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ESS Instrument Construction Proposal
CAMEA

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Comparison to the Cold Chopper Spectrometer

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EXECUTIVE SUMMARY

We propose the construction of a highly innovative spectrometer – **CAMEA** – offering **Continuous Angular and Multiple Energy Analysis**. Combining indirect time-of flight with multiple consecutive analyser arrays, this instrument will provide massive flux on the sample and strongly enhanced efficiency in detecting neutrons scattered in the horizontal plane. The combination yields a spectrometer with completely unprecedented performance - with **gains from 2 up to 4 orders of magnitude compared to current state of the art**.

This increase in neutron detection efficiency will bring current fields of neutron spectroscopy to a new level, and will open the powerful technique of neutron spectroscopy to new scientific communities. While ~1000mm^3 samples is currently the practical limit for neutron spectroscopy **CAMEA makes it possible to study <1mm^3 samples**. Furthermore, being optimized for collecting the maximum number of neutrons scattered in the horizontal plane, CAMEA is superior in combination with large split-coil magnets and anvil-type high-pressure cells. The dramatic reduction in required sample size and the extreme conditions capabilities will enable a series of new possibilities:

- Neutron spectroscopy will become a powerful tool in the discovery of new functionally advanced materials, including search for new superconductors, multiferroics, thermo-electrics etc.
- Neutron spectroscopy will become possible at pressures >10 GPA both at low temperature for tuning fundamental electronic states of matter and at high temperatures, which will attract the fields of planetary science to use neutron scattering under geophysically relevant conditions.
- The study of molecular dynamics in biological matter will become feasible.
- Complete mapping of excitation spectra will become possible in higher magnetic fields than currently possible
- Excitation maps can be measured sufficiently fast that in-situ and real-time studies become possible with 20 micro-second stroboscopic time-resolution.

The strong scientific case for CAMEA is described in this proposal, in the dedicated Science Case Report, and documented by letters of support from leading scientists in **research fields ranging from fundamental quantum magnetism and correlated electron physics over materials discovery and planetary sciences to life sciences**.

While the complete CAMEA instrument is highly innovative and goes beyond any previous similar multiplexing crystal analyser instrument, each of its technical solutions have already been implemented in different instruments. Furthermore, the results of the extensive analytic and Monte-Carlo simulations of the instrument and its performance, including resolution and background, have been verified by dedicated prototyping, as we detail in enclosed reports. This provides very **high confidence that the instrument can be built with a very low risk level**, and that it will perform as predicted. In summary, **CAMEA will lift neutron spectroscopy to a new level of applicability, thereby contributing to the goal that ESS will enable new science hitherto uncharted**.

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1. INSTRUMENT PROPOSAL

1.1 Instrument Capability and Performance Summary

We propose an indirect geometry neutron spectrometer optimized for high efficiency neutron counting rates within the horizontal scattering plane to be constructed as one of the instruments at the ESS. To obtain the highest count rate we use a 165 m long guide and take advantage of the full neutron flux of a medium bandwidth of incident neutron wavelengths. The analyser concept is called CAMEA, the Continuous Angle Multi-Energy Analysis spectrometer, and it utilizes the high transmission rate of neutron analyser crystals to place 10 arcs of analyser crystals behind each other to detect different final neutron energies of scattered neutrons, over a large angular range. The analyser arcs are placed at distances of 1 – 1.8 m from the sample position, scattering neutrons downwards into position sensitive detectors to detect both the horizontal scattering direction and energy.

The analysers give the instrument an energy resolution somewhat better than most cold neutron triple axis spectrometers, $\Delta E/E$ of 1.2-4.2 %, similar to the typical energy resolution of direct geometry time-of-flight cold neutron chopper spectrometers. We have optimized the instrument to study excitations of materials in the energy range of 0-20 meV, with an extended range up to 60 meV. The optimization is ideally suited to the needs of the established research communities in quantum magnetism and strongly correlated electron systems. Optimization for a horizontal scattering plane is chosen as this scattering plane matches well with the restricted neutron access of complex sample environments, such as cryomagnets and high pressure anvil cells. Optimization for working with complex sample environments also opens the possibility for the instrument to perform in-situ and time-dependent studies of excitations. In the Supplementary Material, we show that CAMEA has a count rate for down-scattered neutrons 20 times higher than cold direct Time of Flight spectrometers on identical guides when using extreme sample environment, and a factor 1.5 times higher when no sample environment is used. The instrument concept was invented following scientific needs within several communities [Scientific demand for CAMEA]. The instrument performance and optimization have been determined by the use of computer simulations. Analytic calculations were performed in parallel to the simulations to gain an understanding of the simulation results. A prototype of the secondary spectrometer has been built in combination with an existing time-of-flight spectrometer and was extensively tested with neutrons. The prototype testing has been used to develop techniques for construction and formulating the method for commissioning this instrument type. The prototyping also confirmed the validity of our computer simulations and analytical calculations.

This instrument project is developed as a Swiss-Danish work package. The contributors are based at the University of Copenhagen (KU, Denmark), the Technical University of Denmark (DTU, Denmark), École Polytechnique Fédérale de Lausanne (EPFL, Switzerland), and the Paul Scherrer Institut (PSI, Switzerland). The work unit has considerable experience in inelastic neutron instrumentation (RITA-2; Focus; Mars at PSI, IN8; IN22 at ILL; EXED at HZB). Work in the proposal has been carried out from September 2011 to 31st March 2014 and has been developed with the aid of scientific feedback from the Indirect Geometry Spectrometers Scientific and Technical Advisory Panel of the ESS.

1.1.1 Scientific Impact

The central goal of our proposed instrument is to make maximum use of the neutron flux from the ESS pulse with high energy resolution, to achieve the highest possible neutron count rates within a horizontal scattering plane, with a high signal-to-noise ratio. Scientific output from this instrument will include studies that present neutron instrumentation cannot achieve. CAMEA has gain factors in the orders of 1000 compared to existing instruments [bench marking].

Material Discovery: The ability to study samples down to 1mm^3 [bench marking] will promote the technique of neutron spectroscopy from its current role of examining well established compounds to become an integrated part of the iterative process to discover new materials classes. Not only will neutron spectroscopy be applicable much earlier after a material is discovered, it will also become possible for materials synthesized under conditions that will never produce large crystals, such as high-pressure synthesis (which is how the highest T_c iron-based superconductors were first crystalized) and hydrothermal synthesis (which is how the best known realization of a kagome quantum magnet is synthesized)[concept and science case]. This will lead to input from inelastic neutron scattering immediately after materials are discovered, or directly lead to discovery of materials. At present a large amount of experimental and theoretical work is wasted due to incorrect assumptions made about the spin and lattice interactions in materials, inelastic neutron scattering unambiguously resolves these issues.

Quantum Magnetism, High Definition Mapping: The good energy and momentum resolution will enable high definition mapping of excitations in the scattering plane, greatly facilitating interpretation of complex excitation spectra. In systems such as quantum magnets there is often a weak continuum of excitations spread across large areas of reciprocal space. The detailed structure of this continuum that can be measured by neutron spectroscopy presently is inferior to that which can be theoretically predicted. High definition mapping with high count rates on CAMEA will bridge this gap to test our fundamental understanding of quantum magnetism, leading to both detailed tests of theories and the identification of new quantum phenomena.

Rapid Mapping to Study Critical Transitions: The high count rate and essentially complete angular and energy coverage in a single acquisition will enable continuous parametric scanning of excitations. At phase transition boundaries, current instrumentation can only be used to map out excitation spectra at a few selected positions on the two sides of the phase transitions, whereas rapid mapping of excitations by CAMEA will resolve the evolution of spectra as the control parameter (temperature, magnetic field etc.) is tuned continuously across the phase transition. CAMEA can be aligned on a specific excitation and study that excitation dependence of a sample parameter in a continuous manner, equivalent to a temperature ramp in powder neutron diffraction.

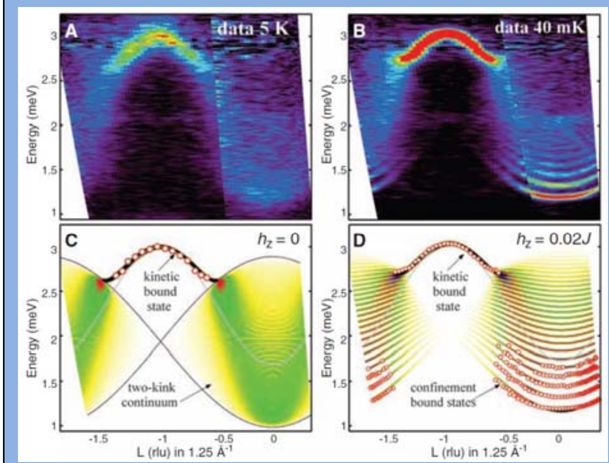
Time Resolved Studies: With a time resolution of ~20 μs, see section 1.2.2.1 CAMEA opens up the possibility for studying the time evolution of excitations following a change of parameters, such as a laser pulse, an electric field pulse etc. This time resolution is for instance sufficient to capture the magnetic field dependence during a pulsed magnet cycle[concept and science case].

Due to the long-pulsed nature of ESS, any particular wavelength will impinge on the sample over a time span of 3 ms, during which, the mean wavelength varies only slightly. Hence, a particular value of scattering vector and energy transfer is probed during 3 ms, with a time resolution at least 100 times better. In this way, CAMEA gains over the direct time-of-flight spectrometers, which chop the incident beam, so that an incident pulse will probe one specific energy only during some tens of μs. Hence, to examine a particular signal over 3 ms, with the same time resolution as CAMEA, requires on a direct geometry spectrometer 100 settings of the time-delay.

The time resolved capabilities of CAMEA will allow for pump-probe experiments to study the out-of-equilibrium evolution of systems, of relevance to functional materials for energy research, such as catalysts. It will also enable studies of the response of soft matter to external stimuli such as light.

Complex Sample Environment and Small Samples: The CAMEA instrument has been designed to achieve a high signal-to-noise ratio with complex sample environment by minimizing the background count rate. In direct geometry time-of-flight spectrometers, a neutron that scatters elastically off the sample environment may enter the neutron detectors with a time offset that will be misinterpreted as inelastic scattering[Comparison to Cold Chopper]. Even if this background signal on direct geometry spectrometers can be reduced by radial collimators, the elastic scattering from complex sample environment may render parts of the inelastic spectra unusable. In this respect, CAMEA will have two advantages: 1) The tightly defined neutron flight path (by shielding and collimation) reduces visibility of the sample environment and diffuse background scattering. 2) The long primary flight path ensures that any time offset from elastic sample environment scattering does not place background neutrons in the inelastic spectrum.

CAMEA will use a series of absorbing jaws in the guide to control the incoming beam divergence. This concept has been implemented on the WISH instrument at ISIS [Chapon11] and together with traditional slits close to the sample it will also allow a very good definition of the beam spot. A small beam size is vital for studying small samples of crystals that do not exist in large size, e.g. newly discovered materials. A small beam size is also essential for studies in pressure cells where the sample volume is very limited. With CAMEA at ESS we will be able to study excitations in 1 mm^3 sized samples[bench marking].



The Perfect Sweet Spot. On the indirect time-of-flight spectrometer Osiris a fortuitous combination of conditions enabled the first ever observation of the E_8 symmetry, an emergent state at the quantum critical point of $CoNb_2O_6$ R. Coldea *et al.* *Science* **327**, 177 (2010). Critical to the success of this experiment was the very-good one-dimensionality of the system, the strong easy axis resulting in Ising chains, a weak spin interaction along the chain that can be perturbed by moderate applied magnetic fields, a very weak spin interaction between the chains, and being able to grow a large 8 g single crystal sample.

The figure shows (A + B) neutron scattering data at two different temperatures, in comparison to (C + D) theoretical calculation with the experimental dispersion indicated by open symbols. The confinement bound states observed due to the very weak inter-chain spin interaction can be tuned by application of a transverse field into the bound states of quasi-particles with E_8 symmetry just below the quantum critical point of $CoNb_2O_6$.

Magnetism Under Applied Magnetic Fields: This instrument represents a significant advancement for inelastic neutron scattering in scientific fields where application of a strong magnetic field is required. In quantum magnetism and strongly correlated systems the cleanest way to study transitions, and reach new magnetic phases of matter is to use a tuning variable. In the case of using applied magnetic fields this instrument creates the ability to scan across the transition to determine the nature of magnetic quantum phase transitions [concept and science case].

