering instruments, particularly DNA at J-PARC.

The core user community of KVASIR counts the scientists who today use cold-neutron spectroscopy for hard condensed matter, and of those who would be attracted in this direction with the new capabilities of KVASIR. To study the current community, we have performed a literature study, selecting neutron spectroscopy papers that used energy transfers below 1 meV. We searched the time span 2010-2019 for papers in journals of impact factor (IF) 6+; and the time span 2020-2025 for papers in journals of IF 3+. This resulted in 393 publications from facilities around the world and although is not perfect the results are indicative of a growing trend to study low lying modes. The publications are dominated by Physics, Chemistry, and general journals: Science, the Nature family, the Physical Review family, Chemical Science and JACS. Typically Physical Review Letter, the Nature family and Science have an impact factor > 10 . We therefore compare the number of papers with high IF (IF >10) to those with lower IF (IF <10), to verify the trend, see Fig. 5.

- Quantum Materials: Quantum magnets [1, 9, 36–106], Frustrated magnets [4, 5, 22, 23, 107–258].
- Functional materials: Molecular magnets [2, 6, 11, 18, 259–273], Thermoelectrics [19, 274, 275], Magnetocalorics [7, 276], Spintronics [34, 277–282], Quasicrystals [283], Superconductors [284–318].
- Energy materials: Superionics [319], Optoelectronics [320–322], Battery materials [21, 323].
- Other functional materials: Magnetic nanoparticles [324–326], Multiferroics and magnetoelectrics [10, 327–339], Magnetoelastics [340, 341], Piezoelectric [342], Ferroelectrics [16, 343, 344], Photovoltaics [15, 17, 26, 345–348], Permanent magnets [349], Colossal magnetoresistance [350].
- Other fundamental topics: Topological insulators [3, 351–363], Skyrmions [25, 364–369], Weyl metals [370–374], van der Waals magnet [375–381] Correlated structural disorder [382], Heavy fermions [383–389], Kondo materials [390–392], Magnetic MOF [393], Nuclear magnetism [394], Other antiferromagnet physics [395–403], Other ferromagnet physics [404–407].

The sheer volume of recent high impact publications shows a large and active community that generates important and topical results. Fig. 5 shows a clear and positive trend in the low impact numbers indicating a

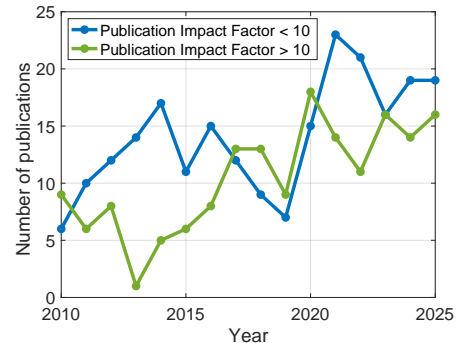


Figure 5. Number of publications with low, (IF <10), and high impact factors, (IF > 10), as function of year (2010-2025) of publications that would benefit from KVASIR, details outlined in text.

strong base community while the high impact papers also increases nearly linearly with time highlighting the increasingly high impact of these scientific domains. The large number of supporting letters, see appendix, shows the enthusiasm for KVASIR from a broad scientific community.

D. Complementary techniques

Neutron backscattering with pico to nanosecond timescales and sufficient spatial resolution is uniquely placed in the landscape of techniques that access low-lying dynamics of single crystals. In terms of hard condensed matter physics and inorganic chemistry, complementary techniques include light scattering, muon spectroscopy (μ SR), X-ray scattering, Nuclear Magnetic Resonance, Electron Spin Resonance and ac susceptibility. Light scattering is optimised for low-Q regions with dynamics on the μ s to ms range. Nuclear Magnetic Resonance techniques and ac susceptibility provide sensitivity in the μ s to s timescales but provides no spatial information. μ SR studies dynamics in the 10^{-8} - 10^{-6} s time window and is optimised for spin dynamics of slow magnetic phenomena. However, one cannot, from μ SR data, reconstruct correlations as a function of distance. High-resolution X-ray scattering techniques, such as resonant X-ray scattering and ARPES, are complementary to neutron spectroscopy but access much higher energy scales and corresponding broader energy resolutions (1-3 meV at the tightest energy resolutions), much inferior to that afforded by neutron scattering techniques (μ eV). Additionally, X-ray scattering suffers from beam heating effects, effectively preventing access to mK temperature scales where quantum effects are most prevalent.

III. AN INITIAL TECHNICAL OVERVIEW OF THE PROPOSED INSTRUMENT

KVASIR is an indirect geometry spectrometer based on the SHERPA concept [35, 408] with a distinctly different science case. SHERPA is optimised for PA of disordered materials while KVASIR is optimised for single crystals. The primary spectrometers of KVASIR are modified to utilise the ESS pulse while the secondary spectrometer is optimised for the target instrument parameters. KVASIR uses the prismatic analyzer concept [409] as demonstrated on CAMEA [410], BIFROST [411], and SHERPA [35]. A detailed overview of the technical details and simulations is available on Ref. [412].

Considering the scientific case, the target instrument parameters that we aim for are:

- Simultaneous good Energy and Q resolutions: $\Delta E = 4 \mu\text{eV}$; $\Delta Q = 0.03 \text{ \AA}^{-1}$.
- Maximize the flux on a sample area of $1 \times 1 \text{ cm}^2$ and optimise signal to noise.
- Sufficient sample space to apply large magnetic fields.

PA will be an option on KVASIR, allowing to separate magnetic scattering, with differing polarisations, from coherent and spin-incoherent scattering. As stated previously, we do not focus on PA in this proposal, but rather aim to closely follow the recent method developments within inelastic neutron scattering. We will future proof the instrument to ensure that the latest PA developments can be implemented on KVASIR.

A. Use of the ESS long-pulse source.

On an indirect geometry spectrometer, the energy resolution, ΔE , depends on the resolution of the primary, ΔE_i and secondary spectrometer, ΔE_f , added in quadrature to obtain the final resolution. The primary spectrometer resolution is given by:

$$\frac{\Delta E_i}{E_i} = \frac{2\Delta t}{t}; t = \frac{L}{v}, \quad (1)$$

where E_i is the incident energy, L the moderator-sample distance, v the neutron velocity, t the time of flight, and Δt is the time uncertainty, stemming either from the source pulse length or from the pulse width of the pulse shaping chopper.

The energy resolution can further be simplified to

$$\frac{\Delta E_i}{E_i} \propto \frac{\Delta t}{L}. \quad (2)$$

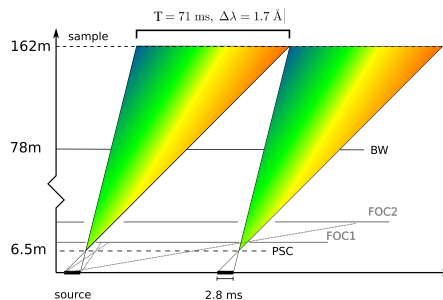


Figure 6. Overview of natural length determination for spallation source spectroscopy instruments.

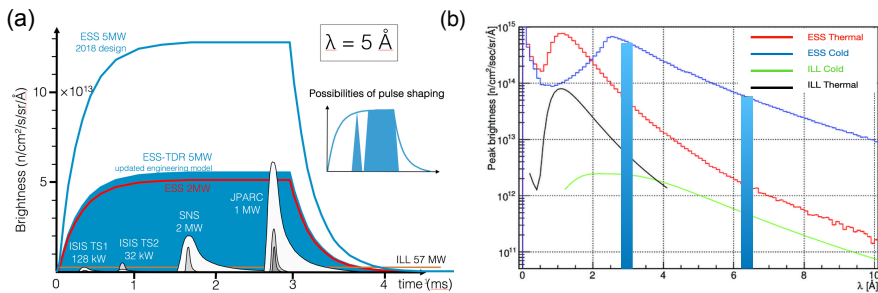


Figure 7. (a) Comparing the brightness and time structure of the pulse spectra for various neutron scattering facilities. (b) Wavelength dependence of the peak brightness of the ESS and ILL thermal and cold moderators. Blue shaded regions highlight the optimal flux for the cold moderator at the ESS, $\lambda = 3 \text{ \AA}$, in comparison to the incident wavelength needed for high energy resolution measurements, $\lambda = 7 \text{ \AA}$, on cold direct geometry spectrometers.

It can be seen that, for constant resolution, the chopper opening time will be proportional to the length of the primary spectrometer. Therefore, for the same energy resolution, a long instrument will extract more flux at the elastic line.

On a long-pulsed spallation source like ESS, the "natural length", L , of an instrument is given by $L_{PS}/L = \tau/T$, where L_{PS} is the distance from moderator to the pulse shaping chopper, PSC, T is the time between pulses, and τ is the pulse length. For ESS, $L_{PS} = 6.5 \text{ m}$, $T = 71 \text{ ms}$, and $\tau = 2.86 \text{ ms}$, leading to a natural length of $L \approx 160 \text{ m}$ and a wavelength band width of $\Delta\lambda = 1.7 \text{ \AA}$ [413]. At a short-pulsed source, on the other hand, the optimal length of an indirect geometry spectrometer is found by matching the primary and secondary resolutions. Table I shows the lengths of various instruments and the pulse width on the sample for equivalent ΔE_i ; relative to the KVASIR pulse length. At ESS, the natural length of 160 m means that for the same ΔE_i KVASIR will extract twice the flux of BASIS (SNS) and approximately four times more flux than IRIS (ISIS, TS1) with moderator to sample length of 80 and 36 m respectively. In order to compensate

Table I. Relative peak brightness, see Fig. 7, instrument flight path lengths and corresponding relative pulse widths required to achieve equivalent incident neutron energy resolution, following eq. (2).

Instrument	Length (m)	Relative Δt for equivalent ΔE_i	Relative Peak Brightness ($\sim 5 \text{ \AA}$)
KVASIR (ESS)	160	1.0	1
BASIS (SNS)	80	0.5	0.4
IRIS (ISIS, TS1)	36	0.225	0.038
SHERPA (ISIS, TS2)	35	0.225	0.0868
DNA (J-PARC)	42	0.26	1.19

for such a loss, one can broaden the divergence, from $\pm 0.75^\circ$ for the present KVASIR design, to up $\pm 5^\circ$ for short pulse instruments. Broadened divergence profiles naturally results in broader Q resolutions. As such, at ESS, KVASIR has the opportunity both to strongly limit the incident divergence due to the high brightness of the source, see table I, and still obtain high energy resolution. In addition, it is possible, unlike for short pulse spallation instruments, to extend the opening time of PSC to degrade the energy resolution in favour of significant flux gains. In conclusion, the high brightness of ESS enables KVASIR to deliver both high energy and Q resolution. As such, KVASIR is optimally suited for the ESS long-pulse and time structure.

B. Analytical considerations: Primary spectrometer

For the preliminary design of the primary spectrometer, we adopt the realised design of the BIFROST neutron guide and the chopper cascade. [411] The beam is extracted from the ESS cold moderator with a curved ballistic neutron guide to deliver a wavelength band of 1.7 \AA around an incident energy E_i with a divergence profile of $\pm 0.75^\circ$ onto a beam spot of $1 \times 1 \text{ cm}^2$ at the sample position, 162 m from the moderator [31, 413, 414]. A pair of counter-rotating PSCs, 0.7 m in diameter, is positioned at 6.5 m from the moderator and is the key defining element of the primary energy resolution [415, 416]. As such the incident neutron path from the PSC to the sample is $L_i = 155.5 \text{ m}$.

