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ESS Instrument Construction Proposal
CAMEA

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	Name (name, title, e-mail address)	**Affiliation** (name of institution, address)
Proposer	Henrik Ronnow, Prof., Henrik.ronnow@epfl.ch	EPFL SB ICMP LQM PH D2 455 (Bâtiment PH) Station 3 CH-1015 Lausanne Switzerland
Co-proposers	Kim Lefmann, Prof., lefmann@fys.ku.dk	University of Copenhagen, Universitetsparken 5, D 2100 København Ø, Denmark
	Niels Bech Christensen, Prof. nbch@fysik.dtu.dk	Technical University of Denmark, Fysikvej, 311 DK-2800, Kgs. Lyngby, Denmark
	Christof Niedermayer , Prof., christof.niedermayer@psi.ch	Paul Scherrer Institute, 5232 Villigen – PSI, Switzerland
	Fanni Jurányi, Dr., fanni.juranyi@psi.ch	Paul Scherrer Institute, 5232 Villigen – PSI, Switzerland
	Márton Markó, Dr. marton.marko@psi.ch	Paul Scherrer Institute, 5232 Villigen – PSI, Switzerland
	Jonas Okkels Birk, Mr., jonaso@fys.ku.dk	University of Copenhagen, Universitetsparken 5, D 2100 København Ø, Denmark
	Mads Bertelsen, Mr., mads.bertelsen@gmail.com	Niels Bohr Institute, Universitetsparken 5, D 2100 København Ø, Denmark
	Jacob Larsen, Dr., jacb@fysik.dtu.dk	Technical University of Denmark, Fysikvej, 311 DK-2800, Kgs. Lyngby, Denmark
	Paul Gregory Freeman, Dr., paul.freeman@epfl.ch	EPFL SB ICMP LQM, CH-1015 Lausanne, Switzerland.

ESS coordinator	Nikolaos Tsapatsaris	

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	Name
Document submitted to	Ken Andersen
Distribution	Dimitri Argyriou, Oliver Kirstein, Arno Hiess, Robert Connatser, Sindra Petersson Årsköld, Richard Hall-Wilton, Phillip Bentley, Iain Sutton, Thomas Gahl, relevant STAP

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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 scattering. 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 ~1000mm3 samples is currently the practical limit for neutron spectroscopy **CAMEA makes it possibly to study <1mm3 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 in up to pressures of >10GPa 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 geo-physically 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 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 without risk**, 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 Scientific Case

We propose an indirect geometry neutron spectrometer optimized for high efficiency neutron counting within the horizontal scattering plane to be constructed as one of the instruments in the spectrometer instrument suite at the ESS. To obtain the highest count rate at the ESS we take advantage of the large neutron flux of a medium bandwidth of incident neutron wavelengths, and utilize 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 concept is called CAMEA, the Continuous Angle Multi-Energy Analysis spectrometer. The proposed instrument is 170 m long from neutron source to sample, with 10 analyser arcs at distances of between 1m – 1.6 m from the sample position, scattering neutrons vertically downwards into position sensitive detectors to detect the horizontal scattering direction and energy.

The distance collimated analysers gives the instrument an energy resolution slightly better than most cold neutron triple axis spectrometers, $\Delta E/E$ of 1.2-4.2 %, which matches 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. For a comparison CAMEA and cold direct Time of Flight spectrometers, see [Comparison to Cold Chopper]

The instrument concept was invented following scientific needs within several communities [Scientific demand for CAMEA]. The instrument performance and optimization has 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 and tested with neutrons. Prototype testing of the concept 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.

With the chosen energy resolution the instrument has well established uses in inelastic neutron scattering that can be extended to new experimental techniques. 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). Within the work package there is considerable experience in inelastic neutron instrumentation, with Henrik Ronnow (EPFL), Kim Lefmann(KU), Niels Bech Christensen (DTU) and Christof Niedermayer (PSI) involved in work on the RITA concept, plus the experience of Fanni Jurányi (PSI) on the FOCUS and MARS spectrometers at PSI, Márton Markó's (PSI) experience of the MARS spectrometer and Paul Freeman's (EPFL) experience on IN8 at I.L.L., France and EXED at H.Z.B., Germany. The work in the proposal has been carried out from September 2011 to 31st October 2013. This proposal 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 high neutron flux of the ESS pulses brings the possibility to conceive novel instrument concepts that utilize both the high peak intensity and the integrated intensity to open up new experimental possibilities in neutron scattering. 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:

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 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]. We note that presently S = ½ magnetic excitations can be measured in 10 mm^3 single crystals on the highest flux double focusing thermal triple-axis-spectrometer in the world, IN8 at the ILL.