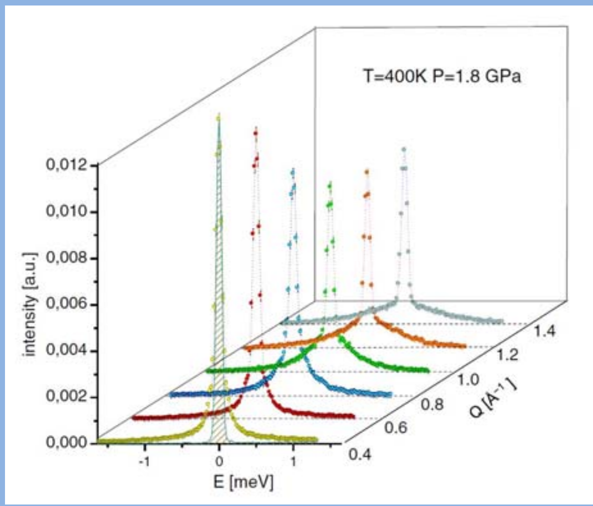
Magnetism Under Extreme Pressure: Applying extreme pressures to study materials is presently of minimal use in inelastic neutron scattering due to the limited sample volume that can be used in pressure cells. By allowing spectroscopy on smaller samples, CAMEA will open the door to systematic studies of excitation spectra up to very high pressures. Pressures of 1-10 GPa are sufficient to induce measurable changes in hopping integrals that govern electronic motion between states and hence effects the electronic interactions driving phase transitions. By changing the hopping integral we will therefore allow testing interpretations and theories predicting materials' magnetic and electronic properties. In this fashion, the unique scientific output from studies under pressure will become a significant evolution in neutron scattering.

Functional Materials: CAMEA has many advantages for studying complex materials with properties that have potential for practical applications. The rapid mapping capability of CAMEA provides a way to scan many materials providing a way to explore complete series of materials which will direct the evolution in material design, of e.g. thermoelectric materials, fuel cell materials and molecular magnets. Use of radial collimation on CAMEA to remove the visibility of the sample environments allows functional materials to be studied in-situ. In-situ studies on CAMEA will for instance investigate working components of fuel-cells, batteries, magnetic cooling systems, and the processing of materials. By the use of the beam definition jaws, a well-defined incident neutron beam will enable the scanning with precision down to 3 mm the in-situ performance across the active volume.

***Soft Matter*:** Inelastic neutron scattering from soft matter has previously concentrated on neutron spin echo techniques to determine materials elasticity and compressibility, while quasi-elastic neutron scattering (QENS) is used to study incoherent motions of the molecules in materials. Incoherent processes in molecules include vibrations, rotations, librations (hindered rotations) and diffusion. Molecular dynamic computer models have however evolved to describe molecule behaviour over the complete energy and wavevector range of inelastic neutron scattering. Inelastic neutron scattering is developing into studies of collective (hence wave-vector-dependent) dynamics in soft matter. For example in membranes, collective dynamics are believed to drive transport of molecules, pore opening, membrane fusions and protein-protein interactions [Rheinstädter12]. Inelastic neutron scattering is required to measure the dispersion of these collective motions [Rheinstädter04]. In soft matter research CAMEA will study incoherent processes with moderate resolution QENS, compared to ultra-high energy resolution backscattering QENS, and provide high resolution measurements of the collective dynamics in soft matter. At CAMEA soft matter experiments will take advantage of the small sample capability, the efficient screening of background from sample environments on CAMEA, and the ability of polarization analysis to separate coherent and incoherent motions. Furthermore, CAMEA provides the ability for time resolved studies of soft matter stimulated out of equilibrium using pump-probe techniques.

Geoscience: There exist a great hitherto unaccommodated interest to study lattice dynamics in simple material under extreme pressure, and for geo- and planetary science related studies such as hydrogen diffusion in materials of the Earth's upper mantle. CAMEA is ideally suited for both purposes. Despite the fact that water is vital for life on Earth we have little knowledge on the extent of the water cycle in the Earth's mantle, with estimates on the water in the mantle varying from ten percent to two and a half times the water on the Earth's surface. The uptake of water into the material of the Earth's mantle greatly influences the properties of the materials, which has consequences for flow of material and sound velocities in the mantle, studying these materials has the potential to provide great insight into plate-tectonics and seismic activity[concept and science case, Hirschmann12].

The Hidden Water Cycle. Little is known about the behaviour of water under extreme conditions, and how far into the interior of planets the water cycle goes. Researchers are only presently able to study the dynamics of pure water under gigapascal pressure and elevated temperatures in an energy range well suited to CAMEA. To understand water's effects on the Earth's mantle and the hidden water cycle, CAMEA will be able to measure the dynamics of hydrogen in the extreme conditions of Earth's upper mantle, where water concentrations may be at the one percent level and greatly influence the properties of the Earth's mantle [D. G. Pearson *et. al.*, Nature **507**, 221 (2014)].



Inelastic neutron scattering of the dynamics of water under high pressure and temperature. [L. E. Bove *et. al.*, Phys. Rev. Lett. **111**, 185901 (2013)].

Complimentary Techniques: Development of x-ray scattering techniques has led to complementarity and occasional competition with inelastic neutron scattering in measuring excitations. X-ray scattering techniques have the advantage of being able to study small samples typically down to 100 μm. However, inelastic X-ray scattering (IXS) cannot readily observe phonon modes involving light elements, and the best energy resolution that is achieved is 0.8 meV compared to below 20 μeV for CAMEA. Resonant Inelastic X-ray Scattering (RIXS) can be used to study magnetic excitations but today's 30 meV resolution is poor and fundamental limitations makes it highly unlikely that resolution will improve below 5-10 meV even by 2020. Furthermore, the soft x-rays used will be unable to penetrate complex sample environments, and it will be difficult to achieve low temperatures significantly below 10 K due to sample heating. Last, the long x-ray wavelength needed to access the most important L-edge of transition metals provides a fundamentally limited coverage in reciprocal space. It is therefore clear that the wavevector and energy dependencies that can be obtained by cold inelastic neutron scattering are unique.

Grand Challenges: In 2007 in the USA the National Research Council of the National Academies produced a report commissioned by the Department of Energy, and the National Science Foundation, on the grand challenges in condensed matter and materials physics for the coming decade[grand_challenges]. The grand challenges identified in this report remain for the next decade and beyond. Of the six grand challenges that were identified, three can be directly addressed by CAMEA with capabilities far beyond present instrumentation i) How do complex phenomena emerge from simple ingredients? ii) How to meet the energy demand of future generations, and iii) What happens far from equilibrium and why? In magnetism a prominent way to discover emergent phenomena is the use of extreme environments to tune the magnetic interactions in materials, which CAMEA is ideally suited for. The ability of CAMEA for studies on functional materials in-situ in the components of fuel-cells, batteries, magnetic refrigeration, superconductors and the processing of materials, address the challenge of future energy demands. In-situ experimentation on CAMEA, including time resolved studies, will enable novel experiments providing insight into out of equilibrium processes, in both functional materials, in fundamental model materials and in the complex behaviour of soft matter.

1.1.2 User Base and Demand

The proposed instrument addresses the needs of multiple user communities in condensed matter physics, especially but far from exclusively in magnetism. Inelastic neutron scattering has provided a unique experimental tool for the investigation of the wavevector and energy dependence of magnetic fluctuations in electronically complex materials. In research fields such as quantum magnetism and high temperature superconductivity the results of inelastic neutron scattering provide unique information that often lead to break-through understandings. By understanding the magnetism of correlated electron systems we gain fundamental knowledge that may provide vital insight for conceiving materials for devices in the future. An illustrative analogy is how the development of the theory of electrons in solids, notably semi-conductors, enabled the development of solid state devices such as the transistor.

We have studied the user base and demand for the proposed instrument, as can be found in the report “concept and science case”. The correlated electron and magnetism research fields dominate the user community of many inelastic neutron spectrometers, as can be observed in the publication lists for these spectrometers. Despite the significant increase in the number of spectrometers available for studying the magnetic excitations, the user demand for beamtime has continued to grow outpacing the availability of beamtime. Currently, one third of the user beamtime on cold neutron spectrometers in Europe is conducted with application of magnetic fields – for which the CAMEA instrument is ideally suited. With present neutron instrumentation studies of magnetism under extreme pressures is virtually non-existent due to the limitation on sample size, a shortcoming which will be addressed by the enhanced performance of CAMEA.

Indeed, there is a strong existing neutron scattering user community eagerly awaiting to use CAMEA to perform spectroscopy of materials under extreme pressures, and there is no existing spectrometer to perform these experiments [ESS-SymposiumonSpinDynamics12]. On top of the existing demand, we expect emergence of research communities within a number of topics, which do not present have established neutron user communities due to lack of proper instrumentation: In-situ measurements of excitations; time resolved studies (i.e. pulsed magnetic/electric fields); excitations in soft matter aligned by high fields; and high pressure and high temperature studies of materials (geo- and planetary sciences).

The strongest present demand for CAMEA clearly comes from the magnetism community, but as shown above there is a strong potential for a scientific impact in other fields of research. These communities will grow with the capabilities of the ESS, and further increase the demand for beamtime on CAMEA.

1.1.3 Strategy and Uniqueness

The instrument we are proposing here fits into the strategy of the indirect spectroscopy to provide instrumentation that covers from high resolution low energy studies, over medium energy resolution studies to high energies. CAMEA bridges the dynamic energy range from the ultra-high resolution low energy studies of backscattering spectroscopy to that of medium resolution vibrational spectroscopy. This instrument also provides additional experimental capabilities compared to the capabilities of cold direct geometry time-of-flight chopper spectrometers. In particular CAMEA can fulfil the demand by the magnetism user community for an inelastic spectrometer that can perform experiments under extreme conditions [ESS-SymposiumonSpinDynamics12].

Instrument	CAMEA Flux Gain	CAMEA Analyser ±1.4° Solid Angle Gain§	CAMEA Gain Factor
IN14 with Flatcone	105	27.7	2910
PANDA with Flatcone*	947	27.7	26200
THALES with Flatcone#	51	27.7	1410
MACS+	36	17.8	640
OSIRIS	554	7.7	4270
IRIS	1500	8.4	12600
PRISMA	>20Ξ	82.4	>1650

§The full multiplied gain factor is only applicable for cases where the entire coverage of S(q,ϖ) is scientifically relevant. The solid angle gain includes a comparison of the total analyser coverage of CAMEA corrected for transmission efficiency of the CAMEA analysers, conservatively estimate as a total gain factor of 7.1 for the 10 analysers.
*Flatcone is not available at FRM-II for PANDA. The CAMEA flux gain is in comparison to PANDA using a monochromator with vertical focusing only.
#This gain factor is reduced to 135 for THALES using a CAMEA type secondary spectrometer.
+ Flux gain compares CAMEA to the low energy resolution, high flux thermal setup of MACS.
ΞThe absolute flux of Prisma is unknown, and this gain factor is a very conservative estimate.

Table 1: The flux and solid angle performance gain of CAMEA compared to multiplexed triple axis and indirect geometry spectrometers [Bench marking].

At present there exists no other neutron spectrometer like the one we are proposing for ESS. Previous indirect spectrometers such as PRISMA (ISIS) and CQS (Los

Alamos) worked with variable final neutron energies but only analysed one neutron energy at a specific scattering angle. For spectrometers the successful development of position sensitive detectors led to the development of direct geometry chopper spectrometers over indirect geometry spectrometers. The strength of direct geometry chopper spectrometers is in measuring excitations over large volumes of reciprocal space. However, direct geometry chopper spectrometers cannot concentrate on specific areas or planes of reciprocal space. CAMEA maps out scattering planes by performing a sample rotation. In the event that the area of reciprocal space of interest is known, the sample rotation scanned by CAMEA can be significantly smaller than a 90° or 180° rotation required to map out all of the reciprocal plane. When working with sample environments that have restricted neutron access only a fraction of the detectors of direct geometry chopper spectrometers are illumnitated, so CAMEA's in-plane optimization scans excitations at 20 times higher count rates than corresponding direct ToF spectrometers when the vertical access is limited to $\pm 2^o$ (see Comparison_to_the_Cold_Chopper_Spectrometer section 3.1). The indirect geometry spectrometer we are proposing provides a way to concentrate on measuring excitations in specific scattering planes, and is well matched to performing experiments in sample environments that have restricted neutron access. The instrument we propose can be seen as an advanced evolution of multiplexed triple-axis spectrometers (TAS) with multiple analyser channels that have been developed in the last decade [Rodriguez08, Kempa06]. It multiplexes both in angle and in energies, and it exploits the time-of flight method for incident energy determination. Building this instrument at the 5 MW source at the ESS delivers neutron spectroscopy with count rates largely surpassing any existing spectrometers. In table one we highlight the gain factor that CAMEA achieves over both multiplexed TAS and present indirect geometry spectrometers.