In the high resolution mode of KVASIR, we consider an opening time of 100 \mu s , delivering a flux of 10^8 n/s/cm^2 at the sample. The corresponding PSC speed is 196 Hz, which is well within technical feasibility. Neglecting deviations from time of flight due to beam divergence, the primary spectrometer energy resolution is $\Delta E_i = 2E_i \Delta t/t = 1.5 \text{ \mu eV}$ (FWHM), where $t[\text{μs}] = 252.78 L_i[\text{m}] \lambda[\text{Å}]$. A higher flux can be obtained at the

cost of energy resolution by increasing the PSC opening time. However since the energy resolutions between the primary and secondary spectrometer are not very well matched opening the PS chopper slightly would not degrade the total energy resolution very much and yet provide a linear increase in flux on sample. The bandwidth is centered around the fixed final wavelength of the secondary spectrometer of $\lambda_i \approx 6.5 \text{ \AA}$, the reflected wavelength from near backscattering off PG [0 0 2] planes. A shift of the wavelength band, to be centered on $\lambda_i \approx 3.25 \text{ \AA}$, allows one to utilise the [0 0 4] Bragg planes, in effect doubling the Q-range and increasing the E range by an order of magnitude. This will provide a broader overview of energy and momentum transfer as illustrated in Fig. 10.

C. Analytical considerations: Secondary Spectrometer

As pointed out by R. Bewley [408], the use of pyrolytic graphite (PG) analysers with a large mosaic spread provides large gains for a near-backscattering instrument. KVASIR utilises this by employing PG [0 0 2] analyzer crystals scattering at $2\theta_A = 150^\circ$, giving $E_f = 1.95 \text{ meV}$. The sample-analyzer and analyzer-detector distances were optimized by taking into account both the E- and Q-resolutions, while limiting the sample-analyzer distance to 2.5 m for practical and budget reasons [412, 417]. The focusing of the analyzer array has been optimised to provide the best overall energy resolution. A number of strategies were considered, as illustrated in Fig. 9(b). The asymmetric Rowland geometry provides a constant E_f , but different secondary flight path lengths, thus giving uncertainties in the determination of E_f from the time-of-flight reconstruction. Similarly, a constant flight path will result in a spread in Bragg angles, giving rise to uncertainties in E_f . A numerical optimisation enabled us to find a compromise, the final configuration on Fig. 9(b), where the change in Bragg angle compensates for the different flight path lengths at $\hbar\omega = 0$, as illustrated in Fig. 9(b) and further discussed in Ref. [412]. The analysers are moderately mosaic PG crystals, $\Delta\theta = 1.5^\circ$. The detectors are placed on a cylinder centered at the sample axis of radius 1.4 m, see Fig. 9 (a). In combination with the low beam incoming divergence, $\eta = 0.75^\circ$, the relatively large sample to detector distance results in a narrow Q resolution. We first show analytically that the target parameters are in reach.

a. Energy resolution. The energy resolution of the secondary spectrometer, ΔE_f is given by two terms:

- Δd , the variation of distance between [0 0 2] PG lattice planes; typically $\Delta d/d \approx 0.001$ (FWHM).
- $\Delta\theta_A$, the spread on Bragg angle from the analysers.

These terms result in an energy resolution of

$$\Delta E_f = 2E_f \sqrt{\left(\frac{\Delta d}{d}\right)^2 + (\cot \theta_A \Delta\theta_A)^2}$$

When the prismatic concept is disregarded, the spread of analyzer angles is governed by the analyzer mosaicity ($\Delta\theta_A = 1.5^\circ$) to give $\cot \theta_A \Delta\theta_A = 0.007$, resulting in an energy spread of the analyzed neutrons $\Delta E_f = 27 \mu\text{eV}$ ($\Delta\lambda_f = 0.06 \text{ \AA}$), which in turn leads to significant gains in count time. We then use the prismatic effect, using the vertical position sensitivity of the detectors (5 mm), with the energy spread within one pixel then given by a combination of $\Delta d/d$ and distance collimation $\Delta\theta_A = \Delta h_D/L_{AD}$ such that this matches $\Delta d/d$, ($\cot \theta_A \Delta\theta_A = 0.0011$), to analytically reach $\Delta E_f = 5.4 \mu\text{eV}$.

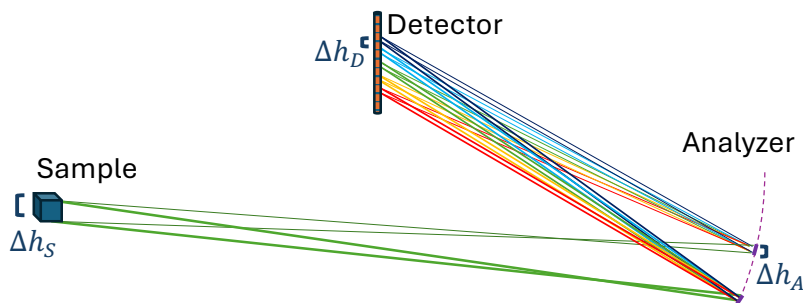


Figure 8. Prismatic effect: reflection a number of neutron energies from analyser crystals scattered with each energy reflected in a specific angle given by Bragg's law.

Using this, the resultant total energy resolution of KVASIR with PG [0 0 2] becomes $\Delta E = 5.6 \mu\text{eV}$. This value is slightly above the target value but is very acceptable.

b. Q resolution. The Q resolution is determined principally by the uncertainty in scattering angle. This is given by η , the divergence of the flux of the primary spectrometer, the uncertainty in the scattering position from sample ($s = 1 \text{ cm}$) (as distance collimation seen at the sample to analyser distance $L_{SA} = 2.5 \text{ m}$), and the discretisation error

in the detector tubes (tube width $d = 1.25 \text{ cm}$, detector and analyser positions $L_{AD} - L_{AD} = 1.25 \text{ m}$). Taken

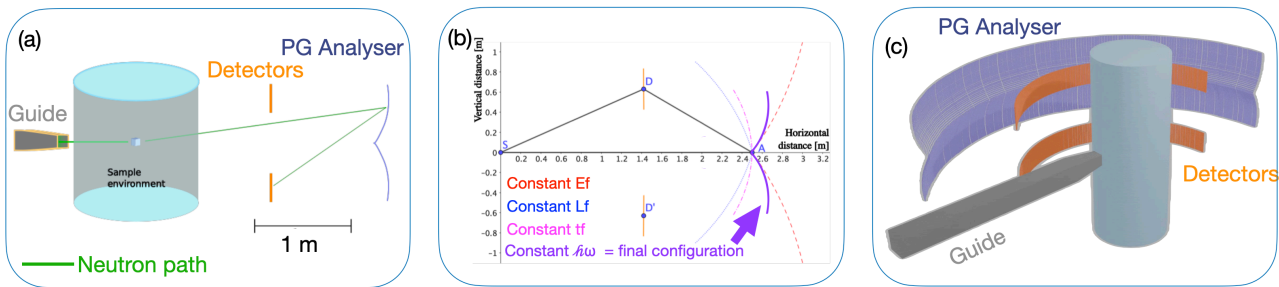


Figure 9. (a) The secondary spectrometer of KVASIR. Neutrons (green) are focused onto the sample, which is placed within the sample environment (light blue). Neutrons scattered from the sample propagate towards the analysers (purple), from which an almost-monochromatic beam will be scattered onto the a detector array (orange). (b) Optimising the analyser configuration. Various configuration were considered: Red (dashed line): Asymmetric Rowland circle (Constant E_f). Blue (dotted line): Ellipse with focal points at sample and detector positions (constant L_f). Pink (dotted and dashed line): Ellipse with correction (constant t_f). Purple (solid line): Conic section for constant ΔE , the optimised configuration. (c) Figure highlights the broad analyser array ($5^\circ < 2\theta_{\text{hor}} < 175^\circ$, $-13.5^\circ < 2\theta_{\text{ver}} < 13.5^\circ$.)

together, and ignoring the change in neutron direction caused by the analyser mosaicity, these terms lead to an analytical approximation for the Q-resolution:

$$\Delta Q = \frac{4\pi}{\lambda} \sin \sqrt{(\eta)^2 + \left(\frac{s}{L_{SA}}\right)^2 + \left(\frac{d}{L_{SA} - L_{AD}}\right)^2}.$$

The analytical Q resolution is thus $\Delta Q = 0.0329 \text{ \AA}^{-1}$, and also close to the technical requirement.

The analytical values of ΔE and ΔQ almost match the scientific specifications. However it is imperative that ray tracing is performed since the cumulative effects of a large analyser crystal array, the prismatic and analyser mosaicity may lead to broadening of these values.

D. Simulating the complete spectrometer

A preliminary design has been made using the McStas simulation package [418, 419] and is documented in Refs. [412] and [417]. It proved possible to use the prismatic concept for two analyser arrays; one above and one below the scattering plane, as seen in Fig. 9(a). Each of the analyzer arrays ranged from the scattering plane to ± 60 cm away from the plane, corresponding to $\pm 13.5^\circ$ from the plane, or an out-of-plane component to the scattering vector of $|Q_z| \leq 0.23 \text{ \AA}^{-1}$. We envisaged that it will be possible to subdivide these analyzer sections into two separately focusing parts, thus improving the out-of-plane resolution. The various analyser configurations considered are shown in Fig. 9(b) with the final configuration highlighted. A sketch of the full instrument is shown in Fig. 9(c) with a horizontal analyser coverage of $5^\circ < 2\theta < 175^\circ$ and a vertical analyser coverage of $\pm 13.5^\circ$. This analyser coverage, and the matching detector coverage, was used to determine the final energy and Q resolutions, see Figs. 10. Centering the elastic line at the center of the bandwidth of the instrument will provide a range of energy transfers of $-0.35 \leq \hbar\omega \leq 0.81$ meV for PG [0 0 2] and $-2.81 \leq \hbar\omega \leq 7$ meV for PG [0 0 4]. The resulting dynamic ranges for the two cases are shown in Fig. 10(a).

Further simulating the geometry described above, each analyzer crystal, $1.27 \times 2.2 - 2.4 \text{ cm}^2$ (height \times width (according to spherical requirement)), scatters an energy range of $\approx 27 \mu\text{eV}$, while the prismatic concept reduces the energy spread on each detector pixel to $\approx 3 \mu\text{eV}$ (FWHM) (MonochromatorFlat component). This is less than the analytically derived result and we are trying to understand the origin. The energy and Q resolutions are determined from a Vanadium and a powder $\text{Na}_2\text{Ca}_3\text{Al}_2\text{F}_{14}$ component from the McStas library. This slight geometric aberration from the full 60 cm tall analyzer array, combined with the uncertainty from the primary spectrometer E_i , produces a total energy resolution (integrated over Q) of $\Delta E = 5.7 \mu\text{eV}$, see Fig. 10(b) for PG [0 0 2], while the Q-resolution varies from $0.025 < \Delta Q < 0.035 \text{ \AA}^{-1}$, see Fig. 10(c). In the case of the PG [0 0 4], the energy resolution broadens to $\Delta E = 65 \mu\text{eV}$ with a Q-resolution of $0.08 < \Delta Q < 0.046 \text{ \AA}^{-1}$, see Fig. 10(d).