The good energy and momentum resolution will enable high definition mapping of excitations in a flat scattering plane, greatly facilitating interpretation of complex excitation spectra. In systems such as quantum magnets there are often a weak continuum of excitations spread across large areas of reciprocal space. The detailed structure of these modes that can be measured by neutron spectroscopy presently is inferior to that which can be theoretically predicted. High definition mapping by high count rates on CAMEA will bridge this gap to test our fundamental understanding of quantum magnetism.

The high count rate and essentially complete angular and energy coverage in a single acquisition will enable continuous parametric scanning of excitations and time resolved studies. 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 the materials' 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 to a sample parameter in a continuous manner, equivalent to a temperature ramp in powder neutron diffraction. With a time resolution better than 30 μs 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. The time resolution is also sufficient to capture the magnetic field dependence during a pulsed magnet cycle[concept and science case].

The CAMEA instrument has been designed to achieve a high signal-to-noise ratio by minimizing the background count rate. In comparison to the open scattering geometry of double focusing and direct geometry time-of-flight spectrometers, CAMEA will have a tightly defined neutron flight path that reduces visibility of the sample environment and diffuse background scattering by use of neutron shielding, radial and cross-talk collimation. Collimation between the sample position and the analysers removes the visibility of the sample environment that is not achieved on direct geometry time-of-flight spectrometer. In direct geometry time-of-flight spectrometer neutrons that scatter off the sample environment scatter directly into the neutron detectors as additional structured background. Added to collimation is the ability to tightly define the incident neutron beam with a series of jaws to reduce the number of neutrons not reaching the sample position, this concept has been implemented on the WISH instrument at ISIS[Chapon11]. A small beam size is vital for studying small samples of crystals that cannot be grown in large size due to special growth techniques, e.g. single crystals of newly discovered materials. A small beam size is also essential for studying samples in pressure cells where the sample volume is very limited. With this instrument concept at the ESS we will be able to study excitations in 1 mm^3 sized samples[bench marking].The multi-energy analysis provides several benefits in addition to the order of magnitude gain in count rates. By having 10 analysers the instrument covers all the desired energy resolution for performing cold neutron spectroscopy. By simultaneously measuring with different energy resolutions, phenomena such as damping of excitations can be tracked from long-lived sharp excitations to highly damped broad signals using a single experimental setting with ample overlap between different resolution settings to achieve highly robust analysis of the data. The large sample space of 90 cm diameter provides significant room for the needs of complex sample environment. Although CAMEA will be adapted for studying excitations in the 0-20 meV energy range, the use of an order sorting chopper and second order Bragg reflections from the analyser crystals will allow excitations to be studied out to 60 meV.

This instrument represents an advancement for inelastic neutron scattering in scientific fields where clear applications can be identified. 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, such as applied magnetic fields or applied pressure. In the case of using applied magnetic fields this instrument creates the ability to scan across the transition to determine the nature of quantum magnetic phase transitions[concept and science case].

Applying extreme pressures to study materials is presently of minimum use in inelastic neutron scattering due to the limited sample volume that can be used in pressure cells. CAMEA will open the door to systematic studies of excitation spectra up to very high pressures. Pressures of 1-10GPa are sufficient to induce measurable changes in hopping integrals that govern electronic motion between states and hence effects the electronic interactions. 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 can become as significant an evolution in neutron scattering as the introduction of position sensitive detectors on direct geometry time-of-flight spectrometers. Beyond studies of magnetic excitations, there exist a great hitherto unaccommodated interest to study of phonons in fundamental materials under extreme pressure, and for geo- and planetary science related studies such as hydrogen diffusion in materials of the Earth's upper mantle.

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 of e.g. 100 μm in diameter. But x-ray scattering has significant disadvantages in comparison to inelastic neutron scattering. In measuring phonons 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 10 μeV for inelastic neutron scattering. 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 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. It is therefore clear that the wavevector and energy dependences that can be obtained by cold inelastic neutron scattering are unique.