This instrument concept incorporates a large sample space that is necessary for sample environments such as cryomagnets, and provides adaptability to accommodate complex sample environment for in-situ studies. The use of a collimated secondary flight path also reduces the visibility of the complex sample environment, which would otherwise produce large quantities of structured background signal. To provide an extended energy range we will use a new order sorting chopper technique and the second order reflections of the analyser crystals, we expect that for in-situ studies of phonons the extended energy and q range will be of great importance.

1.2 Description of Instrument Concept and Performance

1.2.1 Instrument Description

Primary Spectrometer	
Moderator	Cold
Wavelength range (Energy range)	1 Å to 8 Å (81.8 meV to 1.3 meV)
Bandwidth at sample position	1.7 Å
Guide length and shape	165 m - Parabolic feeder to double elliptical guide
Line-of-sight removal	Kink between elliptical guide sections
Number of choppers	7, operating from 840 rpm to 12600 rpm
Incoming divergence	2.0° vertical, 1.5° horizontal
Divergence control	5 divergence jaws integrated in guide
Incoming energy resolution	Adjustable from 0.1 % to 3 % at 5 meV
Sample	
Maximum flux on sample position	1.8 * 10^{10} n/s/cm^2/1.7 Å
Wavevector range at elastic position (including PG(004) reflections)	PG(002) reflections: 0.058 $Å^{-1}$ to 3.6 $Å^{-1}$ PG(004) reflections: 0.12 $Å^{-1}$ to 7.26 $Å^{-1}$
Background count rate	< 5e-5 compared to elastic signal of vanadium (result from prototype testing)
Beam size at sample position	1.5 cm * 1.5 cm
Beam size optimization	0.1 cm * 0.1 cm - 1 cm * 1 cm
Sample environment space	90 cm diameter, side access possible
Magnetic fields	>20T, >10T with 10GPa, 0.1K-350K
Pressure	30GPa with 5mm3 sample, T=3-2000K 10GPa with 50mm3 sample, T=0.1-1800K
Secondary Spectrometer	
Collimation	Radial collimation after sample. Cross talk collimation in secondary spectrometer.
Filter	Removable cooled Be-filter before analyzers
Analyzer crystals	2 m^2 cooled pyrolytic graphite (PG) - 60” mosaicity, using (002) and (004) reflections
Detectors	2.5 m^2 Position sensitive ^{3}He at 7 bar
Number of analyzer arcs	10
Number of analyzer-detector segments	15 (9° per segment, 6° active)
Sample to analyzer distances	1.00 m to 1.79 m
Analyzer to detector distances	0.80 m to 1.45 m
Horizontal angular coverage	3°-135°
Horizontal angular resolution	0.79° to 0.46°
Vertical angular coverage	±1.4°
Final neutron energy range	PG(002): 2.5 meV to 8.0 meV PG(002)+PG(004): 2.5 meV to 32 meV
Secondary energy resolution	0.77 % to 1.3 %
Time resolution	20 μs
Neutron polarization and analysis	Polarizing supermirrors

ESS-CAMEA is a new cold-neutron inverse-geometry time-of-flight spectrometer concept. It combines several different techniques to achieve an unprecedented high count rate in the horizontal scattering plane together with good resolution.

First, the inverse time-of-flight primary spectrometer ensures that the sample receives a broad incoming wavelength band, where we have the flexibility to choose between good incoming energy resolution, or a high flux mode that utilises the entire ESS long-pulse.

After the sample, analysers arranged in arcs around the sample ensures that a large fraction of the in-plane scattering angles are covered. Each analyser bank covers 6° and reflects neutrons down towards position sensitive detectors in order to combine a large angular coverage with good angular resolution. Further the analysers are focusing in the vertical direction to increase the covered solid angle.

CAMEA uses 10 concentric PG analyser arcs to reflect 10 energy bands towards the detectors, thereby increasing the energy-coverage greatly.

Finally a new multi wavelength analyser technique enables separation of the reflected neutrons from each analyser arc into 3 separate bands thereby both increasing the energy-coverage and improving the resolution.

In the following we will describe each feature in more detail. An overview of the instrument is seen in figure 1.

CAMEA will have two modes for selecting the energy coverage of the measurement, and two modes of resolution for both energy coverages.

The **Maximum Coverage Mode** uses the order sorting chopper pairs to avoid any overlapping of the neutrons selected by the first or second order scattering of the analysers. The order sorting choppers reduce the incident intensity, but provide increased q and energy range in a one-shot measurement.

The **Focused Mode** uses Be filter between the sample and analysers, while the order sorting choppers are stopped. In this mode the full incident intensity and the first 7 out of 10 analysers are used. This mode gives high intensity in a limited q and energy range.

After selection of the energy coverage mode, a choice of resolution setting is made:

The **Resolution Matching Mode** employs the pulse shaping chopper in order to provide matching between primary and secondary resolution at a given energy transfer. It is possible to match the resolutions up to an energy transfer of 20 meV, though at a more moderate flux than in the high flux mode.

The **Maximum Flux Mode** opens the pulse shaping choppers to use the full pulse. This produces an even higher flux but relaxes the Energy resolution to $\Delta E/E$=4% at 5 meV elastic scattering.

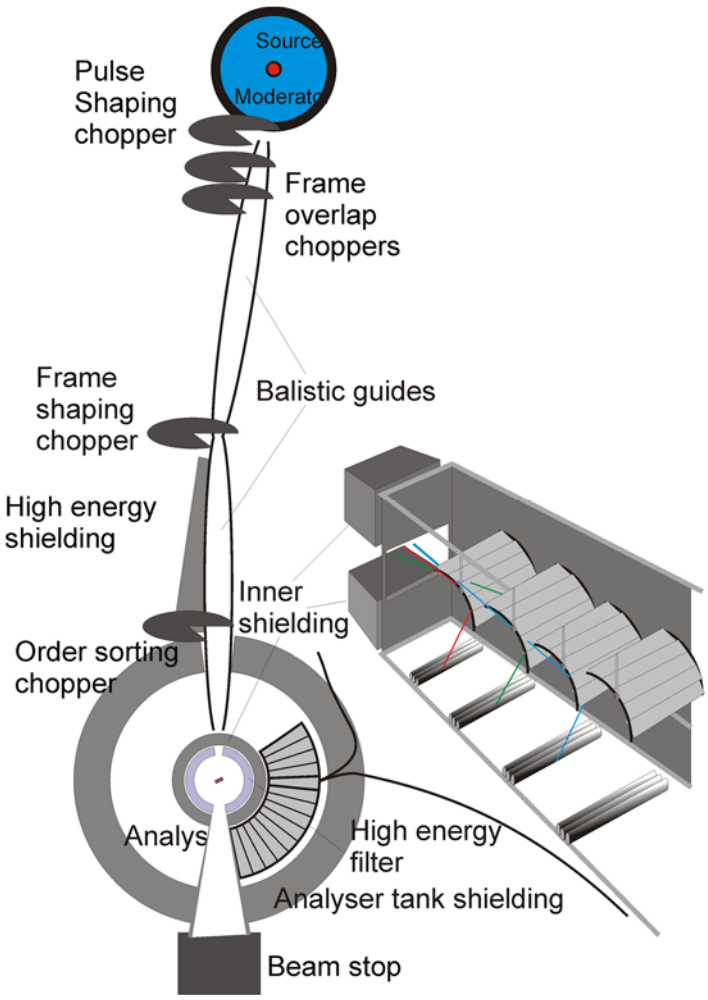


Figure 1: An overview of the CAMEA instrument (not to scale). Two long ballistic guides lead the neutrons from moderator to sample. The guides are kinked by a small angle to avoid direct line-of-sight. The sample is surrounded by the analyser-detector chamber that covers a large angle within the horizontal plane. A cross section of one multi-analyser-detector module is shown as an insert. The positions of the most important choppers are sketched.

1.2.1.1 Moderator and Guide

CAMEA is optimized for the study of excitations in the energy range 0-20 meV, and the analyser settings cover the energy range 2.5-8 meV. The most frequently used incident energies will cover the energy range 1.6-28 meV, or in wavelength 1.7-7 Å. Since much of the science case covers magnetism and correlated electrons, many experiments will be performed at low temperatures. Hence, CAMEA is designed mostly for energy down-scattering, while the quasi-elastic range is still covered.

We choose to use the ESS cold moderator, which covers the desired wavelength range well. We have discarded the use of the bispectral beam extraction system [jacobsen13, zendler12], to eliminate risk. In a bispectral system, degradation of the first reflecting supermirrors very close to the moderator would lead to a dramatic loss of cold neutrons and would potentially compromise the whole instrument.

A key strength of CAMEA is the possibility to combine good resolution and (q,ϖ) coverage with a higher intensity in each channel than direct time-of-flight instruments. To take full advantage of this feature the instrument needs to be long. If the instrument was moved to half distance and used a frame multiplication system the intensity for a given (q,ω) pixel would be halved, but the coverage in incoming wavelength doubled. It is however also possible for a long instrument to trade flux for coverage by rotating the choppers at a lower frequency thus skipping every second pulse. The opposite is not possible for frame multiplication instruments. So we have chosen an instrument with a length of 165 m as this is the natural length where the 71 ms frame can be filled by one pulse for all resolutions, when the pulse-shaping chopper is placed at the minimum position of 6.5 m [schober08, lefmann13]. This gives a 1.7 Å wide wavelength band. In the high-flux mode, the instrument can run even without using the pulse-shaping chopper.

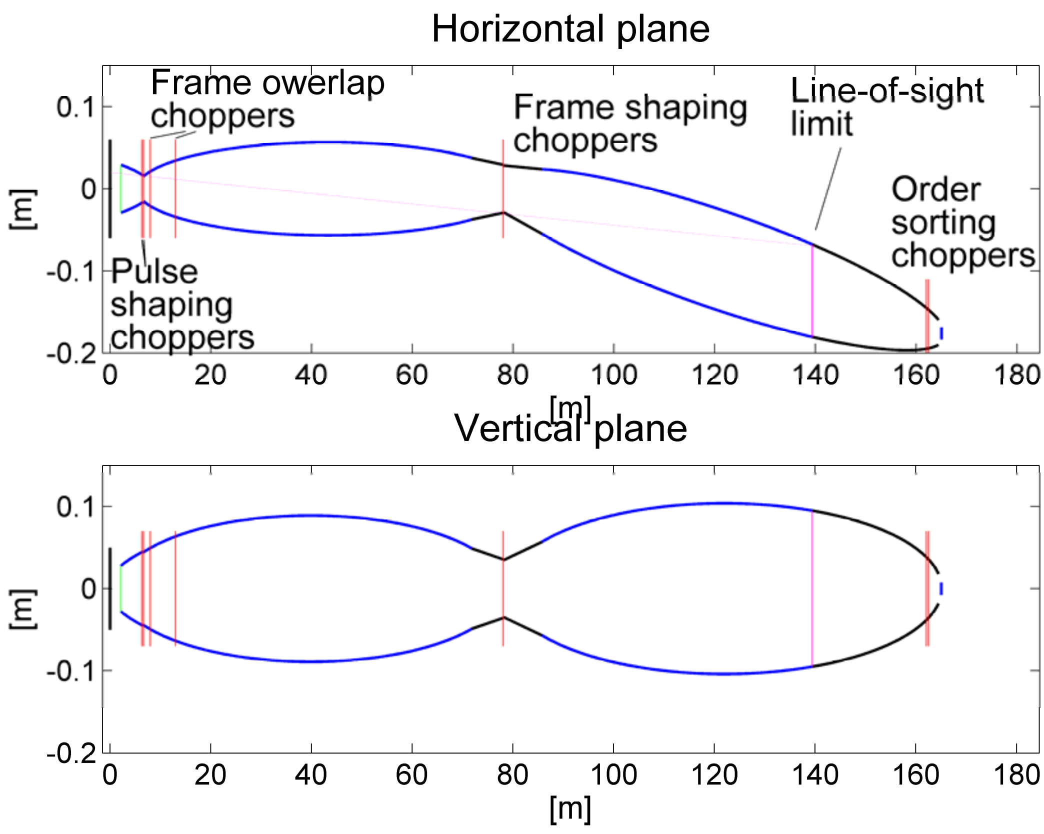


Figure 2: Sketch of guide and chopper system as seen from above.