E. Technical feasibility

The primary spectrometer builds on an elliptically focusing guide and chopper cascade, of the type already used for BIFROST. In a detailed design phase, the guide and chopper cascade design will be optimized specifically for the KVASIR instrument. This is expected to result in a somewhat higher flux on sample, but not an

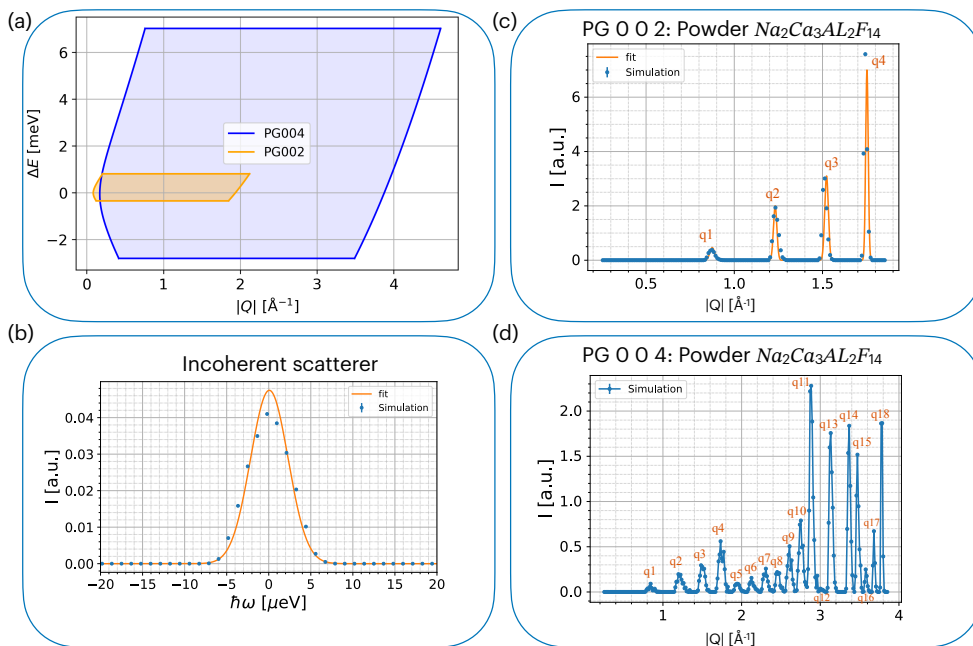


Figure 10. (a) The dynamic range of KVASIR in the PG [0 0 2] and [0 0 4] settings for an incoming wavelength band of 1.7 \AA and a scattering angle coverage from $5^\circ - 175^\circ$. (b) McStas simulated detected profile for a Vanadium sample, using the analyser PG [0 0 2] reflection. (c,d) McStas simulated detected profiles for a $\text{Na}_2\text{Ca}_3\text{Al}_2\text{F}_{14}$ powder sample for the PG [0 0 2] analyser reflection and PG [0 0 4] analyser reflection.

essentially different geometry or resolution if the instrument views the base moderator. There are opportunities with a moderator optimised for smaller samples.

For the secondary spectrometer there are concerns related to the procurement of PG crystals, since the usual supplier (Panasonic) is no longer available. However, the KVASIR analyzers envisage poor quality, in mosaic spread, PG which are available elsewhere, according to recent investigations by the VESPA team. We envisage employing half-inch position sensitive ^3He detector tubes in the prismatic mode; a set-up already used for BIFROST. Alternatively, new boron based detector technologies could be considered to reduce potential saturation risks [420]. The most important difference to BIFROST is that in KVASIR the analyzer solid angle coverage is higher and the analyzers scatter in near-backscattering. There are engineering challenges when considering how to incorporate a movable Be filter and possibly further collimators and/or cross-talk shielding as employed in BIFROST. In addition, phonon scattering from PG crystals in backscattering must be strongly suppressed to optimise signal to noise.[421, 422] Hence, cooling the PG crystals is envisaged, preferably below 50 K.

KVASIR will rely on lessons learned from the construction of BIFROST and VESPA (both PG based spectrometers at ESS). In addition, we will collaborate with the ISIS instruments teams of IRIS, ORISIS and SHERPA, as well as the DNA instrument scientists at J-PARC, to ensure optimal knowledge transfer.

IV. PLANS OR REQUIREMENTS FOR SAMPLE ENVIRONMENT AND LABORATORY ACCESS.

For optimal use of KVASIR, it must be possible to align single crystals with Laue x-ray and neutron diffraction. These requirements are similar to those of other ESS instruments: MAGIC (single crystal magnetism diffractometer), BIFROST (Extreme environment spectrometer), CSPEC (Cold chopper spectrometer) and T-REX (Bispectral chopper spectrometer). ESS has recently installed an X-ray diffractometer for these purposes, and the Neutron Test Beam Line will also provide facilities for single crystal alignment. We deem this to be adequate for our purpose.

The requirement for KVASIR sample environment is similar to most other cold neutron spectrometers, *e.g.* BIFROST, CSPEC and T-REX. Measurements at cryogenic temperatures will be the most common mode of operation; often in the milli-Kelvin range, meaning that access to Orange-type cryostats with dilution inserts will be required. Additional application of high magnetic fields (initially up to 15 T) and the use of hydrostatic or uniaxial pressure will be common. It should be possible to combine all of these, *e.g.* a cold experiment in a high magnetic field, where the sample is under pressure. The background associated with the sample environment should be carefully considered and limited, *e.g.* through the use of shielding and collimation.

V. KVASIR IN THE GLOBAL HIGH-RESOLUTION SPECTROSCOPY LANDSCAPE.

KVASIR will provide new capabilities in the neutron landscape with optimised flux on a small sample ($1 \times 1 \text{ cm}^2$), as well as good resolution ($\Delta E \approx 5 \text{ } \mu\text{eV}$, $\Delta Q \approx 0.03 \text{ } \text{\AA}^{-1}$), and space for both Be filter, radial collimator, large sample environments such as 15 T magnets, and PA. This combined capability does not currently exist and is only possible with the enhanced flux of the ESS.

Within ESS, KVASIR will be complementary to BIFROST and CSPEC, the cold direct geometry spectrometer of ESS. The energy resolution of KVASIR complements that of BIFROST, $\Delta E \geq 20 \text{ } \mu\text{eV}$, while for CSPEC, energy resolutions of $\Delta E \geq 10 \text{ } \mu\text{eV}$ are possible but, as discussed previously, would be greatly limited in flux. One can also compare KVASIR with MIRACLES, the backscattering instrument of ESS. While BIFROST AND CSPEC address a science case similar to KVASIR, MIRACLES is optimised for diffuse scattering from weak disordered materials with high energy resolution ($\Delta E = 2.5 \text{ } \mu\text{eV}$) and broad Q resolution, $\Delta Q = 0.2 \text{ } \text{\AA}^{-1}$. MIRACLES also cannot accommodate high field magnets. Importantly, the instruments that are focussed on disordered materials tend to have large sample areas (MIRACLES/IN16 and BASIS = $3 \times 3 \text{ cm}^2$) which would result in a high background for the mm^2 sized samples envisaged on KVASIR.

Globally, a number of high-resolution (backscattering) instruments exist, most of which are occupied with soft matter spectroscopy, partially due to their broad Q-resolution, $\Delta Q = 0.1 - 0.2 \text{ } \text{\AA}^{-1}$. One exception is DNA at J-PARC, which also has a strong soft matter community but has in recent years seen an upsurge in demand of hard matter single crystal experiments due to its excellent Q-resolution, $\Delta Q = 0.04 \text{ } \text{\AA}^{-1}$. The $14 \text{ } \mu\text{eV}$ resolution mode at DNA is very popular due to its high incoming flux. DNA is currently unable to apply a magnetic field.

For comparison with KVASIR, we have chosen DNA, a Si based backscattering instrument at J-PARC. Both instruments are located at high brightness spallation sources. Both instruments provide a flux of $\psi \approx 10^8 \text{ n/s/cm}^2$ on the sample. This can be understood from the equivalent peak brightness of the two facilities, see Fig. 7, the ratio of their instrument lengths and the width of the divergence extracted from the moderator. The instrument lengths, 160 m of KVASIR versus 40 m of DNA, provides a time pulse at equal energy resolution, that is 4 times greater for KVASIR than for DNA ($\psi_{KV}/\psi_{DNA} = 4$). However, the divergence profiles, $\eta_{KVASIR} = 0.75^\circ \times 0.75^\circ$ and $\eta_{DNA} = 1.5^\circ \times 1.5^\circ$ provides 4 times more flux to DNA ($\psi_{KV}/\psi_{DNA} = 1/4$). As a result, the two instruments have approximately equivalent flux on sample, for $1 \times 1 \text{ cm}^2$ sample areas, for equal energy resolutions.

As highlighted in Ref. [408], the power of an indirect geometry spectrometer is not only given by the incoming flux, ψ , but rather by the number of neutrons detected, $\nu = \psi AS(\Omega_a/4\pi)R\Delta\lambda$. Here, A is the area of the sample presented to the beam, S is the fraction of neutrons scattered by the sample (which depends on the sample cross section and thickness), Ω_a is the solid angle of the analyzer, R is the reflectivity of the analyzer, and $\Delta\lambda$ is the wavelength spread of neutrons scattered from the analyzer.

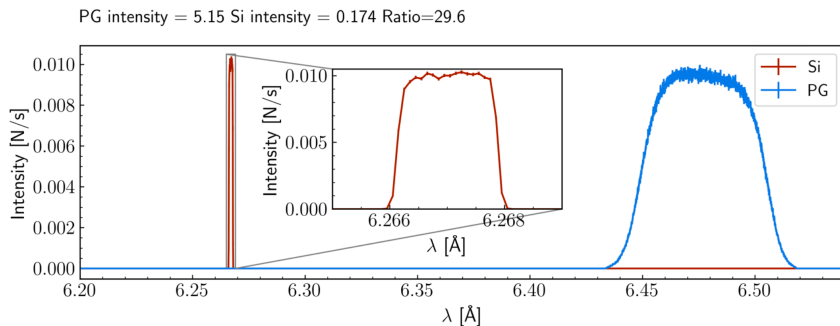


Figure 11. McStas simulation of the wavelength band extracted by neutrons reflected from PG (0 0 2) and bending Si (1 1 1), as outlined in the text, showing the increased detected flux expected on KVASIR (PG crystals) with respect to a Si based backscattering instrument.

The gains on KVASIR are derived by the broad wavelength band accepted, and scattered, by the PG crystals in comparison to the narrow acceptance of Si crystals. On KVASIR the analytically calculated wavelength band, determined earlier, is $\Delta\lambda = 0.0454 \text{ } \text{\AA}$, while the analytically calculated wavelength band for Si is $0.0015 \text{ } \text{\AA}$ due to the acceptance of bent Si analyser (considering $\Delta d/d = \mu D/r = 2.4 \times 10^{-4} \mu = 0.4 = \text{Poisson ratio of Si}$, $R = 2.5 \text{ m} = \text{radius of curvature}$ and $D = \text{thickness of Si crystals}$

$= 1.5 \text{ mm}$). Considering that the other values in the above equation are approximately equal, the number of neutrons detected in KVASIR with mosaic PG crystals is expected to be $0.0454/0.0015 = 30$ times greater than for the bent Si analysers at DNA. Of course, the high resolution mode at DNA obtained with Si analyser crystals is not available for a PG crystal instrument as KVASIR. We performed McStas simulation of Si and PG crystal components using the $\Delta d/d$ and mosaic spreads outlined previously, see Fig. 11. The resultant relative intensities in the detector (PG/Si) is indeed a factor of 30. We would expect that engineering constraints could alter this factor slightly, but in any case significant intensity gains can be made from using the FARO/SHERPA design for KVASIR.

VI. IN CONCLUSION

In conclusion, we show the feasibility of a high flux and high resolution backscattering spectrometer ($\Delta E = 5.7 \mu\text{eV}$) with excellent Q resolution ($\Delta Q = 0.03 \text{ \AA}^{-1}$) that allows ample space for complex sample environment, PA, Be filters and radial collimators. We believe that further optimisations, and the use of further collimation, would enable us to reach the technical requirement of $\Delta E = 4 \mu\text{eV}$. KVASIR will be an exceptionally powerful instrument, providing a new worldwide capability, to determine very low energy excitations in hard condensed matter and will be a great complement to the existing ESS single crystal spectroscopy suite, in particular CSPEC, T-REX, and BIFROST. In particular, the instrument will be uniquely suited for investigating quantum magnetic materials, correlated electron systems, and functional materials for which key dynamics occur in the μeV to sub-meV energy range, the spatial scale of which are very difficult to access with current instrumentation. The combination of high energy and spatial resolution and the possibility to perform experiments under strong magnetic fields or other extreme conditions will open new avenues for exploring emergent phenomena.

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APPENDIX. SUPPORT LETTERS FROM:

- Prof. Dr. Christian Pfleiderer, Technische Universität München, Germany.
- Professor Maths Karlsson, Chalmers University of Technology, Sweden.
- Associate Professor Olivier Delaire, Duke University, Germany.
- Prof. Dr. Dmytro Inosov, Technische Universität Dresden, Germany.
- Prof. Bella Lake, Helmholtz-Zentrum Berlin, Germany.
- Prof. Andre M. Strydom, University of Johannesburg, South Africa.
- Prof. Julian Oberdisse and Dr. Dalila Bounoua: Directors of the French « Federation Française de Diffusion Neutronique » (2FDN), France.
- Prof. Dr. Ellen Fogh, Technische Universität München.
- Prof. Radu Coldea, University of Oxford Physics Department. United Kingdom.
- Prof. Dr Siân Dutton, University of Cambridge, Director Winton Programme for the Physics of Sustainability.
- Prof. Frederic Bourdarot, Scientific director at Commissariat à l’Energie Atomique et aux Energies Alternatives, France.
- Prof. Henrik M. Rønnow, Head of Laboratory for Quantum Magnetism, Director of Institute of Physics – IPHYS, École Polytechnique Fédérale de Lausanne, Switzerland.
- Dr. Masato Matsuura, Comprehensive Research Organization for Science and Society (CROSS), Japan. Instrument scientist for DNA, J-PARC, Japan.
- Assoc. Prof. Yasmine Sassa, KTH Royal Institute of Technology, Sweden.
- Assoc. Prof. Martin Månsson, KTH Royal Institute of Technology, Sweden.
- Dr. Virginie Simonet, University Grenoble Alpes, L’Institut Néel, France.
- Prof. Nic Shannon, Theory of Quantum Matter Unit, Okinawa Institute of Science and Technology Graduate University, Japan.
- Dr. Stéphane Raymond, Research Director at CEA, IRIG / MEM / Laboratoire de Magnétisme et Diffraction Neutronique. University Grenoble Alpes, France.
- Associate Prof. Niels Bech Christensen, Department of Physics, Technical University of Denmark.
- Dr. Martin Boehm, Science Division, Head of the Spectroscopy Group. Institut Laue Langevin, France.
- Dr. Elsa lHotel, Institut Néel and CNRS, France.

- Prof. Tatiana Guidi, University of Camerino, Italy

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To the ESS Instrument Proposal Committee,

I am writing to express my enthusiastic support for the proposed KVASIR backscattering neutron spectrometer at the European Spallation Source (ESS). The KVASIR concept addresses a critical gap in current neutron instrumentation by providing simultaneous high resolution in both energy and momentum transfer, specifically optimized for small single-crystal samples.

The uniqueness of KVASIR lies in its ability to achieve energy resolutions on the order of a few μeV alongside a momentum resolution of approximately 0.03 \AA^{-1} . This capability is transformative for functional materials research. By enabling the precise observation of low-energy excitations within complex crystal lattices, KVASIR will allow researchers to disentangle intricate dynamic processes that are currently overlapping or inaccessible. Its design facilitates the study of subtle atomic-scale motions and long-period structural dynamics, which are fundamental to understanding the macroscopic properties of advanced materials.

My own research focuses on the dynamics of energy-related materials, specifically Li-ion conductors. In these systems, the μeV to sub-meV energy range contains crucial information regarding both the hopping mechanisms of mobile ions and the underlying lattice dynamics of the framework. KVASIR will provide the unprecedented experimental capability required to resolve these features across a wide range of momentum transfer. This high-resolution data is essential for developing a microscopic understanding of ionic diffusion pathways, which directly informs the design of next-generation solid-state batteries.

I believe KVASIR will become an indispensable tool for the international condensed matter community. I strongly urge the committee to support its construction as a flagship instrument for the ESS.

Sincerely,

Masato Matsuura

Research and Development Division, Neutron Science and Technology Center

Comprehensive Research Organization for Science and Society (CROSS), Japan

ESS Instrument Proposal Committee

Lausanne, March 24, 2026

To the ESS Instrument Proposal Committee,

I would like to express my strong support for the proposed **KVASIR** backscattering spectrometer at the European Spallation Source.

The KVASIR concept fills a clear and important niche within the ESS instrument suite. Its combination of μeV energy resolution with well-defined momentum resolution represents a capability that is presently only accessible in a very limited way worldwide, and not for small single-crystal samples under realistic experimental conditions. The targeted performance—energy resolution in the few μeV range and momentum resolution on the order of 0.03 \AA^{-1} —together with compatibility with complex sample environments, will substantially extend what can be measured in practice, rather than merely improving existing benchmarks.

From a scientific perspective, KVASIR will enable direct access to low-energy excitations that are central to a wide range of problems in condensed matter physics. This includes quantum magnets, strongly correlated electron systems, and functional materials where the relevant dynamics occur on μeV to sub-meV energy scales and over finite momentum ranges. These regimes are currently difficult to probe in a unified manner, and the ability to do so with a single instrument will open qualitatively new experimental approaches. In particular, the possibility to combine high resolution in both energy and momentum with external tuning parameters such as magnetic field, pressure, or temperature is likely to be transformative for the study of emergent phenomena.

Besides many experiments on quantum spin models, strongly correlated electron materials and unconventional superconductors, my research collaborators and I would use KVASIR to study coherent entanglement between localized spin qubits and collective excitations.

Localized rare-earth spin states—whether electronic, nuclear, or electronuclear in nature—are increasingly recognized as promising building blocks for quantum technologies, both for quantum memory and for transduction between microwave and optical domains. Rare-earth ions provide a unique platform due to their narrow optical transitions and long-lived spin degrees of freedom. More recently, the prospect of universal quantum computing based on erbium ions has been articulated, highlighting the potential of rare-earth systems as scalable quantum platforms. A key limitation, however, remains the weak coupling strength and low quantum efficiency of individual ions. This has led to growing interest in hybrid approaches where localized spin qubits are coupled to collective excitations—such as magnons or electronuclear spin waves—which can act as coherent mediators and amplifiers. In systems with strong hyperfine interactions, this gives rise to entangled electron–nuclear spin excitations with characteristic energies in the μeV (GHz) range. A detailed understanding of these collective electronuclear modes, including their dispersion, coherence, and response to external microwave or optical driving, is currently limited by experimental constraints. KVASIR, with its combination of μeV energy resolution and finite momentum resolution, will provide precisely the capability needed to map these excitations in reciprocal space and to establish their role in quantum-coherent phenomena.

In this sense, KVASIR is not only a natural addition to the ESS instrument portfolio, but a necessary one. It will provide access to a regime of energy and length scales that is central to many contemporary research directions, and which is presently underexplored due to instrumental constraints.

I therefore strongly support the realization of KVASIR and am convinced that it will become a key instrument for the international user community.

Do not hesitate to contact me should any further information be desired.



Prof. Henrik M. Rønnow
Head of Laboratory for Quantum Magnetism
Director of Institute of Physics – IPHYS
École Polytechnique Fédérale de Lausanne

To the ESS Instrument Proposal Committee,

I, Frederic Bourdarot, scientific director at Commissariat à l'Energie Atomique et aux Energies Alternatives and scientific manager of IN22, thermal triple-axis at ILL, am writing to express my strong support for the proposed KVASIR backscattering neutron spectrometer for the European Spallation Source (ESS).

The KVASIR concept will bring a new instrumental element to the study of low- and medium-energy transfer excitations with high q and energy resolution, making it particularly unique. As described in the instrument concept paper, KVASIR aims to study small single crystals with energy resolutions on the order of a few μeV together with a momentum resolution of approximately 0.03 \AA^{-1} , while maintaining the flexibility to accommodate demanding sample environments. These capabilities will enable unprecedented studies of low-lying excitations in single hard condensed matter systems.

In particular, the instrument will be uniquely suited for investigating quantum magnetic materials, correlated electron systems, and functional materials for which key dynamics occur in the μeV to sub-meV energy range, the spatial scale of which are very difficult to access with current instrumentation. The combination of high energy and spatial resolution and the possibility to perform experiments under strong magnetic fields or other extreme conditions will open new avenues for exploring emergent quantum phenomena.

From the perspective of my scientific interest in the study of unconventional superconductivity, strongly correlated electron systems or magnon-phonon coupling in thermoelectric compounds, KVASIR would provide exactly the type of experimental capability required to address these challenges at ESS.

I therefore strongly support the development of the KVASIR instrument and believe it will become an essential tool for the international condensed matter physics community.

Sincerely,

A handwritten signature in black ink, appearing to be 'FB', written over a horizontal line.

Grenoble, March 27th, 2026

To the ESS Instrument Proposal Committee,

Support to the KVASIR instrument project

I am writing to express my strong support for the proposed KVASIR backscattering neutron spectrometer for the European Spallation Source (ESS).

The KVASIR concept addresses an important gap in the current instrumentation landscape by providing simultaneous high resolution in both energy and momentum transfer. As described in the instrument concept paper, KVASIR aims to study small single crystals with energy resolutions on the order of a few μeV together with a momentum resolution of approximately 0.03 \AA^{-1} , while maintaining the flexibility to accommodate demanding sample environments. These capabilities will enable unprecedented studies of low-lying excitations in single hard condensed matter systems.

In particular, the instrument will be uniquely suited for investigating quantum magnetic materials, correlated electron systems, and functional materials for which key dynamics occur in the μeV to sub-meV energy range, the spatial scale of which are very difficult to access with current instrumentation. The combination of high energy and spatial resolution and the possibility to perform experiments under strong magnetic fields or other extreme conditions, also including the possible use of polarized neutrons, will open new avenues for exploring emergent quantum phenomena.