The guide geometry was chosen by using the guide simulation package GuideBot for McStas [bertelsen14] that allowed investigation and optimization of about 150 different guide geometries as well as many different parameters. The final choice was a guide without line of sight to the sample with very good transport capabilities and a smooth beam profile both in real space and in divergence space.

For the beam extraction system, CAMEA uses a pinhole with a ''feeder'' guide piece close to the moderator [bertelsen13] for the horizontal part (See figure 2). The vertical part of the beam extraction is an expanding parabola. This extraction system feeds a double ballistic guide [Guide Report]. We have selected the guide system from the requirements that the illuminated beam spot is 15 x 15 mm^2 and that the desired divergence is ± 1.0° vertical and ± 0.75° horizontal. Optimising for a smaller beam spot would only give marginal higher central flux, at the expense of the possibility to measure samples as large as 15 mm diameter. A combination of analytical calculations, and GuideBot optimizations led us to choose a 30 mm wide pinhole, after a gap for the pulse shaping chopper at 6.5 m. The guide opening is 98 mm tall at 6.6 m (see also section 1.3.1).

The guides have a maximum width of 0.23 m in the vertical part and 0.15 m in the horizontal direction. The guide sections are kinked with respect to each other by 0.056° in the horizontal plane to avoid direct line-of-sight through the guide [cussen13]. The kink point is narrow, 50 × 95 mm^2, and is shielded for additional suppression of the fast neutron background. For further background suppression, a tungsten beam block (equivalent to a stopped T-zero chopper) may be inserted in the ''fat'' part of the first guide with flux reduction below 10%, but resulting in a factor 10 background suppression [filges13].

1.2.1.2 Chopper System

The pulse shaping chopper pair is placed as close to the moderator as possible at 6.5 m and will run in the same direction at 14-210 Hz. The chopper has a diameter of 700 mm with an opening angle of 170°. This makes it possible to use the entire ESS pulse in a high flux mode or reduce the opening to improve the resolution. An opening time of 0.08 ms will be needed to achieve good resolution at typical high energies (20 meV), matching the resolution contribution of the 5 meV analyser (54 μeV). To achieve the short opening times with a good pulse shape it is necessary to increase the chopper frequency to 210 Hz.

Both frame overlap and the extra pulses generated when running the pulse shaping chopper will be removed by two 14 Hz choppers placed 8 and 13 m from the moderator, see figure 3. The diameter of these choppers is 700 mm.

A 14 Hz band-defining chopper, 700 mm diameter and with a 158° opening, is placed at the kink point where the guide is narrow. This allows for a precise definition of the wavelength band.

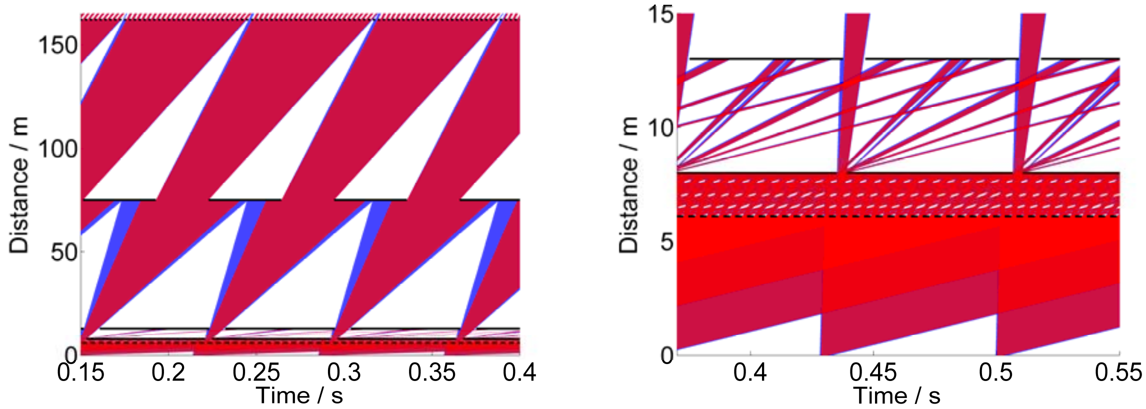


Figure 3: Left: Time-distance diagram of the CAMEA guide system; right: Zoom of the first 15 m. The pulse is shaped by the first chopper pair at 6.5 m, while the next two choppers are eliminating frame overlap and the shaping of the wavelength band is done by the last chopper. The chopper close to the sample is an "order sorting chopper" to be detailed in fig. 4.

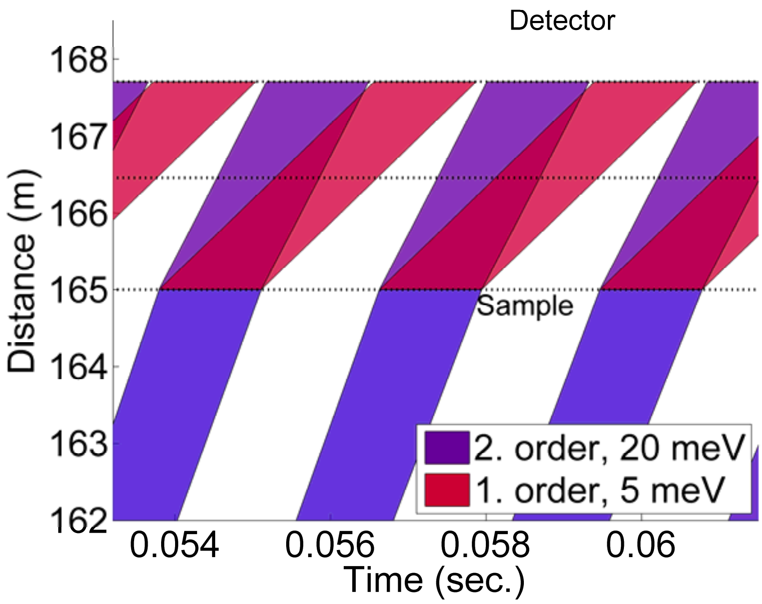


Figure 4: Time-of-flight diagram of the order sorting chopper. At 162 m the chopper divides the pulse into about 25 pulses, at 3 m the neutrons hit the sample and scatters. After that only neutrons that can reflect on the analyser (166.46 m) as first or second order scattering is displayed. The two different velocities will be fully separated at the sample position. The white gaps between the pulses will be filled with overlapping signals mainly due to the choppers open and closing time The Time-of-Flight diagrams are different for each analyser, here the 7th analyser (E_f = 5 meV) is displayed.

At 3 m before the sample we place an optional double chopper. This "order-sorting chopper" has two openings of 80° and spins with 180Hz. The effect of this chopper is to allow for time-of-flight discrimination of second-order scattering from the analyser crystals. This method is illustrated in fig. 4. By changing the opening time of the chopper it is additionally possible to discriminate first and second order scattering as well as third order scattering if needed. The flight paths in the secondary instrument are chosen to give the same flight time for each analysed energy, thus one setting of the order sorting chopper will select the first and second order scattering of all of the 10 analyser arrays. The chopper frequency is not a multiple of 14 Hz to ensure that the entire wavelength band is uniformly covered (in this case in just 7 pulses).

1.2.1.3 Sample and Sample Environment

CAMEA is optimized for single crystal experiments. The sample is placed on a sample table of the type known from triple-axis instruments with a double goniometer and translational stages. We have designed the instrument for sample sizes of 10×10 mm^2 or smaller, but have aimed for a slightly larger beam size of 15×15 mm^2 to allow for homogeneous illumination during sample rotation, which we foresee to be a frequent mode of operation.

The sample table will be prepared for holding a large cryomagnet, i.e. with no magnetic parts. The sample table can rotate, but when using bulk sample environment with a designated incoming beam path, the sample rotation will take place on a stick inside the sample environment, as is common practice, e.g. in the Oxford 15 T magnets.

We aim for the most extreme values of sample parameters we can obtain at the time of purchase. Presently, 16 T is the largest commercially available magnetic field (plus 2.0 T Dy boosters of the HZB type). However, magnets with high-temperature superconducting tapes will most likely become available within the coming 6-8 years, lifting the field limit to around 25 T [oxford13].

The magnets and cryostats will be equipped with variable temperature inserts for 2-350 K temperatures, and with dilution refrigerator inserts for temperatures down to 30 mK.

Sample sticks will be available to provide an additional electrical field up to 10 kV/mm. For performing high pressure studies at low temperatures Paris-Edinburgh cells achieving 10 GPa at 3 K are currently available, and design improvements will lead to lower base temperatures <300 mK. High temperature studies desire a pressure cell capable of reaching 30 GPa and > 2000 K, that can be developed from the 97 GPa pressure cells used for neutron diffraction at the SNS.

To provide flexibility in extreme environments a 10 cm wide bore vertical split coil superconducting magnet (>10 T) for a pressure cell (>3 GPa) that can be cooled to <1K is feasible with current technology. This sample environment will provide a large volume of parameter space to explore.

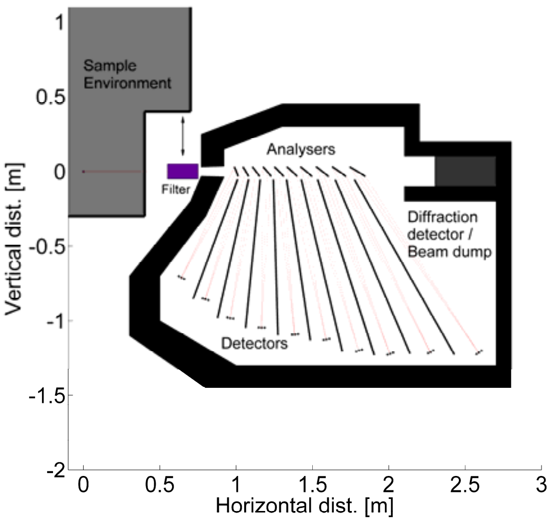
Since CAMEA will be an ultra-high flux instrument, sample activation must be taken seriously. We have designed a movable transport cylinder for active samples, see section 1.3.3.

1.2.1.4 Secondary Spectrometer Tank

The analyser-detector set-up is enclosed in the wedge-shaped secondary spectrometer tank. The inner radius of the tank is 0.50 m, with an outer radius of 3 m. The tank covers 3-135° scattering angle in one scattering direction. A sketch of the tank is shown as figure 5. There is an upgrade possibility to install another tank to the other scattering direction, which could be a medium resolution diffractometer specialized in in-plane scattering.

The analyser-detector module inside the tank is positioned on rails so that it can rotate to slightly different scattering angles. This is necessary to cover the dark angles between analyser arrays, discussed in the next sections. The tank is under vacuum to reduce air scattering and to allow cooling the analysers; details in next sections.

The module consist of 15 segments each covering 9° with a 6° active area. The first segment will be a special half size segment to get as close as possible to the direct beam.



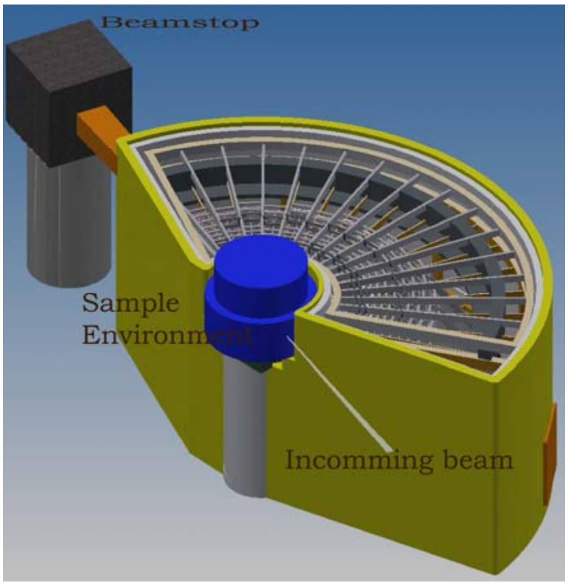


Figure 5: Left: A vertical cut of the secondary spectrometer tank. The sample is at the left, and the neutrons travel from there through the filter. Then the neutrons pass through single-focusing analyser arrays, until scattered towards the detectors. Right: Technical drawing of the tank. The beam enters from bottom-right in the picture.