From the perspective of my scientific interests, I am studying magnetic materials, in the fields of quantum magnetism, multiferroism, frustrated magnetism, topological matter. In these materials, the understanding of their unique properties is elucidated in particular through their peculiar excitations (standard magnons but also fractional excitations such as spinons or magnetic monopoles). Those often appear in the low energy range and their measurements using inelastic neutron scattering and their analysis as a function of wavevector and energy is a fundamental step to identify the ingredients at the origin of quantum matter peculiar properties.

KVASIR would provide exactly the type of experimental capability required to address these challenges at ESS.

I therefore strongly support the development of the KVASIR instrument and believe it will become an essential tool for the international condensed matter physics community.

Sincerely,

Virginie SIMONET





Prof. Tatiana Guidi

Physics Division,
School of Science and Technology,
University of Camerino,
Camerino (MC) I-62032, Italy
Direct line: +39 0737402509
Email: tatiana.guidi@unicam.it

To the ESS Instrument Proposal Committee,

I am writing to express my strong support for the proposed KVASIR backscattering neutron spectrometer for the European Spallation Source (ESS).

The KVASIR concept addresses an important gap in the current instrumentation landscape by providing simultaneous high resolution in both energy and momentum transfer. As described in the instrument concept paper, KVASIR aims to study small single crystals with energy resolutions on the order of a few μeV together with a momentum resolution of approximately 0.03 \AA^{-1} , while maintaining the flexibility to accommodate demanding sample environments. These capabilities will enable unprecedented studies of low-lying excitations in single hard condensed matter systems.

In particular, the instrument will be uniquely suited for investigating quantum magnetic materials, correlated electron systems, and functional materials for which key dynamics occur in the μeV to sub-meV energy range, the spatial scale of which are very difficult to access with current instrumentation. The combination of high energy and spatial resolution and the possibility to perform experiments under strong magnetic fields or other extreme conditions will open new avenues for exploring emergent quantum phenomena.

From the perspective of my research on spin excitations in molecular magnets, KVASIR provides the ideal energy range and resolution to investigate the low-lying, non-dispersive excitations typical of transition-metal clusters. The instrument's broad Q-range will allow for a detailed mapping of the Q-dependence of well-resolved spin excitations, providing a unique 'fingerprint' of the spin Hamiltonian wavefunctions. Furthermore, the availability of high magnetic fields will enable to drive the system into coherent superpositions or entangled states, allowing for a precise study of their evolution. This combination of high field and high resolution offers a new exciting opportunity for our community. Furthermore, the synthesis of large single crystals of molecular magnets is generally a challenge and often in experiments the resolution has been sacrificed for flux. KVASIR would provide exactly the type of experimental capability required to address these challenges at ESS.

I therefore strongly support the development of the KVASIR instrument and believe it will become an essential tool for the international condensed matter physics community.

Sincerely,

Prof. Tatiana Guidi

School of Science and Technology,
University of Camerino

Dr. Martin Boehm
Institut Laue-Langevin
Science Division/ Head of the Spectroscopy Group
boehm@ill.fr
+33 4 76 20 71 10

27 March 2026 in Grenoble, France

Subject: Letter of support for the ESS instrument project Kvasir

To the ESS Instrument Proposal Committee,

I am writing to express my strong support for the proposed KVASIR backscattering neutron spectrometer for the European Spallation Source (ESS).

The KVASIR concept addresses an important gap in the current instrumentation landscape by providing simultaneous high resolution in both energy and momentum transfer. As described in the instrument concept paper, KVASIR aims to study small single crystals with energy resolutions on the order of a few μeV together with a momentum resolution of approximately 0.03 \AA^{-1} , while maintaining the flexibility to accommodate demanding sample environments. These capabilities will enable unprecedented studies of low-lying excitations in single-crystal systems.

In particular, single-crystal neutron spectroscopy combining very high energy resolution with medium momentum resolution is expected to have a strong impact in the study of quantum and functional materials. This includes systems such as magnetic skyrmions, where collective excitations occur at very low energies, as well as investigations of magnetic anisotropies, softening of excitation spectra, and other subtle features of emergent behavior. Access to this regime is essential for understanding the microscopic dynamics governing these systems.

I strongly support the KVASIR project and believe it will become a key instrument for the international neutron scattering community.

Yours sincerely

Martin Boehm



Dr Siân Dutton

*Professor in Physics and Solid State Chemistry,
Director Winton Programme for the Physics of Sustainability
Department of Physics*

13 March 2026

Letter in support of KVASIR Instrument ESS Instrument Proposal Committee

To the ESS Instrument Proposal Committee,

I am writing to express my strong support for the proposed KVASIR backscattering neutron spectrometer for the European Spallation Source (ESS).

The KVASIR concept addresses an important gap in the current instrumentation landscape by providing simultaneous high resolution in both energy and momentum transfer. As described in the instrument concept paper, KVASIR aims to study small single crystals with energy resolutions on the order of a few μeV together with a momentum resolution of approximately 0.03 \AA^{-1} , while maintaining the flexibility to accommodate demanding sample environments. These capabilities will enable unprecedented studies of low-lying excitations in single hard condensed matter systems.

In particular, the instrument will be uniquely suited for investigating quantum magnetic materials, correlated electron systems, and functional materials for which key dynamics occur in the μeV to sub-meV energy range, the spatial scale of which are very difficult to access with current instrumentation. The combination of high energy and spatial resolution and the possibility to perform experiments under strong magnetic fields or other extreme conditions will open new avenues for exploring emergent quantum phenomena.

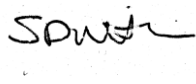
From the perspective of my scientific interest the concept is very exciting and would greatly expand the range of materials that can be studied. My own work focuses primarily on the study of polycrystalline powders since preparation of large crystals suitable for neutron studies is challenging and time consuming. The KVASIR concept with the ability to measure small samples will allow us to explore in more detail multiple systems. Coupling this with high magnetic fields opens opportunities for our work on magnetocaloric as we would be able to directly observe the changes in magnetism which give rise to the magnetocaloric effect allowing for a more detailed understanding of the phenomena. The possibility of measurements under pressure or in-situ electrochemical

measurements are also of interest for ongoing projects on magnetoelectric coupling and next generation battery cathodes.

KVASIR would provide exactly the type of experimental capability required to address these challenges at ESS.

I therefore strongly support the development of the KVASIR instrument and believe it will become an essential tool for the international condensed matter physics community.

Sincerely,



Siân Dutton



Professor Radu Coldea
Clarendon Laboratory
University of Oxford Physics Department
Parks Road
Oxford
OX1 3PU
United Kingdom

Tel: + 44 1865 272335
Fax: + 44 1865 282208
E-mail: radu.coldea@physics.ox.ac.uk
<https://www.physics.ox.ac.uk/our-people/coldear>

26 March 2026

To the ESS Instrument Proposal Committee,

I am writing to express my strong support for the proposed KVASIR backscattering neutron spectrometer for the European Spallation Source (ESS).

The KVASIR concept addresses an important gap in the current instrumentation landscape by providing simultaneous high resolution in both energy and momentum transfer. As described in the instrument concept paper, KVASIR aims to study small single crystal samples with energy resolutions on the order of a few μeV together with a momentum resolution of approximately 0.03 \AA^{-1} , while maintaining the flexibility to accommodate demanding sample environments. These capabilities will enable unprecedented studies of low-energy excitations of single crystals of hard condensed matter systems.

In particular, the instrument will be uniquely suited for investigating quantum magnetic materials, correlated electron systems, and functional materials for which key dynamics occur in the μeV to sub-meV energy range, the spatial scale of which are very difficult to access with current instrumentation. The combination of high energy and spatial resolution and the possibility to perform experiments under strong magnetic fields or other extreme conditions will open new avenues for exploring emergent quantum phenomena.

Over the years I have extensively used time-of-flight cold neutron spectroscopy for research projects in quantum magnetism, including the first experimental realization in the laboratory of quantum criticality in an Ising chain in transverse field and observation of its universal E8 spectrum near criticality, development of a generic method combining neutron spectroscopy and high magnetic fields to quantitatively determine spin Hamiltonians -- now widely used in the quantum magnetism community, studies of spinon excitations and bound state formation in quantum magnets, studies of spin-orbital quantum criticality, order-by-disorder induced by spin-orbital fluctuations and the experimental manifestation of topological magnetic quasiparticles.

I am particularly excited by the prospect of the KVASIR spectrometer being able to explore the spectrum of small single crystals with really fantastic resolution in both momentum and energy and in the presence of extreme sample environments, requirements which have been a major limiting factor in my selection of scientific projects that I have developed in my career so far. Many projects that I had deemed very promising scientifically in quantum criticality and frustrated quantum magnetism I had to in the end not pursue due to a combination of 1) the momentum and/or energy resolution of available spectrometers was not sufficient to permit access to the region of interest, 2) it was technically not feasible to obtain large enough single crystals to get a strong enough signal with current instruments to allow a detailed quantitative study (all our quantitative studies so far have required single crystal samples of more than 5 grams, which is a very tall order !), 3) accessing high resolution conditions and extreme sample environment has not been feasible. From this perspective KVASIR would provide exactly the type of experimental capability required to fill this gap and address these challenges at ESS.

Therefore, I strongly support the development of the KVASIR instrument and believe it will become an essential tool for the international condensed matter physics community and I look forward to be among the first users of this exciting new instrument at the ESS.

Sincerely,

A handwritten signature in blue ink that reads "Radu Coldea". The signature is written in a cursive style with a blue background behind the text.

Radu Coldea
Professor of Physics
Fellow of the American Physical Society

Morges, 23rd of March 2026

Dear Evaluation Committee,

I am excited about the neutron backscattering spectrometer, KVASIR, proposed for the next round of instruments at the ESS.

This instrument provides not only excellent energy resolution but also very high resolution in Q , a combination which is currently not offered at the ESS. This comes together with an optimized signal-to-noise ratio and the flexibility to employ different kinds of sample environments such as pressure cells, magnets and dilution refrigerators.

KVASIR is therefore a very interesting concept in my line of research, in particular with respect to high-pressure and high-magnetic-field studies of quantum spin-liquid candidate materials. They typically display complex magnetic excitation spectra at very low energy transfers. This together with their weak magnetic moments and disordered nature calls for high energy and Q resolutions as well as low background. To control their magnetic ground state and to compare with model predictions, extreme conditions of low temperatures, high pressures and high magnetic fields are needed. All of this is provided by KVASIR.

For these reasons, I believe that KVASIR will be a gamechanger in the field of quantum magnetism and I truly hope to see this instrument built at the ESS.

Yours sincerely,



Prof. Dr. Ellen Fogh

Chair of Quantum Magnetism
Center for QuantumEngineering
Department of Physics
School of Natural Sciences
Technical University of Munich

LHOTEL Elsa

Institut Néel / CNRS

25 av. des Martyrs

38042 GRENOBLE Cedex 9

FRANCE

+33-4.76.88.12.63

elsa.lhotel@neel.cnrs.fr

Grenoble, FRANCE

March 27, 2026

To the ESS Instrument Proposal Committee

Subject: LETTER OF SUPPORT for the KVASIR backscattering neutron spectrometer

I am writing to express my strong support for the proposed KVASIR backscattering neutron spectrometer for the European Spallation Source (ESS).