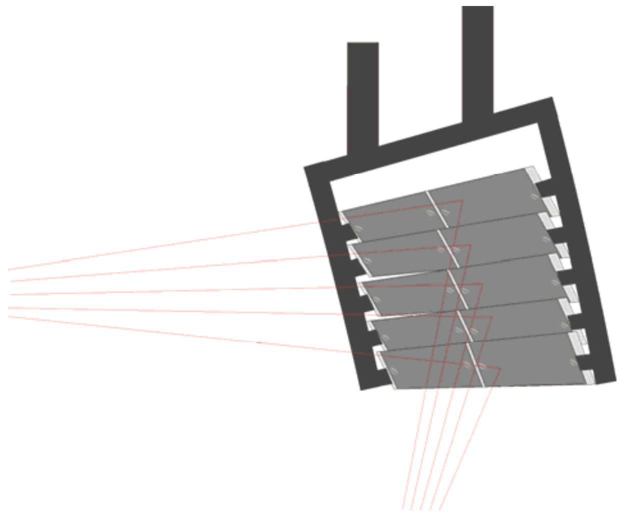


Figure 6: Illustration of analyser arrangement. The PG analysers are mounted on Si wafers that are in turn mounted on an Al frame. The individual PG crystals are aligned to the Si beforehand using small Al spacers if needed. The analysers closest to the sample will have 7 wafers each carrying 3 analyser crystals. These numbers increase to 11 wafers each carrying 5 crystals for analysers furthest from the sample.

1.2.1.5 Analyser-Detector Geometry

One truly novel part of the CAMEA spectrometer is the analyser-detector arrangement. We use thin (1 mm) pyrolytic graphite of medium grade (60 arc minutes mosaic). These crystals have a good cold-neutron reflectivity, 60-70%, and importantly a high transmission. We can therefore place 10 analyser arcs behind each other, scattering at slightly different angles (and henceforth final neutron energies), as sketched in Fig. 5. This allows for detection of a large fraction of the neutrons scattered within the horizontal plane.

The analysers employ vertical Rowland focusing much like the horizontal focusing of a TAS analyser (See figure 6). The PG is held in place by Si wafers on aluminium holders that ensures the focusing condition.

The detectors are 1/2 inch (12.5 mm) ^{3}He tubes, with 5 mm resolution along the tube - or similar technology depending on ESS detector policy and the He-3 situation. The analyser-detector distance is around 1 m, matched for each scattered wavelength to comply with restrictions from the order-sorting scheme. We position 3 detector tubes in parallel to measure additional energies. The energy resolution is, in fact, determined solely by distance collimation (i.e. the collimation arising from the small angles that detector, analyser and sample see each other under due to their small sizes and the long distances between them). Neutrons with slightly different energies are scattered at different Bragg angles – and reach in turn different detector tubes. The extended PG mosaicity ensures reasonable reflectivity for all directions [birk14]. This effect is illustrated in Fig. 7.

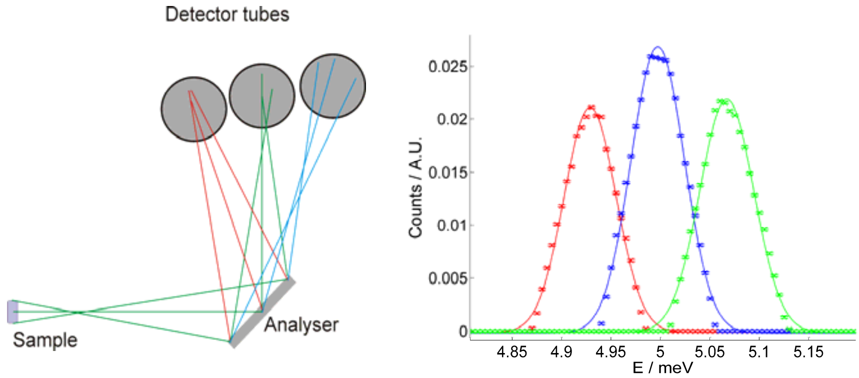


Figure: 7: An analyser crystal with relaxed mosaicity will reflect a band of different energies in slightly different directions. The left panel illustrates the principle for a single analyser crystal and 3 detector tubes. Right panel shows a simulation of how the principle works if the single crystal is replaced by a focusing analyser. The detector consists of a system of three 1/2 inch detector tubes. Simulations show that several energies from the same analyser crystal can be separated; thus improving resolution compared to a big-detector scheme, but without losing intensity.

Since space is needed for the analyser mounts, there are "dark" angles, not covered by the analysers in any particular setting. In the experiment, the dark angles are covered by moving the whole analyser-detector setup by a few degrees. With 3 settings all angles can be covered twice as all analyser arcs each has at least 67% angular coverage.

In total, the secondary spectrometer tank will deploy 2.4 m^2 detectors and 2 m^2 PG crystals.

1.2.1.6 Shielding, Filter, and Collimators

To reduce background, we employ a number of known techniques. As discussed earlier, the guide system is designed by the pinhole concept to reduce background from fast neutrons. To further minimize the background contributors, we place a 10 m "get lost tube" after the instrument, to stop the remaining fast neutrons only at a position far from the detectors.

To eliminate unwanted neutrons at the sample position, the guide is designed to transport as few unwanted neutrons as possible. In addition, to tailor the beam, we use the WISH "divergence jaws" method [chapon11]. Both jaws and slits before the sample will use boron as absorber to lower the energy of the secondary gamma radiation.

Background considerations will be integrated into the design of the central sample environment, i.e. magnets and pressure cells, so that walls are thinned in the beam path and bulky material is covered by neutron absorbing Gd paint and possibly with build-in radial collimators.

Most of the neutrons scattering from the sample environment will be absorbed in a radial collimator, which is placed in the ''nose'' part of the secondary analyser tank. For experiments where secondary energies higher than 5 meV are not needed, a 10 cm thick Be filter (with its own radial collimator) can replace the radial collimator. Two radial collimators will be available for CAMEA, one for 15 mm by 15 mm samples and one for 5 mm by 5 mm samples.

Cross-talk and other background events inside the tank will be minimized by a careful materials choice for the components inside the tank. Placing absorbing walls between analyser modules and by placing collimation between each analyser and the corresponding detectors, radially as well as vertically. Such a type of shielding, albeit on a smaller scale, was found to strongly reduce the background level of the RITA-2 spectrometer at PSI [lefmann06,bahl06].

The tank itself will consist of an Al pressure vessel, with 30 cm borated polyethylene on the outside and a Cd layer on the inside to reduce penetration of fast, epithermal, and thermal neutrons. In addition, the detectors will be mounted in Cd-clad detector housings with a directional field-of-view towards the analyser modules.

1.2.1.7 Polarization Analysis

For polarizing the incoming neutron beam CAMEA will have a guide changer that places into the guide a short supermirror polarizer. To cover the largest possible wavelength band an s-bender supermirror polarizer will be used. This polarizer will give a highly stable time-independent polarized neutron beam. The flipping of the incoming beam can be achieved by a field flipper as used on D3 at the ILL in conjunction with high field magnets[D3].

To analyse the polarization of the scattered neutron beam we will employ a polarization supermirror analyser. A wide angle ^{3}He polarization analyser was considered, but this is unable to work with the majority of required sample environments, or in stray magnetic fields. A polarization supermirror analyser will analyse the neutron polarization in front of the 10 PG analysers which will then analyse the energies of the scattered neutrons. We will use a supermirror polarization analyser that has been developed by PSI for the HYSPEC instrument at SNS, that is to be used in conjunction with a 14 T cryomagnet.

The cost estimate of the supermirror polarize to cover all scattering angles is 2.1 M€ (PSI). This system is however can be modular, so that the polarization analyser is built form individual sections for each analyser segment. An initial polarization analyser could be built to cover 5 of the 15 analyser segments.

1.2.2. Instrument Performance

1.2.2.1 Model of the Back-end

We have performed a thorough investigation of the back-end performance by McStas simulations [Simulations and Kinematic Calculations], analytical calculations [Resolution Calculations], and measurements on a prototype built inside the MARS ToF backscattering spectrometer at PSI [Prototype Report]. This has led to the numbers shown in table 2.

$E_{Analyser}$ (meV)	2.5	2.8	3.1	3.5	4.0	4.5	5.0	5.5	6.5	8.0
$D_{Sample-Analyser}$ (m)	1.00	1.06	1.13	1.20	1.28	1.37	1.46	1.56	1.67	1.79
$D_{Analyser-Detector}$ (m)	0.80	0.90	1.00	1.05	1.10	1.15	1.25	1.30	1.35	1.45
E_f resolution (μeV)	19	23	27	33	41	49	54	61	79	104
E_f resolution (%)	0.77	0.83	0.85	0.94	1.02	1.08	1.09	1.12	1.21	1.30
Outgoing Angular resolution (degrees)	0.79	0.77	0.75	0.71	0.65	0.61	0.59	0.55	0.51	0.46
Time resolution (μs)	37	28	23	22	22	22	21	22	21	19

Table 2: The main numbers of the secondary spectrometer. Only the middle detector in each detector bank is shown. The side detectors will look at an energy approximately one HWHM away and have the same resolutions. For second order reflections the absolute energy resolutions are multiplied with 4 while the time resolutions are multiplied with approximately 0.8.

1.2.2.2 Flux and Coverage

At the high flux mode the instrument will receive a (simulated) flux of up to 1.8×10^{10} n/s/cm^2/1.7 Å on the sample (above 1.4×10^{10} n/s/cm^2/1.7 Å for any 1.7 Å wavelength band fully between 1.7 Å and 5.0 Å), for the specified guide delivering a total divergence of 1.5° × 2.0°. Comparing to a triple-axis spectrometer on the same source, the flux should be around a factor 30 higher, as divergences match and we have here a wavelength band of 1.7 Å, where a triple-axis would integrate over 0.05 Å. This matches well with the predicted values of the new THALES at ILL, where the maximal flux is 4×10^8 n/s/cm^2, given the rule of thumb that a cold-neutron monochromator instrument would perform about equally well at ILL and ESS due to the similar time-averaged fluxes.

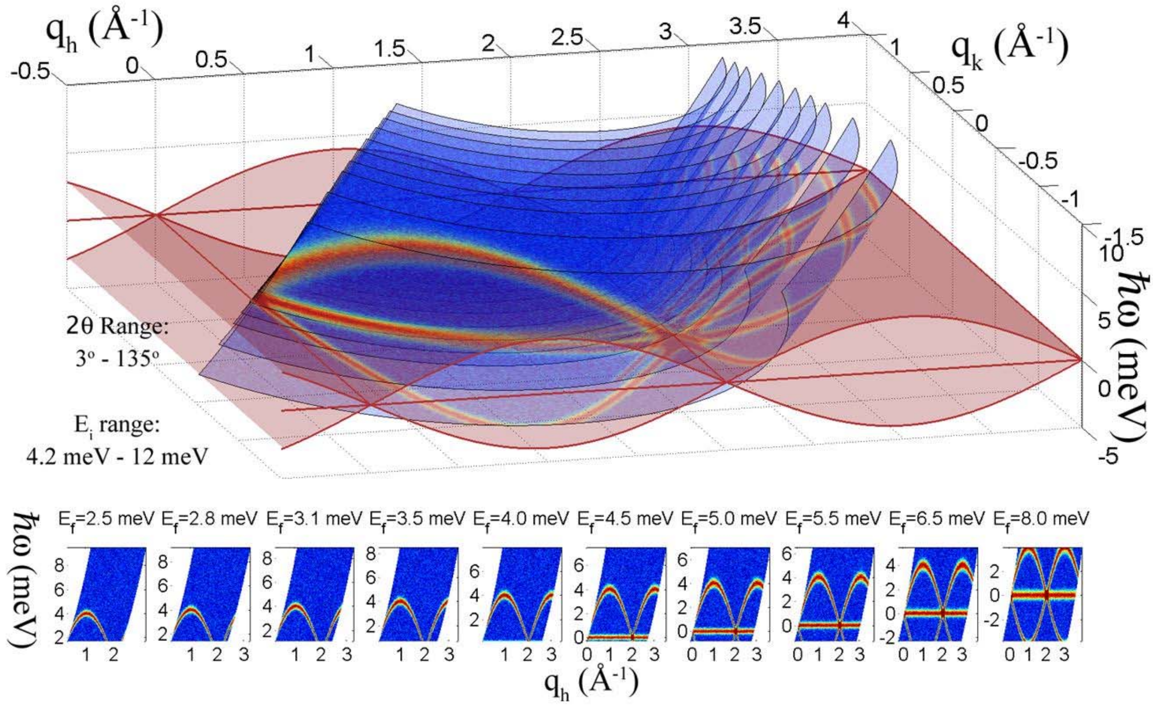


Figure 8: Simulation of data from a single CAMEA data acquisition, using a system with an elastic line and a magnon. The simulation is done for the high flux mode. For clarity we show only 10 surfaces, corresponding to 10 analyser-detector groups. When including the 3 energies from each analyser, the number would be as high as 30 (60 when including the order sorting chopper). The panel below shows the 10 individual datasets.

The graphite has a reflectivity of 60-70% and will cover a total solid angle of 0.13 steradians × 10 analysers. The neutron count rate in the detectors will of course depend on the scattering strength of the sample. For a single crystal Bragg peak, the signal in one single detector will be similar to that of a triple-axis spectrometer at ILL, e.g. IN12, but with the difference that the counts would come pulsed. Hence, the instantaneous count rate is potentially a factor 30 higher on CAMEA. Thus to protect the detectors special electronics will limit the current running through the illuminated detector.

The many angles and energies means that CAMEA will provide a selective mapping of a large part of the horizontal scattering plane in just one setting (See figure 8). In many cases this will be enough for parametric studies but it is possible to make a completely continuous map of most of the scattering plane by rotating the sample (See figure 9), or increase the energy and q range by changing the chopper settings.

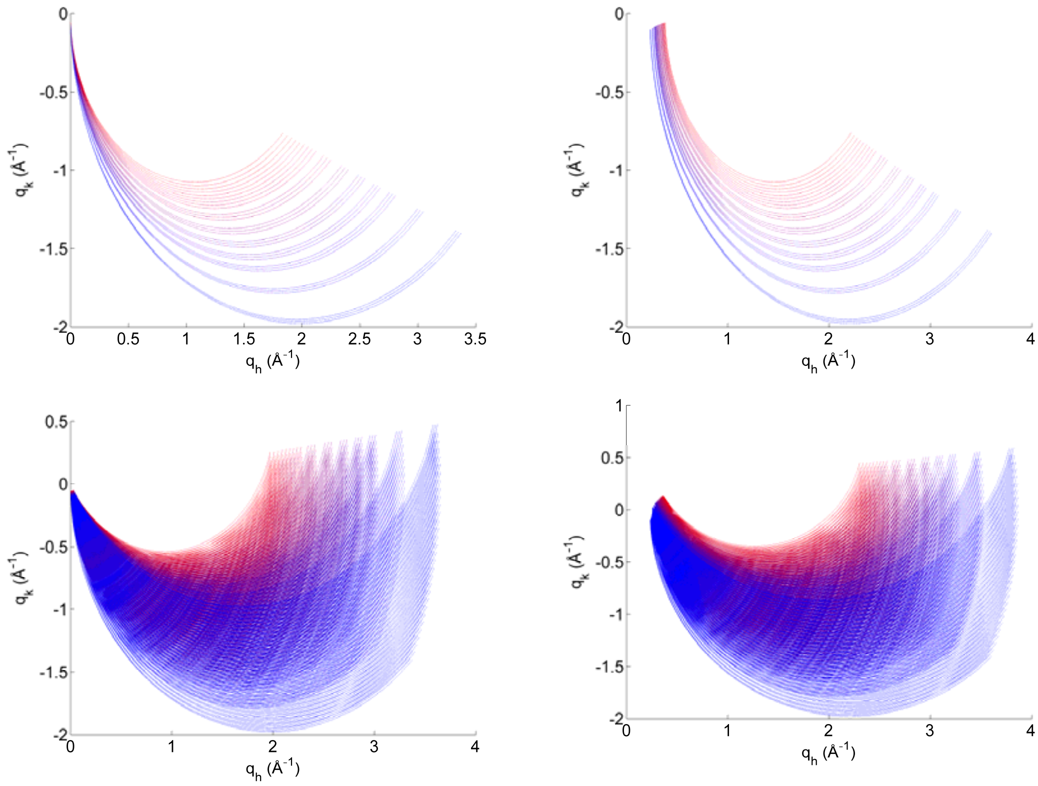


Figure 9: Schematic diagram of constant ħϖ coverage with ħϖ = 0 at left and ħω = 2 meV at right. On the top a single scan step is shown and below 31 steps of 1°. The number of analysers, that are active for a given energy transfer will depend on the chosen incoming wavelength band.

1.2.2.3 Resolution

The contributions to the energy resolution are variable for the incoming neutrons and fixed for each analyser for the outgoing neutrons. The outgoing energy resolution is ΔE/E=1.1% (FWHM) at E=5 meV. The incoming resolution at 5 meV can be varied between 3.0% and 0.1% by varying the opening time of the pulse shaping chopper, where the lower limit comes from the flight time uncertainties in the secondary spectrometer. Combining the two, one gets elastic resolutions between 4.2% and 1.1%. However, the instrument will perform best with 1.6 % where primary and secondary resolutions are matched. The latter gives a vanadium linewidth of a 78 μeV at 5 meV, twice as good as a standard TAS at that energy (See figure 10).

The angular resolution of the secondary spectrometer at 5 meV is of the order of 0.6° outgoing (See figure 11). This resolution is as good as TAS width a 40 arc minutes outgoing collimator or about 4 times better than on a focusing TAS. The incoming resolution can be varied from 1.5° and downwards leading to a total angular resolution of an elastic powder scan of between 0.8° and 1.7°. The backmost analysers will have the best angular resolution due to the longer sample-analyser distance. This will somewhat compensate the better q resolution from lower energies, as these come from the front analysers. This fact will make it easier to merge data from several analysers into one map.

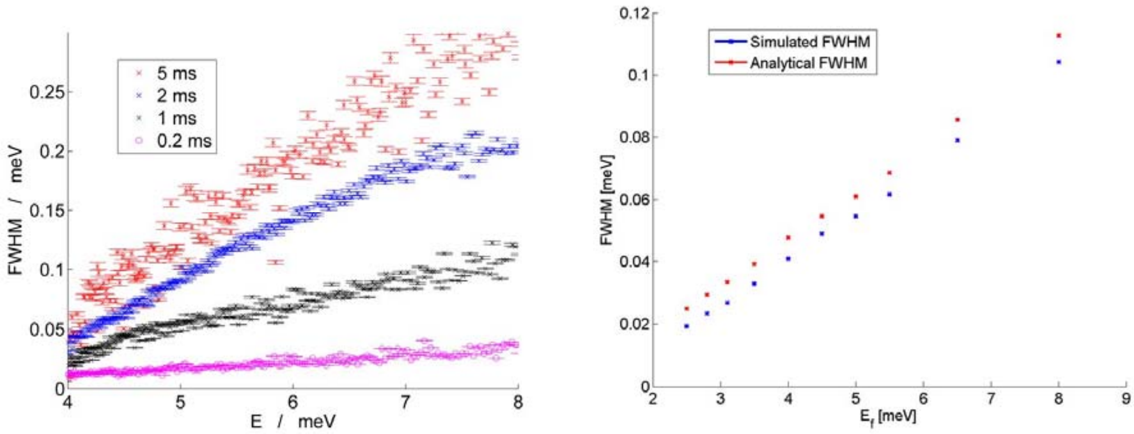


Figure 10: Left: Simulated incoming energy resolution with varying opening time of the pulse shaping choppers, running at up to 210 Hz. Right: Simulated and calculated outgoing energy resolutions for the 10 analysers.

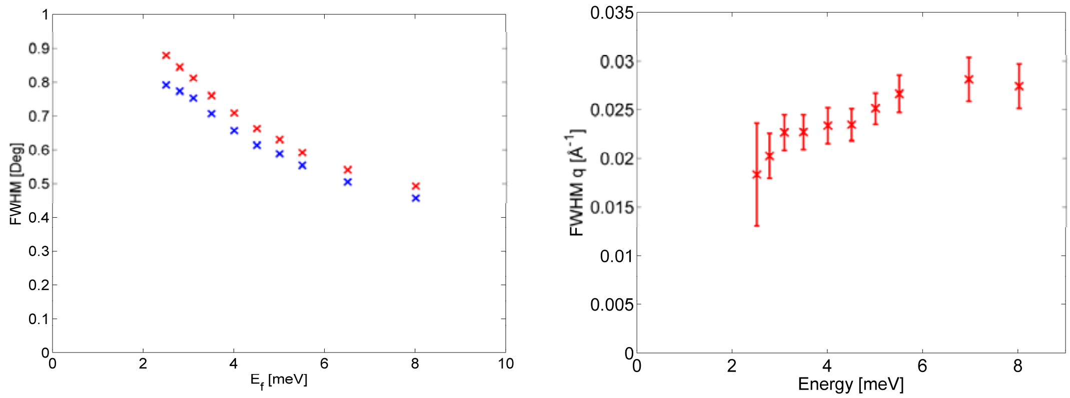


Figure 11: Left: Simulated (blue) and calculated (red) angular resolution of the secondary spectrometer. Right: momentum-resolution at the elastic line for 1 ms pulse shaping and 2θ = 60°

For time resolved studies, we need to consider also the real-time resolution. It has two main components: Uncertainty in the flight-path and uncertainty in the final energy. The two main contributors change from analyser to analyser but they are generally well matched and for most analysers the total time uncertainty is between 20 and 30 µs as seen in table 1.

This is sufficiently low for CAMEA to be competitive with other neutron spectrometers for time resolved studies, and makes it possible to resolve the field changes from a pulsed magnet.

1.2.2.4 Fast-neutron background

The fast-neutron background is a cause for concern at ESS, in particular since the accelerator is being run with a very high proton energy, creating neutrons of very high energies. The intensity of these fast neutrons decay as $1/L^2$, where L is the distance from the target and even instruments as long as CAMEA cannot ignore this contribution (as seen from e.g. background counts on instruments at ISIS TS2, where the TS1 pulse is clearly seen). Hence, line-of-sight must be broken. In the case of CAMEA, we break line-of-sight by a kink in the guide. This leads to a contribution from secondary fast neutrons. Being once out of line-of-sight may be sufficient. However, later general studies at ESS will address this question in detail.

As an additional safeguard against background, we consider the option to place a tungsten beam stop to block line-of-sight between the pinhole and the kink point in the first guide. Essentially, this is equivalent to a stopped T-zero chopper, but without the mechanical complications. This will lower the guide transmission by around 10%, an acceptable price to pay for a reduced background. To investigate this plan B, a simulation of the fast-neutron background at the sample position was performed [filges13], resulting in the order of 100 fast n/sec/cm^2. The beam block reduction factor was around 10.

For an estimation of the background from this fast-neutron flux, we imagine an illuminated area of (conservatively) 10 cm^2 and an interaction rate with a thin sample environment of (conservatively) 10 %. These tertiary background neutrons will spread in 4π steradians, and there an estimated 2 % of these will fly towards the detectors. Assuming all of these are detected, this gives us 2 fast neutrons/second background over an area corresponding to 1000 single detectors, or 0.1 count/min/detector. Even this conservative estimate gives smaller background than typical electronic noise and our background-reducing scheme is thus adequate.