The KVASIR concept addresses an important gap in the current instrumentation landscape by providing simultaneous high resolution in both energy and momentum transfer. As described in the instrument concept paper, KVASIR aims to study small single crystals with energy resolutions on the order of a few μeV together with a momentum resolution of approximately 0.03 \AA^{-1} , while maintaining the flexibility to accommodate demanding sample environments. These capabilities will enable unprecedented studies of low-lying excitations in single hard condensed matter systems.

In particular, the instrument will be uniquely suited for investigating quantum magnetic materials, correlated electron systems, and functional materials for which key dynamics occur in the μeV to sub-meV energy range, the spatial scale of which are very difficult to access with current instrumentation. The combination of high energy and spatial resolution and the possibility to perform experiments under strong magnetic fields or other extreme conditions will open new avenues for exploring emergent quantum phenomena.

This is especially true from the perspective of my scientific interest in quantum frustrated magnetism, where we are looking for emergent excitations in quantum spin liquids which are characterized by very low energy and can be observed only at very low temperatures, a prominent example being the emergent photon on quantum spin ice. A very high resolution is thus crucial to detect these excitations, and validate the quantum condensed matter theories that predict them. KVASIR would provide exactly the type of experimental capability required to address these challenges at ESS.

I therefore strongly support the development of the KVASIR instrument and believe it will become an essential tool for the international condensed matter physics community.

Yours sincerely,

A handwritten signature in black ink, appearing to read 'E. Lhotel', written over a horizontal line.

Elsa LHOTEL

To the European Spallation Source Instrument Proposal Committee:

The French Federation for Neutron Scattering (2FDN) strongly supports the proposed KVASIR backscattering neutron spectrometer as a new instrument for the user community within the upcoming ESS instrument suite.

Owing to its innovative concept, KVASIR is expected to hold a leading position at the international level and play a pivotal role in advancing investigations of hard condensed matter and inorganic chemistry. Indeed, KVASIR addresses a critical gap in the current instrumentation landscape by delivering simultaneously excellent resolution in both energy and momentum transfer, surpassing current state-of-the-art capabilities.


As described in the instrument concept paper, KVASIR aims to study millimeter-sized single crystals with high energy resolution on the order of a few μeV , combined with a momentum resolution of approximately 0.03 \AA^{-1} . This unique combination represents a major breakthrough in neutron spectroscopy. At the same time, the instrument will maintain the flexibility to accommodate extreme sample environments such as high magnetic fields, high pressure, dilution fridges, and will offer prospects for polarization analysis. These capabilities will enable unprecedented studies of low-lying excitations in hard condensed matter systems, while also allowing investigations of higher energy transfers with resolutions on the order of tens of μeV .

KVASIR will be uniquely suited for investigating quantum magnetic materials, correlated electron systems, energy and functional materials for which key dynamics occur in the μeV to sub-meV energy range while offering high Q-resolution, a dynamic range which remains largely unexplored due to technical challenges with current instrumentation. The combination of high energy and spatial resolution, and the possibility to perform experiments under external perturbations, such as strong magnetic fields or other extreme conditions will open new avenues for exploring emergent quantum phenomena.

The research conducted by the French hard matter neutron community covers a wide range of scientific cases that fall into the scope of the capabilities offered by KVASIR. The scientific cases include: low-dimensional magnets, quantum spin liquids, frustrated magnets, altermagnetism, high temperature superconductivity, topological materials, molecular magnets, skyrmionics lattices and other topological textures, multiferroics and a variety of functional materials such as magnetocalorics, and magnetic heat conductors. In many of these examples, magnetic anisotropies, dipolar interactions, exotic magnetic states involving higher order multipoles, peculiar symmetry properties, or doping induce low-energy features such as slow dynamics, sub-meV magnetic excitations (pseudo)gaps, as well as magnon splittings that require pushing the limits of existing instruments. KVASIR will overcome these limitations, enabling detailed exploration of the μeV to sub-meV energy range across a wide Q-range, providing a more complete description of the magnetic spectrum and subtle interactions and their evolutions under external perturbations, which will likely lead to the discovery of new phenomena that have so far remained hidden due to experimental constraints.

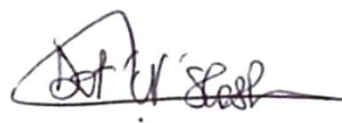
For all these reasons, the 2FDN thus strongly supports the implementation of KVASIR in the upcoming ESS instrumental suite.

Sincerely yours,



Julian Oberdisse

Directors of the French « Fédération Française de Diffusion Neutronique » (2FDN)



Dalila Bounoua

To the ESS Instrument Proposal Committee,

I am writing to express my strong support for the proposed KVASIR backscattering neutron spectrometer for the European Spallation Source (ESS).

The KVASIR concept addresses an important gap in the current instrumentation landscape by providing simultaneous high resolution in both energy and momentum transfer. As described in the instrument concept paper, KVASIR aims to study small single crystals with energy resolutions on the order of a few μeV together with a momentum resolution of approximately 0.03 \AA^{-1} , while maintaining the flexibility to accommodate demanding sample environments. These capabilities will enable unprecedented studies of low-lying excitations in single hard condensed matter systems.

In particular, the instrument will be uniquely suited for investigating quantum magnetic materials, correlated electron systems, and functional materials for which key dynamics occur in the μeV to sub-meV energy range, the spatial scale of which are very difficult to access with current instrumentation. The combination of high energy and spatial resolution and the possibility to perform experiments under strong magnetic fields or other extreme conditions will open new avenues for exploring emergent quantum phenomena.

From the perspective of my scientific interest there are several design aspects of the proposed instrument that would make this an extremely useful avenue for providing a unique view into the physics of strongly correlated electron systems. The simultaneous high resolutions in energy and momentum transfer will, -in my experience, place this instrument in a league of its own. The capability to study small single crystals is going to make this an attractive instrument in a field where limited physical dimensions and tiny single-crystal sample material is all too often a fact of life in the synthesis and procurement of research samples. Further, the targeted very low-energy dynamic range is going to be an extremely valuable attribute in the study of quantum criticality which has been a subject at the bleeding edge of condensed matter physics, and is sure to remain so for the foreseeable future. I envisage that the proposed KVASIR is going to be an instrument that sets the pace at the ESS and as a leading example for neutron facilities other than the ESS as well, for research into phenomena at and near equilibrium of phase formation and transition.

KVASIR at ESS would provide precisely the design of experimental capability required to address many of the experimental challenges posed by my field of research.

I therefore strongly support the development of the KVASIR instrument and believe it will become an essential tool for the international condensed matter physics community.

Sincerely,



André M. Strydom.
Professor of Physics, University of Johannesburg, South Africa.
March 25, 2026.



OKINAWA INSTITUTE
OF SCIENCE AND TECHNOLOGY
GRADUATE UNIVERSITY

Prof. Nic Shannon
Theory of Quantum Matter Unit, OIST
1919-1 Tancha, Onna-son,
Okinawa, 904-0495 Japan
Phone. +81-98-966-8711
<https://groups.oist.jp/tqm>
nic.shannon@oist.jp

27th March 2026

To the ESS Instrument Proposal Committee,

Proposal to build KVASIR backscattering neutron spectrometer at ESS

I am writing to express my strong support for for the proposal to build the KVASIR backscattering neutron spectrometer at ESS.

Much of the most exciting science of our times revolves around the attempt to characterize and manipulate quantum states. Quantum processors have now reached the point where it is possible to contemplate entangling hundreds of qubits. In quantum magnets, at comparable temperatures, billions of spins may be entangled, making them a precious resource as we seek to learn how to build a quantum computer.

Inelastic neutron scattering remains the tool of choice for unlocking the secrets of the entanglement found in quantum magnets. And in recent years, back-scattering spectrometers, capable of characterizing spin dynamics at low energies, have played a crucial role in rolling back this frontier. The many successes of this approach include the first hints of the emergent photons of quantum spin ice, and the ability to resolve the ω/T scaling associated with quantum criticality.

The proposed KVASIR backscattering neutron spectrometer would be an invaluable addition to the instruments already available, extending capabilities in momentum resolution and sample environment. It also speaks to the particular strengths of ESS, since high neutron flux makes it practical to use polarization analysis on a routine basis, to separate quantum signal from incoherent, classical noise. The ability to study samples in applied magnetic field also enhances the value of the instrument, since this makes it possible to tune between different quantum phases, and through quantum critical points.

For all of these reasons, KVASIR could be a game-changing instrument, and it would be exciting to see it built at ESS. Please feel free to contact me if you wish to discuss the related science further.

sincerely,

nic shannon

**European Spallation
Source Instrument
Proposal Committee**

Prof Bella Lake
**Quantum Phenomena in Novel
Materials QM-IQM**
Hahn-Meitner-Platz 1
14109 Berlin
Germany
Tel +49 (0)30 8062-42058
Bella.lake@helmholtz-berlin.de

Berlin 19th March 2026

Letter of support for the KVASIR backscattering neutron spectrometer

To the ESS Instrument Proposal Committee,

Please accept this letter of support for the KVASIR backscattering neutron spectrometer proposed for the European Spallation Source. KVASIR is an exceptional instrument in that it is able to simultaneously provide both ultra high energy resolution (3-6 μeV) and a good wavevector resolution (0.03 \AA^{-1}) achieving a truly unique capability and thus occupying a currently unfilled niche within the suite of neutron instruments. It is ideally matched to the study of low energy excitations in single crystal samples. At the same time the sample space has been designed to accommodate complex and bulky sample environments providing the possibility to explore multi-dimensional phase diagrams.

From the perspective of my scientific interest which is quantum magnetism, I am very excited by KVASIR. Quantum magnets typically have low energy scales requiring high energy resolution and milliKelvin temperatures (dilution refrigerator) while their spectra form complex and distinctive patterns as a function of wavevector requiring good wavevector resolution. Furthermore, the states of quantum magnets can be manipulated by magnetic field and pressure thus combinations of sample environments are needed. KVASIR would provide exactly the type of experimental capability required to address these challenges.

I strongly support the development of the KVASIR instrument and believe it will become an essential tool for the international condensed matter physics community.

Sincerely,



Bella Lake

To the ESS Instrument Proposal Committee,

I am writing to express my strong support for the proposed KVASIR backscattering neutron spectrometer for the European Spallation Source (ESS).

The KVASIR concept addresses an important gap in the current instrumentation landscape by providing simultaneous high resolution in both energy and momentum transfer. As described in the instrument concept paper, KVASIR aims to study small single crystals with energy resolutions on the order of a few μeV together with a momentum resolution of approximately 0.03 \AA^{-1} , while maintaining the flexibility to accommodate demanding sample environments. These capabilities will enable unprecedented studies of low-lying excitations in single hard condensed matter systems.

In particular, the instrument will be uniquely suited for investigating quantum magnetic materials, correlated electron systems, and functional materials for which key dynamics occur in the μeV to sub-meV energy range, the spatial scale of which are very difficult to access with current instrumentation. The combination of high energy and spatial resolution and the possibility to perform experiments under strong magnetic fields or other extreme conditions will open new avenues for exploring emergent quantum phenomena.