1.2.2.5 Background from sample surroundings

Traditionally time-of-flight instruments have challenges when handling multiple scattering from the sample surroundings (see figure 12 left). This is due to scattering events in the sample surroundings that changes the flight length and thereby the calculated energy of the neutrons, moving the elastic background of the sample surroundings into the inelastic region. Since CAMEA is an inverse time-of-flight spectrometer the change in flight path should be compared to the primary flight path of 165 m and not the approximately 4 m secondary flight path that is the source of the problem at direct time-of-flight instruments. The difference is discussed further in the supplementary reports and leads to a distribution in the maximal region that can potentially be covered by background as shown in figure 12 right. Even for 45 cm diameter sample surroundings the broadening of the elastic line is less than $\Delta E/E$ = 0.5% on the most important positive energy transfer side for CAMEA, and is thus hidden by the instrument resolution.

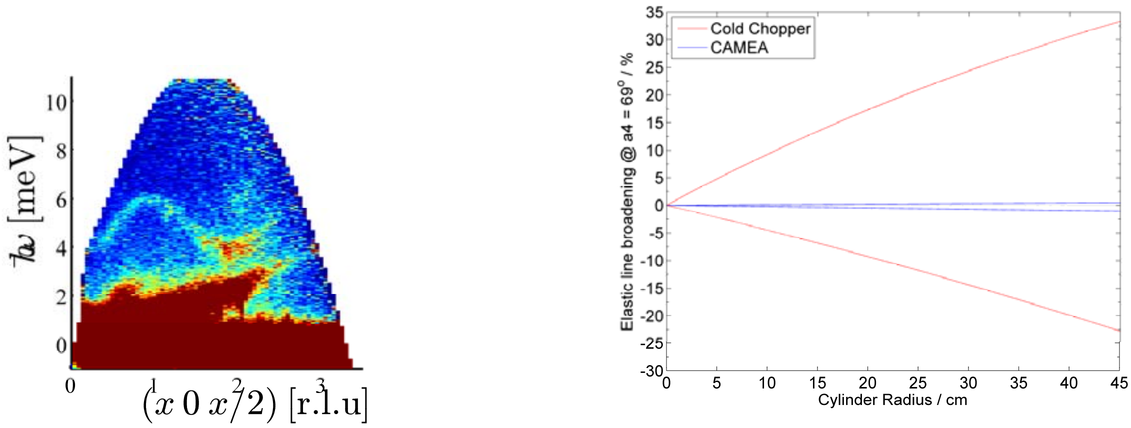


Figure 12: Examples of direct time-of-flight spectroscopy data polluted by sample surroundings. Left: CNCS, LNS data on $CoCl_2{\cdot}D_2O$ taken with the 40.5 cm radius 16 T magnet Fat Sam. No inelastic data below 3.5 meV can be seen directly due to the noise from the magnet. Right: The maximal region that can be covered by neutrons performing two scatterings in a cylinder of a given radius as seen from the centre of the CAMEA detector.

Important progress has been made on this issue for direct time-of-flight and today instruments like CNCS can perform better than suggested on the figure using a new radial collimator. However the underlying problem is still there and will be a challenge when moving towards smaller samples or bigger sample environments such as 25 T split coil magnets or pressure cells. In both cases the primary flight path of CAMEA will contain the background within the elastic line, making inelastic experiments virtually untouched by the extra background.

1.2.2.6 The prototype and performance verification

Figure 13: The prototype before (left) and after (middle) installation in the MARS tank. In the right panel all of the shielding elements are mounted (side walls, walls between the banks, slits between analysers and detectors, and a slit between the sample and the first analyser.

We have built and tested the performance of a prototype of CAMEA [Prototype report]. The prototype was designed and built at DTU and was installed at PSI in the tank of the MARS inverse time-of-flight backscattering spectrometer.

During the prototyping the following results were achieved:

- We proved that the optical alignment of the analysers is sufficient in the given geometry.
- We confirmed that by using three detector tubes we can detect three different final energies selected by one analyser (see figure 14).
- We measured the energy resolutions and the resolution ellipsoids in several different configurations. We proved that the energy resolution is independent on the analyser mosaicity. The measurement results are in good agreement with the analytical calculations and simulations.
- We identified the sources of background, and reduced the background level in a Vanadium measurement to 5×10^{-5} compared to the elastic line.
- We made measurements on a single crystal of $LiHoF_4$ and compared with the same measurement obtained at FOCUS (direct TOF spectrometer at PSI).
- We measured magnon dispersions in a $YMnO_3$ single crystal.

  Finally, we have proved that the CAMEA concept works and gathered experience in performing actual experiments on a CAMEA type instrument. The detailed description of the Prototype, and the descriptions of the measurements can be found in the [Prototype report].

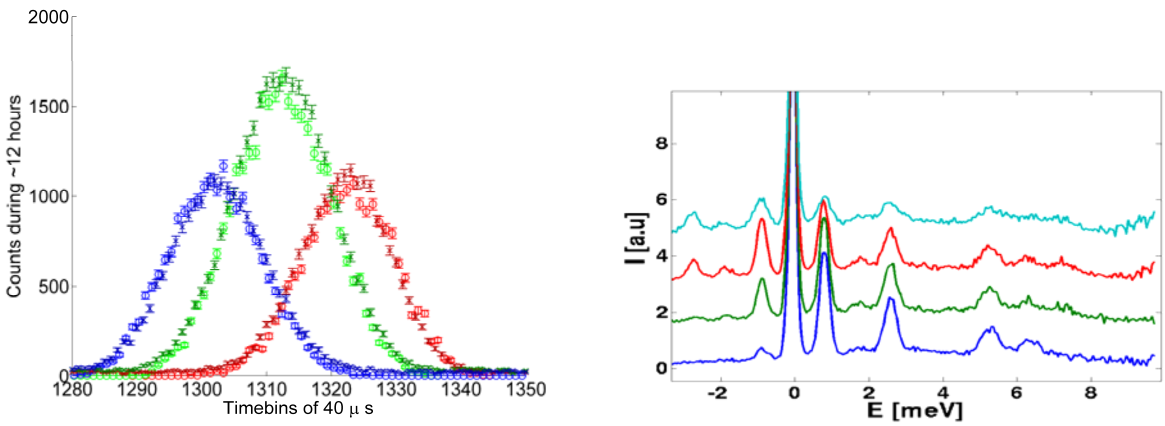


Figure 14: Left: Prototype results (crosses) and simulated data (circles) confirming that 3 detectors (blue, green and red) can detect 3 slightly different energies from one analyser and illustrating that the resolutions are well understood. Right: Inelastic prototype measurement on LiHo4F sample at 4 K (blue), 10 K (green), 25 K (red), and 70 K (magenta). The base line of each data is shifted for the sake of visibility.

1.3 Technical Maturity

While the complete CAMEA instrument is highly innovative and goes beyond any previous similar multiplexing crystal analyser instrument, each of its technical solutions have already been implemented in different instruments. All technical solutions have been discussed with and agreed upon by ESS neutron technology staff. Below we detail the feasibility and technical maturity.

1.3.1 Guide

Since ESS is the first long pulsed source the guide will be longer than what have previously been constructed in other facilities and rely on modern guide geometries to transport the flux. The CAMEA guide will however be very similar to most other long cold neutron instruments at ESS, and also to e.g. the instrument Wish as ISIS. This means that we can rely on the huge work done by ESS and simulator teams to secure that these guides will indeed deliver as promised.

1.3.2 Choppers

The proposed chopper system consists of the following choppers: Two pulse shaping choppers at 6.5 m running at up to 210 Hz, at 8 and 13 m there are bandwidth and frame overlap choppers running at 14 Hz, a frame shaping chopper at 85 m running at 14 Hz and two order sorting choppers 3 m before the sample running at 180 Hz. The choppers will be standard solutions seen at many instruments today. The proposed 210 Hz limit is far below the 360 Hz that choppers at other instruments routinely reach.

The order sorting choppers run at 180 Hz with two symmetric openings, providing effective 360 Hz. They are placed relatively close to a strong magnetic field. While significant engineering work remains for constructing a 25 T magnetic the suppliers are confident in calculating the stray field such a magnet will have. They estimate that a 25 T vertical magnet with a 1 cm split will have a stray field of 1.04, 0.31 and 0.14 milli-Tesla at respectively 2, 3 and 4 metres from the sample. Running the choppers at 180 Hz in at 3 metres distance is therefore orders of magnitude below the 100 milli-Tesla typically quoted as maximum operating field of choppers.

The chopper system is designed with choppers with big opening angles making it more robust to phase uncertainties than many other chopper systems. We do not foresee any phase uncertainty problems using standard choppers [Simulations and Kinematic calculations].

1.3.3 Sample and Sample Environment

Large field magnet: Through dialogue with magnet manufacturers, it has been shown realistic to expect that a 25 T split-coil all-superconducting magnet can be purchased by the time ESS is built. This is therefore set as the aim of the instrument. The exact price and achievable field remain to be determined, but the field will undoubtedly be better than the 16 T, 1.5 M EUR split coil magnet built in Switzerland and based at SNS. Because CAMEA is a largely superior spectrometer for use with split coil magnets, new science in new materials and previously investigated systems will become possible at any field above 16 T.

The magnet manufactures are certain that the diameter of future magnets will not exceed the 90 cm reserved in the instruments design.

Pressure cells: The limited volume inside pressure cells means that science today is both limited by technology achievable maximum pressure and the working temperature range, as well as the restrictively small sample sizes. Even without any further development in the pressure cells the increased flux and coverage of the scattering plane at CAMEA will lead to new scientific possibilities using so-called Paris-Edinburgh cells. Ongoing research both in improving Paris-Edinburgh cells to higher temperatures, and in sintered-diamond cells for higher pressures with smaller sample volume will be directly applicable for CAMEA.

Sample activation: Both sample and sample environments will be exposed to strong radiation and will become active during and after the experiments. The ESS is performing calculations of the exact doses and decay times for activation of samples on CAMEA. ESS is considering using robotics for sample change. If that method is not used, we have designed a simple mechanical interlock solution for moving active samples and pressure vessels into a storage area for cooling. The sample removal device is awaiting calculations of sample activation for CAMEA, to determine the shielding required for its design. For the magnets only the Aluminium rings are exposed to high primary radiation so it will be possible to remove a magnet shortly after the experiment.

1.3.4 Analysers

CAMEA will have 10 rows of vertically focusing Pyrolytic Graphite analysers covering a large horizontal area. The Graphite crystals are mounted on 1 mm thick silicon (100) blades, which in turn are placed in aluminium holders accurately machined to provide the correct inclinations of the Rowland geometry, thereby eliminating the need for individual alignment, and the risk of losing that alignment through vibrations.

The silicon blades are cut 3° off the Si(100) orientation, which avoids any spurious Si Bragg scattering.

1.3.4.1 Alignment

Since CAMEA rely on distance collimation and relaxed mosaicity it is less sensitive to misalignment than standard crystal analyser spectrometers. Misalignment will not influence the measured wavelength only the intensity. With 1° FWHM mosaicity the intensity in the central detector will still be at 90% even at misalignments of 0.2°. During the building of the prototype of CAMEA we learned that the inclination of the normal of the crystal surfaces and the PG(002) direction are less than 0.1° (we used Panasonic PG). This means that if the graphite crystals and the silicon blades are clean, then there is no need for extra alignment after mounting the crystals. It also means that the alignment can be easily checked by optical methods [Prototype Report].

1.3.4.2 Reduced phonon contamination

Following the literature [carlile92] and our measurements [PGreport], PG scatters the neutrons inelastically close to the Bragg peak due to the low energy phonons. This contamination has no intensity in the (00l) direction going through the PG(002) point [PGreport], but since the analysers of CAMEA will have a large mosaicity, the detectors may see inelastically scattered neutrons from the crystallites oriented out of the Bragg conditions. This phonon contamination is decreased significantly by cooling of the analyser crystals [PGreport]. Since the analysers sit in a vacuum tank, they can be relatively straightforward cooled via a base-plate on which all analyser segments are mounted by a series of pulse tube cryo-coolers. The mounting details for cooled PG has been designed and currently undergoes experimental testing at PSI. There will be no loss of alignment due to cooling.

1.3.4.3 Extinction at higher energies

The PG is polycrystalline around the c-direction, thus the (hkl) peaks (non-zero of h and/or k) will scatter out the part of the beam. This extinction appears only above 5 meV, and has a sharp edge at the lowest possible energy for a given peak at a given orientation [PGreport]. Analysers that work above 5 meV (the 8-10th analysers away from the sample position) work at energies that are chosen to avoid any energy for which the transmission of neutrons through PG mounted on Si support is low.

1.3.5 Detectors

The design work so far has focused on ^{3}He tubes as detectors for CAMEA, but the instrument will work with any of the currently applied detector technologies. The choice of detector technology will be made together with the ESS detector group. Changing to solid state detectors will give almost the same count rates and background suppression but cause an increase in the detector thickness, which will have a small but tolerable influence the separation into several energies per analyser.

The detectors may saturate and potentially be damaged if exposed to high count rates from strong Bragg peaks in the sample. The solution that has been devised together with ESS detector group to eliminate this risk is a circuit which lowers the high-voltage supply and thereby the efficiency of detectors when too high count rates are recorded. This allows measurements to be performed more efficiently than by attenuating the incoming beam and the locally attenuated parts of a dataset can be corrected in the normalisation section of the analysis software. Since Bragg peaks move in and out of scattering condition on the ~seconds time scales of rotating the sample, voltage-controlling electronics can easily follow.

Should for any unforeseen reason this solution not be desired (e.g. in the unlikely case of a novel solid state detector technology, where it is not possible), a mechanical fall back option is a gallery of attenuating strips which lifts into the beam to block the angular range receiving Bragg scattered neutrons.

1.3.6 Electronics

The electronics have two major parts: detector electronics, and chopper driver electronics. These have no special requirements compared to the other instruments at ESS. However, the instrument is designed for extreme sample-environments, and the incoming flux will be high. All motors, encoders and other sensors at the secondary instrument should be designed to work in a high magnetic field and under high dose rates. For the fine movements (eg. driving of slits) piezo motors are recommended. For less fine movements (eg. for rotation of the omega-table or for rotation of the secondary instrument) pneumatic motors can be used. Close to the sample environment mechanical encoders are preferable due to their insensitivity to high magnetic fields and radiation. The challenges have been discussed with the ESS electronics group and they have found electronic solutions that can withstand both the radiation and magnetic field in question.

1.3.7 Shielding

The shielding around the detector tank will be built from tested materials and methods. Open geometry instruments can achieve low background levels by using similar techniques. For example at Rita-2 at PSI, we were able to suppress the background in the inelastic range down to 0.1 counts per minute for a 5 inch by 1 inch detector area [Lefmann 06]. Inside the detector tank shielding “chimneys” will ensure that detectors only “see” the relevant analysers. Slits and collimators will be constructed using standard solutions and materials. Further the prototyping have proven that we can achieve inelastic background levels of $5 \bullet 10^{-5}$ compared to the elastic line of cooled Vanadium, even without the use of radial collimators.

1.4 Costing

The costing of CAMEA is based on information from several sources as indicated in the table below. Costing was done conservatively in all cases. The largest uncertainties concerns the price of guide shielding, the price of shutters, which may be significantly lower if CAMEA does not need a heavy shutter, and finally the price of a 20+ Tesla split coil magnet based on high-T_c technology.

In the table below, the costing is divided into four categories: Guides and shielding, CAMEA spectrometer, sample environment for CAMEA, and manpower. For details, we refer to the CAMEA costing report [Costing Report].

Costing item	Price [M€]	Source of information and comments
Guides and shielding		
Guides	1,310	Swiss Neutronics.
Mechanics and installation	1,295	Swiss Neutronics.
Guide shielding	2,142	ESS. This assumes a ratio of guide cost to shielding cost of 1:2. The ratio is expected to be in the range 1:1 to 1:2.
Instrument cave and beam stop	1.000	ESS.
Shutters	0.790	ESS. MCNPX simulations are needed to decide on the need for a heavy shutter (0.75 M€)
Vacuum pumps for guides	0.056	CAMEA team.
Sum for guides and shielding	**6.593**	
CAMEA spectrometer		
Choppers	1.425	ESS.
Divergence jaws	0.123	ISIS.
Sample table	0.034	CAMEA team.
Vacuum tank	1.058	CAMEA team.
Vacuum pump	0.025	CAMEA team.
PG analyzer crystals and Si wafers	1.466	CAMEA team.
Cooling machines for analyzers	0.255	CAMEA team.
Detectors	0.897	ESS and CAMEA team.
Beryllium filter	0.222	ISIS.
Radial collimator	0.050	JJ X-ray.
Electronics	0.402	ESS.
Polarization analysis	2.100	Neutron optics Berlin, PSI and CAMEA team.
Sum for CAMEA spectrometer	**8.057**	
Sample environment for CAMEA		
Magnets	3.230	CAMEA team in communication with magnet suppliers. This includes a 20+ Tesla split coil magnet estimated at 2.5 M€
Pressure cell	0.580	Stefan Klotz. Université P. & M. Curie, France.
Sum for sample environment	**3.810**	
CAMEA cost excluding manpower	**18.460**	
Manpower		
Lead scientist (5 years) Lead engineer (5 years) Technical staff (11 years)	1.460	CAMEA team.
Sum for manpower	**1.460**	
Total cost of CAMEA	**19.920**	

Schematic spending profile: We consider the following parts of the construction phase (1) Design and Planning; (2) Final Design; (3) Procurement and Installation; (4) Beam Testing and Cold Commissioning, and outline a rough spending profile. We assume a 5-year construction period starting from when the lead Scientist and lead engineers have been recruited. Costs related to the categories “Guides and Shielding” and “The CAMEA spectrometer” will be incurred mostly (~90%) in the Procurement and Installation phase, when the instrument is finally approved to go into physical construction. Some costs (~10%) from these categories can, however be expected during the “Beam Testing and Cold Commissioning” phase. The costs in the category “Sample environment” will be adjusted to match expected delivery times for the magnets, pressure cells and auxiliary equipment.

References

[bahl06] C.R.H. Bahl, K. Lefmann, A.B. Abrahamsen, H.M. Rønnow, F. Saxild, T.B.S. Jensen, L. Udby, N.H. Andersen, N. B. Christensen, H. S. Jacobsen, T. Larsen, P Häfliger, S. Streule, and Ch. Niedermayer, *Inelastic neutron scattering experiments with the monochromatic imaging mode of the RITA-2 spectrometer*, Nucl. Instr. Meth. B, **246**, 452 (2006)

[bertelsen13] M. Bertelsen, H. Jacobsen, U.B. Hansen, H.H. Carlsen, K. Lefmann, *Exploring performance of neutron guide systems using pinhole beam extraction*, Nucl. Instr. Meth. A (2013)

[bertelsen14] M. Bertelsen and K. Lefmann, Optimizing neutron guides : the analytical minimalist concept and the program guide-bot, in preparation for J. Appl. Cryst. (2014)

[birk14] J.O. Birk et al, in preparation for Journal of Applied Crystallography (2014)

[carlile92] C.J. Carlile and M.A. Adams, The design of the IRIS inelastic neutron spectrometer and improvements to its analysers. Physica B 182 (1992) 431-440

[chapon11] L. C. Chapon, P. Manuel, P.G. Radaelli, C. Benson, L. Perrott, S. Ansell, N.J. Rhodes, D. Raspino, D. Duxbury, E. Spill, J. Norris, *Wish: the new powder and single crystal magnetic diffractometer on the second target station*, Neutron News 22:2, 22 (2011)

[cussen13] L.D. Cussen, D. Nekrassov, C. Zendler, K. Lieutenant, Multiple reflections in elliptic neutron guide tubes, Nucl. Instr. Meth. A 704, 121 (2013)

[D3] http://www.ill.eu/instruments-support/instruments-groups/instruments/d3/characteristics/

[ESS-SymposiumonSpinDynamics12] http://europeanspallationsource.se/sites/default/files/spin_dynamics_of_correlated_electron_systems_2012.pdf

[filges13] U. Filges, unpublished MCNPX results (2012,2013) [jacobsen13] H. Jacobsen, K. Lieutenant, C. Zendler, and K. Lefmann, *Bi-spectral extraction through elliptic neutron guides,* Nucl. Instr. Meth. A **717**, 69 (2013)

[Hirschmann12] M. Hirschmann and D. Kohlstedt, Physics Today **65** (3), 40 (2012),

[Kempa06] M. Kempa, B. Janousova,J. Saroun, P. Flores, M. Boehm, F. Demmel, and J. Kulda, Physica B-cond. Mat. **385-86**, 1080 (2006).

[klenø12] K.H. Klenø, K. Lieutenant, K.H. Andersen, and K. Lefmann, *Systematic performance study of common neutron guide geometries*, Nucl. Instr. Meth. A, **696**, 75 (2012)

[lefmann06] K. Lefmann, Ch. Niedermayer, A.B. Abrahamsen, C.R.H. Bahl, N.B. Christensen, H.S. Jacobsen, T.L. Larsen, P. Häfliger, U. Filges, and H.M. Rønnow: *Realizing the full potential of a RITA-type spectrometer,* Physica B **385-386**, 1083-1085 (2006)

[lefmann13] K. Lefmann, K.H. Klenø, J.O. Birk, B. R. Hansen, S.L. Holm, E. Knudsen, K. Lieutenant, L. von Moos, M. Sales, P.K. Willendrup, K.H. Andersen, *Simulation of a suite of generic long-pulse neutron instruments to optimize the time structure of the ESS*, Rev. Sci. Instr. **84**, 055106 (2013)

[oxford13] Oxford Instruments, personal communication (2013)

[Rheinstädter04] M.C. Rheinstädter, C. Ollinger, G. Fragneto, F. Demmel, and T. Salditt, Phys. Rev. Lett. **93** , 108107 (2004)

[Rheinstädter12] M.C. Rheinstädter, Chapter 10 Lipid Membrance Dynamics, Dynamics of Soft Matter. Neutron Applications, Neutron Scatterng Applications and Techniques, V. García Sakai, *C. Alba-Simionesco, S.-H. Chen.* (editors), Springer Sciebnce + Business Media, 2012.

[Rodriguez08] J A Rodriguez, D M Adler, P C Brand, C Broholm, J C Cook, C Brocker, R Hammond, Z Huang, P Hundertmark, J W Lynn, N C Maliszewskyj, J Moyer, J Orndorff, D Pierce, T D Pike, G Scharfstein, S A Smee and R Vilaseca, Meas. Sci. Technol. **19**, 034023 (2008)

[schober08] H. Schober, E. Farhi, F. Mezei, P. Allenspach, K. Andersen, P. Bentley, P. Christiansen, B. Cubitt, R. Heenan, J. Kulda, P. Langan, K. Lefmann, K. Lieutenant, M. Monkenbusch, P. Willendrup, J. Saroun, P. Tindemans, and G. Zsigmond, *Tailored Instrumentation to Long Pulse Neutron Spallation Sources*, _Nucl. Instr. Meth. A **589**, 34 (2008)

[zendler12] C. Zendler, K. Lieutenant, D. Nekrassov, L.D. Cussen, M. Strobl, *Bi-spectral beam extraction in combination with a focusing feeder*, Nucl. Instr. Meth. A 704, 68 (2012)

CAMEA Reports Available Online:

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[PGreport]
https://infoscience.epfl.ch/record/190504?ln=en

[Prototype Report]
http://infoscience.epfl.ch/record/197952?ln=en

[Resolution Calculations]
https://infoscience.epfl.ch/record/190497?ln=en

2. LIST OF ABBREVIATIONS

Abbreviation	Explanation of abbreviation
CAMEA	**Continuous Angle Multiple Energy Analysis**
CQS	**Constant q Spectrometer**
DTU	**The Technical University of Denmark**
EPFL	**The École polytechnique fédérale de Lausanne**
ESS	**European Spallation Source**
FWHM	**Full Width Half Maximum**
HZB	**Helmholtz-Zentrum Berlin**
ILL	**Institut Laue-Langevin**
KU	**University of Copenhagen**
INX	**Inelastic X-ray Scattering**
PG	**Pyrolytic Graphite**
PSI	**Paul Scherrer Institute**
QENS	**Quasi-Elastic Neutron Scattering**
RITA (II)	**Re-Invented Triple Axis**
RIXS	**Resonant Inelastic X-ray Scattering**
SNS	**Spallation Neutron Source**
TAS	**Triple Axis Spectrometer**

PROPOSAL HISTORY

New proposal:	yes
Resubmission:	– no