From the perspective of my scientific interest, i.e. studies of local structure and dynamics in functional – mostly energy relevant materials, such as solid-state ionic conductors, KVASIR will, for example, allow for studies of low-energy dynamics, such as overdamped and anharmonic vibrational dynamics and its relationship to even-lower-energy dynamics such as ion diffusion. Crucially, KVASIR will be designed for studies of single crystal samples, for which there is a lack of neutron scattering studies (and understanding) of solid-state ionic conductors. Hence, KVASIR shows to potential to advance the field of these types of technologically important materials, and I therefore support this application strongly.

Sincerely,

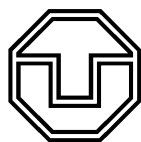
Maths Karlsson, Professor
Department of Chemistry and Chemical Engineering
Chalmers University of Technology
Göteborg, Sweden

Maths Karlsson

2026-03-25



Department of Chemistry and Chemical Engineering
Division Energy and Materials
412 96 Gothenburg



Fakultät Physik

Institut für Festkörper- und Materialphysik, Professur für Neutronenspektroskopie kondensierter Materie

Technische Universität Dresden, 01062 Dresden

Prof. Dr. rer. nat.

To the
ESS Instrument Proposal Committee

Dmytro Inosov

Telefon: +49 (351) 463-34731

Telefax: +49 (351) 463-37734

E-mail: dmytro.inosov@tu-dresden.de

Dresden, 16th March 2026

Letter of support for the ESS instrument concept KVASIR

I am writing to express my strongest support for the proposed KVASIR backscattering neutron spectrometer for the European Spallation Source (ESS). The KVASIR concept addresses an important gap in the current instrumentation landscape by simultaneously providing high resolution in both energy and momentum transfer. As described in the instrument concept paper, KVASIR aims to study small single crystals with energy resolutions on the order of $5 \mu\text{eV}$ together with a momentum resolution of approximately 0.03 \AA^{-1} , while maintaining the flexibility to accommodate demanding sample environments. These capabilities will enable unprecedented studies of low-lying excitations in single crystals. In particular, the instrument will be uniquely suited for investigating quantum magnetic materials, correlated electron systems, and functional materials for which key dynamics occur in the μeV to sub-meV energy range, the spatial scale of which are very difficult to access with current instrumentation. The combination of high energy and spatial resolution and the possibility to perform experiments under strong magnetic fields or other extreme conditions will open new avenues for exploring emergent quantum phenomena.

From the perspective of my scientific interests, this instrument would enable us to measure very small anisotropy gaps in magnetic materials close to the Heisenberg limit, as well as help resolve helimagnon bands in systems with chiral order or multi- \mathbf{q} textures such as skyrmion lattices. Up to now, our attempts to resolve these excitations using existing backscattering instruments such as IN16B at ILL proved unfeasible because of insufficient momentum resolution. Furthermore, this instrument would allow us to measure very small (a few μeV) splittings of localized excitations, such as crystal electric field lines, and thereby directly evidence minute structural distortions or hidden order parameters that may lead to slightly nonequivalent environment of the magnetic ions [see, for example, T. Han *et al.*, arXiv:2511.07606]. Furthermore, research in the current hot topic of altermagnetism with neutron spec-

Postadresse (Briefe)

Technische Universität Dresden
01062 Dresden

Postadresse (Pakete u.ä.)

Technische Universität Dresden
Institut für Festkörper-
und Materialphysik
Helmholtzstraße 10
01069 Dresden

Besucheradresse

Sekretariat:
Recknagel-Bau
Häckelstraße 3
Zimmer D206

Internet

www.tu-dresden.de/physik/ifmp
[www.tu-dresden.de/mn/physik/
ifmp/ifp_neutron](http://www.tu-dresden.de/mn/physik/ifmp/ifp_neutron)

troscopy heavily relies on the observation of a small “chiral” splitting of magnon bands, resolving which at low energies should also be facilitated by an instrument such as KVASIR. Last but not least, KVASIR in combination with a dilution refrigerator should enable access to spin-wave dispersions in very weakly interacting materials such as Tutton salts, which order at subkelvin temperatures and possess sub-meV magnon band widths. Measurements of their dispersions are not feasible with existing instruments, yet probing spin-wave excitations in such systems would enable us to quantitatively estimate weak super-super-exchange interactions that act between magnetic ions via long superexchange paths and over long distances, possibly revealing new physics. An improvement of energy resolution is also strongly desirable for studies of quantum-critical phenomena. Dilution refrigerators routinely available as sample environment for neutron scattering can cool samples down to ~ 20 mK, which corresponds to $1.7 \mu\text{eV}$ in energy units, yet none of the existing spectrometers can match this energy in terms of the resolution in energy transfer without sacrificing resolution in momentum space. KVASIR would essentially close this gap and thereby provide exactly the type of experimental capability required to address all of the mentioned challenges at ESS.

I therefore strongly support the development of the KVASIR instrument and believe it will become an essential tool for the international condensed matter physics community.

Sincerely,



Prof. Dr. Dmytro Inosov.

Postadresse (Briefe)

Technische Universität Dresden
01062 Dresden

Postadresse (Pakete u.ä.)

Technische Universität Dresden
Institut für Festkörper-
und Materialphysik
Helmholtzstraße 10
01069 Dresden

Besucheradresse

Sekretariat:
Recknagel-Bau
Häckelstraße 3
Zimmer D206

Internet

www.tu-dresden.de/physik/ifmp
[www.tu-dresden.de/mn/physik/
ifmp/ifp_neutron](http://www.tu-dresden.de/mn/physik/ifmp/ifp_neutron)



MODÉLISATION,
EXPLORATION DES MATÉRIAUX



Direction de la Recherche Fondamentale

IRIG / MEM / Laboratoire de Magnétisme et Diffraction Neutronique



Dr. Stéphane Raymond, research director at CEA

Grenoble, March 27th 2026

Support letter for the backscattering instrument KVASIR at ESS

I am expressing my strong support for the KVASIR backscattering neutron spectrometer project at the European Spallation Source. The instrument will cover a wide range of energies and momentum transfers with very good energy resolution. This new combination of experimental conditions, together with the high flux of ESS will allow new routes for single crystal investigations of quantum and functional materials and especially for small samples of new materials.

In the field of study of $4f$ and $5f$ correlated electron systems (“heavy fermions” compounds), where the characteristic energy scale is inversely proportional to the correlations strength, the access to lower energies and resolution than the usually investigated ones by more than an order of magnitude could lead to significant new developments. For quantum critical systems, increasing the investigated dynamical range will allow to test scaling hypothesis in new regimes, and more generally to address changes of the spin dynamics at different cross-overs in the quantum critical phase diagram. In unconventional superconductors, it will allow to study the resonance (feedback of the superconductivity on the magnetic excitation spectrum) in systems with much lower superconducting transition temperatures (around 300 mK versus 600 mK nowadays) with promising systems (e.g. non-centrosymmetric cerium-based superconductors).

IRIG, CEA-Université Grenoble Alpes, MEM, Laboratoire Magnétisme et Diffraction Neutronique
Centre CEA de Grenoble - 17, rue des Martyrs - 38054 Grenoble Cedex 9 France



MODÉLISATION,
EXPLORATION DES MATÉRIAUX



Direction de la Recherche Fondamentale

IRIG / MEM / Laboratoire de Magnétisme et Diffraction Neutronique



Access to high magnetic field and high pressure will allow to tune the competition/collaboration between magnetism and superconductivity in such f -electron systems that are very responsive to field of about 10 T and pressure of about 1 GPa, thanks to their low energy scales of a few Kelvin at most. Of particular interest are the fascinating uranium-based triplet superconductors, where superconductivity is enhanced under magnetic field.

More generally, the KVASIR instrument will be essential for the community working on quantum materials where fundamental physics meet recent applications in quantum computing and spintronics. In this emerging ecosystem of quantum sciences and technology, neutron scattering should have a key role for addressing the microscopic mechanisms at play in quantum materials through innovative instruments like KVASIR.

Stéphane Raymond

IRIG, CEA-Université Grenoble Alpes, MEM, Laboratoire Magnétisme et Diffraction Neutronique
Centre CEA de Grenoble - 17, rue des Martyrs - 38054 Grenoble Cedex 9 France

March 20th, 2026

To the ESS Instrument Proposal Committee,

I am writing to express my strong support for the proposed KVASIR backscattering neutron spectrometer for the European Spallation Source (ESS). I am Associate Professor in Mechanical Engineering and Materials Science at Duke University, with secondary appointments in Physics and Chemistry. My research group at Duke University investigates the microscopic structure and dynamics of condensed matter and energy materials, using an array of experimental characterization methods (neutron and x-ray scattering), combined with large-scale first-principles computer simulations. Using these techniques, we investigate microscopic degrees of freedom in solids, and rationalize their roles in both nanoscale and macroscale material properties, ranging from quantum & classical thermodynamics and nanoscale thermal transport, to functional properties (neuromorphic computing, optoelectronics and spintronics, thermoelectrics, solid-state batteries).

The KVASIR concept addresses an important gap in the current instrumentation landscape by providing simultaneous high resolution in both energy and momentum transfer. This is critical to enable our studies to reach a deeper understanding of structural fluctuations and correlated dynamics of ions, crystal lattice and spins in a wide range of material. As described in the instrument concept paper, KVASIR will unlock studies of small single crystals with energy resolutions on the order of a few μeV together with a momentum resolution of approximately 0.03 \AA^{-1} , while maintaining the flexibility to accommodate demanding sample environments. Such capabilities for much smaller sample sizes than is currently practical to study with neutrons will be transformative for our field. The KVASIR instrument will be uniquely suited for investigating a host of cutting-edge materials with applications ranging from neuromorphic computing to solid-state batteries, optoelectronics and spintronics. For instance, in our investigations of cooperative diffusion solid-state batteries and iontronics, dynamical fluctuations modulating electron-phonon coupling in halide perovskites, and correlated dynamics of electrons, ions and spins across metal-insulator transitions, the relevant phenomena critically involve correlated dynamics and structural fluctuations that occur in the μeV to sub-meV energy range, across reciprocal space. We are currently partially blind to the critical spatial and temporal scales of relevance, having to resort to an inefficient and clumsy combination of techniques (backscattering spectroscopy, cold time-of-flight direct spectrometry, neutron-resonant spin-echo on triple-axis, and diffuse neutron/x-ray scattering), but struggling to pull together a cohesive microscopic picture. The combination, in a single instrument, of high energy and spatial resolution and the possibility to perform experiments under a wide range of external fields, stimuli and extreme conditions will open the floodgates to unravel the microscopic mechanisms enabling materials for transformative future technologies.

KVASIR would provide exactly the type of experimental capability required to address these challenges at ESS. I therefore strongly support the development of the KVASIR instrument and believe it will become an essential tool for the international condensed matter physics community.

Sincerely,



Olivier Delaire

Associate Professor, Thomas Lord Department of Mechanical Engineering and Materials Science,
Department of Physics and Department of Chemistry
Duke University
Email: olivier.delaire@duke.edu



27th March 2026

Re: **Letter of support for KVASIR**

To the ESS Instrument Proposal Committee,

I am writing to lend my strong support to the KVASIR instrument proposal for the second round of instruments at the European Spallation Source.

KVASIR combines excellent energy resolution with good **Q**-resolution, making it ideally suited for studying the excitations of quantum magnets and other quantum materials. Furthermore, its high count-rate (thanks to its efficient secondary spectrometer design), means that it should allow measurements on very small single crystals; this is especially important given the difficulty of growing crystals of many of these materials. One example of a material from my own research that would benefit from KVASIR is the one-dimensional frustrated magnet $\text{KTi}(\text{SO}_4)_2(\text{H}_2\text{O})$ (KTi). KTi has been proposed to be the potential host of a spontaneously dimerized state predicted by Haldane (Nobel Prize 2016) in 1982 but never before confirmed experimentally. This state is associated with the opening of a small gap in the spin excitation spectrum at low temperatures that should be observable by inelastic neutron scattering. On the other hand, KTi is metastable, and therefore difficult to synthesize in quantities sufficient for these experiments; doing so required over a year of synthesis effort, and the experiment could only be carried by combining hundreds of unaligned crystals, entailing a significant loss of information. With KVASIR, measurements on the small single crystals of KTi would be possible, and the full details of the excitation spectrum could be resolved for the first time.

Beyond its applications in quantum matter, KVASIR also shows great potential for the study of crystalline energy materials like battery solid electrolytes, where good energy and **Q**-resolution are required to observe diffusion and other stochastic motions and to distinguish them from *e.g.* lattice vibrations. Its high count-rate is also needed to detect the weak signals from mobile ions like Na^+ and Li^+ . KVASIR thus makes an excellent complement to the MIRACLES, BIFROST, and CSPEC instruments, filling gaps in resolution and count-rate between them and thus bringing the ESS spectroscopy suite closer to completion.

To conclude, I wish to restate my strong support for KVASIR, and to add that I believe it will revolutionize the study of a broad range of materials in condensed matter physics and beyond.

Sincerely,

A handwritten signature in black ink, appearing to read 'gln', is written over a light blue horizontal line.

Dr. Gøran J. Nilsen

Polarized Neutrons Scientist
Neutron and Muon Instrument Development Group
ISIS Neutron and Muon Source

Adjunct Associate Professor of Materials Physics
University of Stavanger



To the ESS Instrument Proposal Committee,

I am writing to express my support for the proposed KVASIR backscattering neutron spectrometer for the European Spallation Source. With a simulated white beam flux of upwards of 10^8 n/cm²/s across a 1.7 Å band, KVASIR will allow studies of low-energy excitations with excellent resolution in both momentum and energy. The two modes of operation outlined in the instrument concept paper by A. F. Davidsen *et al* allow access to energy transfers up to 0.6 meV (PG002) and 6.5 meV (PG004), respectively.

27-03-2026

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In combination with the promised energy resolution, $\delta E \approx 0.006$ meV, the former range will be of particularly high interest to the quantum and frustrated magnetism community, e.g. in relation to the study of “zero-energy modes” lifted off the elastic line by subdominant terms in the spin Hamiltonian, or the dispersion of very low-energy spin waves that are beyond the resolving powers of BIFROST, T-REX and CSPEC. Another obvious science case is quantum phase transitions where the ultra-high energy-resolution and excellent Q-resolution of KVASIR promises exciting opportunities to explore the quantum spin dynamics upon approaching field and pressure-induced gap-closure quantum critical points. The prototypical example in this case is TiCuCl_3 where a spin gap $\Delta_{\text{gap}}(H = 0, P = 0) \approx 0.7$ meV can be closed by application of a readily available magnetic field of about 6 T or by the application of about 1 kbar hydrostatic pressure. The advantage of KVASIR in this context is that its resolution allows a closer approach to the quantum critical point than is possible by triple axis spectrometry. A related science case is the exploration of quantum critical spin dynamics and its relation to superconductivity in heavy fermion metals where the low-energy gaps/resonances are typically also in the sub-meV regime, e.g. $E_{\text{res}} \approx 0.6$ meV in CeCoIn_5 and $\Delta_{\text{gap}} \approx 0.2$ meV in CeCu_2Si_2 .

Beyond the sub-meV operational mode of KVASIR, the ability to explore a larger regime of momentum and energy transfer using the PG(004) reflection potentially caters to an even larger research community. For example, the ever-topical cuprate and Fe-based superconductors exhibit superconducting spin gaps in this energy range. Likewise, several magnetoelectric and multiferroic compounds have spin wave bandwidths fully or partially overlapping with the energy range, which is furthermore well-matched with the (sample-dependent) Zeeman energy in a 10T magnetic field.

Finally, I'd like to point out in passing that the study of crystal electric field (CEF) excitations - typically in powder samples - is an important activity that is not well-covered by the existing ESS instruments. CEF-modes are mentioned once in the 2020 ESS instrument paper by Andersen *et al* (in the science case for MIRACLES), even if

their elucidation is an absolute prerequisite in studies of rare-earth based magnetic materials such as spin-ice compounds. Here KVASIR would be able to cover the lowest-energy crystal field levels, their splitting with field or upon magnetic ordering, as well as their possible mixing with coherent low-energy phonons or magnons, while higher energy CEF-modes would need T-REX or a future dedicated powder spectroscopy instrument.

To summarize, KVASIR will impact several topical research fields, including those (superconductivity and magnetoelectricity) of current interest in my research. The instrument will be an important addition to the ESS spectroscopy suite, with unique capabilities in relation to studies of sub-meV magnetic excitations. I therefore support the conceptual and technical development of the KVASIR instrument, and believe it will become an essential tool for the international condensed matter physics community.

Sincerely,

Niels B Christensen 27 March 2026

Niels Bech Christensen
Associate Professor
Department of Physics, Technical University of Denmark



Support for the KVASIR Instrument Proposal for the European Spallation Source (ESS)

To the ESS Instrument Proposal Committee,

We are writing to express our strong support for the proposed KVASIR backscattering neutron spectrometer for the European Spallation Source (ESS).

The KVASIR concept addresses a critical gap in the current neutron scattering instrumentation landscape by combining ultra-high energy resolution in the μeV range with meaningful momentum resolution for single-crystal studies. This unique combination is essential for advancing our understanding of low-energy excitations in quantum, functional, and energy materials, where key physical phenomena occur on extremely small energy scales and require precise momentum-resolved measurements.

Our research focuses broadly on quantum materials, including frustrated and low-dimensional magnetic systems, as well as correlated and functional materials. In these systems, subtle spin dynamics, low-energy excitations, and field-induced phenomena play a central role. The relevant energy scales often lie in the μeV to sub-meV range, making them difficult to access with existing spectrometers that either lack sufficient energy resolution or do not provide adequate Q-resolution for single-crystal measurements.

From this perspective, KVASIR would enable several important research directions that are currently challenging to address. First, it would allow detailed momentum-resolved studies of low-energy excitations, such as small spin gaps, weakly dispersive modes, and slow magnetic dynamics in quantum magnets. Second, it would provide a powerful platform for investigating the evolution of such excitations under extreme conditions, including high magnetic fields and ultra-low temperatures, which are often essential for stabilizing and tuning emergent quantum phases. Third, the combination of neutron spectroscopy with complementary probes, such as muon spin rotation (μSR), would open new opportunities for connecting dynamics across timescales, from quasi-static to μeV regimes.

From a neutron scattering and instrumentation perspective, the KVASIR design is particularly compelling. The combination of backscattering geometry with an optimized prismatic analyser concept and compatibility with polarisation analysis represents a significant step forward compared to existing instruments. In particular, the ability to achieve both high energy resolution and meaningful Q-resolution for single crystals—while maintaining flexibility for complex sample environments—would provide capabilities that are currently not available at neutron facilities. This will be especially important for experiments where resolving subtle features in $S(Q,\omega)$ requires both precision and versatility.

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Skolan för teknikvetenskap
Roslagstullsbacken 21 | 106 91 Stockholm
08-790 60 00 | info@kth.se | www.kth.se



In addition, the ability to work with small single crystals is a significant advantage for many modern materials systems, where sample size is often a limiting factor. The proposed instrument would therefore be highly relevant for a wide range of current and emerging materials, including van der Waals magnets, frustrated systems, and energy-related functional materials.

Beyond our own research programs, we believe KVASIR would provide a unique and much-needed capability for the broader condensed matter community. It would complement existing and planned ESS instruments by opening access to a regime of energy and momentum space that is currently difficult to probe, particularly for single-crystal systems. This will be crucial for addressing a wide range of problems in quantum magnetism, correlated electron systems, and functional materials.

We therefore strongly support the development of the KVASIR instrument and are confident it will become an essential tool for the international neutron scattering community.

Sincerely,

Assoc. Prof. Yasmine Sassa

KTH Royal Institute of Technology
Department of Applied Physics
Leader of the Quantum Technologies and
Materials (QuTM) Group
Tel: +46-(0)73-644 1401
sassa@kth.se

Assoc. Prof. Martin Månsson

KTH Royal Institute of Technology
Department of Applied Physics
Leader of the Sustainable Materials Research &
Technologies (SMaRT) Group
Director of Studies SwedNess: www.SwedNess.se
Strategic Director KTH RELAX: www.kth.se/relax
Tel. +46-(0)73-765 2130
condmat@kth.se

TUM | Forschungs-Neutronenquelle Heinz Maier-Leibnitz (FRM II)
Lichtenbergstraße 1 | 85748 Garching | GERMANY

To the
ESS Instrument Proposal Committee

Prof. Dr. Christian Pfeleiderer

Scientific Director
Research Neutron Source
Heinz Maier-Leibnitz (FRM II)

Phone: +49 89 289 14704
w-direktor@frm2.tum.de

Garching, 26 March 2026

Letter of Support for the KVASIR backscattering neutron spectrometer for the European Spallation Source (ESS)

To the ESS Instrument Proposal Committee,

I am writing to express my strong support for the proposed KVASIR backscattering neutron spectrometer for the European Spallation Source (ESS).

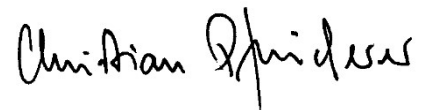
The KVASIR concept addresses an important gap in the current instrumentation landscape by providing simultaneous high resolution in both energy and momentum transfer. As described in the instrument concept paper, KVASIR aims to study small single crystals with energy resolutions on the order of a few μeV together with a momentum resolution of approximately 0.03 \AA^{-1} , while maintaining the flexibility to accommodate demanding sample environments. These capabilities will enable unprecedented studies of low-lying excitations in single hard condensed matter systems.

In particular, the instrument will be uniquely suited for investigating quantum magnetic materials, correlated electron systems, and functional materials for which key dynamics occur in the μeV to sub-meV energy range, the spatial scale of which are very difficult to access with current instrumentation. The combination of high energy and spatial resolution and the possibility to perform experiments under strong magnetic fields or other extreme conditions will open new avenues for exploring emergent quantum phenomena.

From the perspective of my scientific interest in topological quantum materials, KVASIR will be an important addition to the existing neutron instrumentation at ESS and other world leading facilities.

I therefore strongly support the development of the KVASIR instrument and believe it will become an essential tool for the international condensed matter physics community.

Yours sincerely,

A handwritten signature in black ink, reading 'Christian Pfeiderer'.

Prof. Dr. Christian Pfeiderer
Scientific Director FRM II