1.1.2 User Base and Demand

The proposed instrument addresses the needs of multiple user communities in condensed matter physics, especially but not 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 material devices in the future. An illustrative analogy is how the development of the theory of electrons in solids enabled the development of solid state devices such as the transistor.

We have studied the user base and demand for the instrument proposal, as can be found in the report "concept and science case". The correlated electron and magnetism research fields dominate the user community of a large number of 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 study materials under extreme pressures. There is no existing specialist spectrometer in the world to perform the highly demanded extreme environment experiments, and there is a demand from this neutron scattering community for an instrument suited to extreme environment spectroscopy [ESS-SymposiumonSpinDynamics12]. On top of the identified existing demand, additional demand from new research communities can be expected for in-situ measurements of excitations, time resolved studies (i.e. pulsed magnetic fields), excitations in soft matter aligned by high magnetic fields, high pressure and high temperature studies of materials, i.e. geo- and planetary sciences.

1.2 Description of Instrument Concept and Performance

1.2.1 Instrument description

ESS-CAMEA is a cold-neutron inverse-geometry time-of-flight spectrometer: The incoming energy is determined by time-of-flight, while neutrons with particular outgoing energies are scattered into the detectors by crystal analysers. CAMEA differs from usual inverse-geometry instruments by having several analyser banks behind each other. This allows for detection of a large fraction of the neutrons scattered within the horizontal plane. This combination makes CAMEA well suited for mapping of excitations within the scattering plane, and for use in combination with sample environment that limits the outgoing vertical scattering angle, e.g. magnets and pressure cells. An overview of the instrument is seen in figure 1.

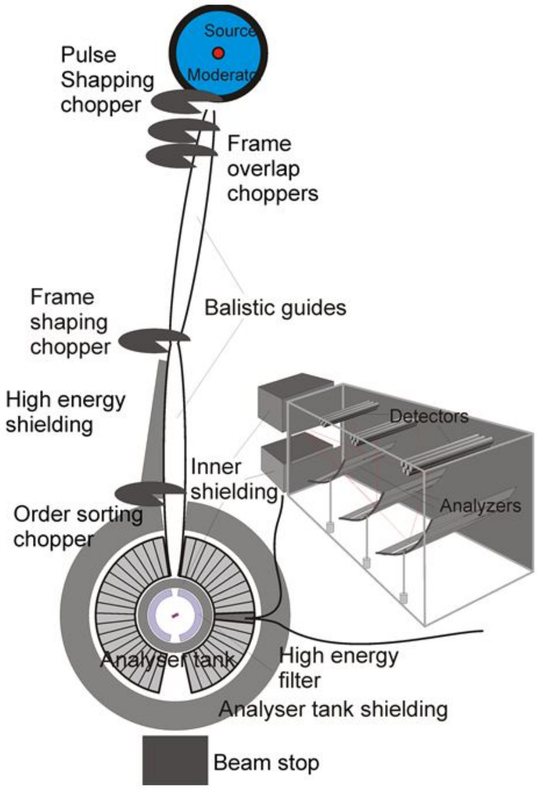

Figure 1: An overview of the CAMEA instrument (not to scale). Two long ballistic guides lead the neutrons from moderator to sample. The guides are kinked by a small angle to avoid direct line-of-sight. The sample is surrounded by the analyser-detector chamber, that covers a large fraction of the 360° scattering 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. 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. The most frequently used incoming energy band will thus cover the range 1.6-28 meV, or in wavelength 1.7-7 Å.

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, zendler13], to eliminate the risk of a novel guide concept. In a bispectral system, degradation of the first reflecting supermirrors could lead to a loss of cold neutrons and thus compromise the whole instrument.

A key strength of CAMEA is the possibility to combine good resolution and 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 resolution would be halved, but the coverage doubled. It is however also possible for a long instrument to trade flux for coverage by rotating the 14 Hz choppers at a lower frequency, whereas the opposite is not possible for frame multiplication instruments. For instruments with monochromating choppers the calculation is different since they will trade dense coverage for a wider coverage and many such instruments choose the later, but in the case of CAMEA the long instrument is simply better in its main focus area. So we have chosen an instrument with a length of 170 m as this is the natural length where the 71 ms frame can be filled by one pulse for all resolutions, when the first chopper is placed at the minimum 6.5 m [schober08, lefmann13]. This gives a 1.66 Å wide wavelength band. In the high-flux mode, the instrument can run even without using the pulse-shaping chopper.

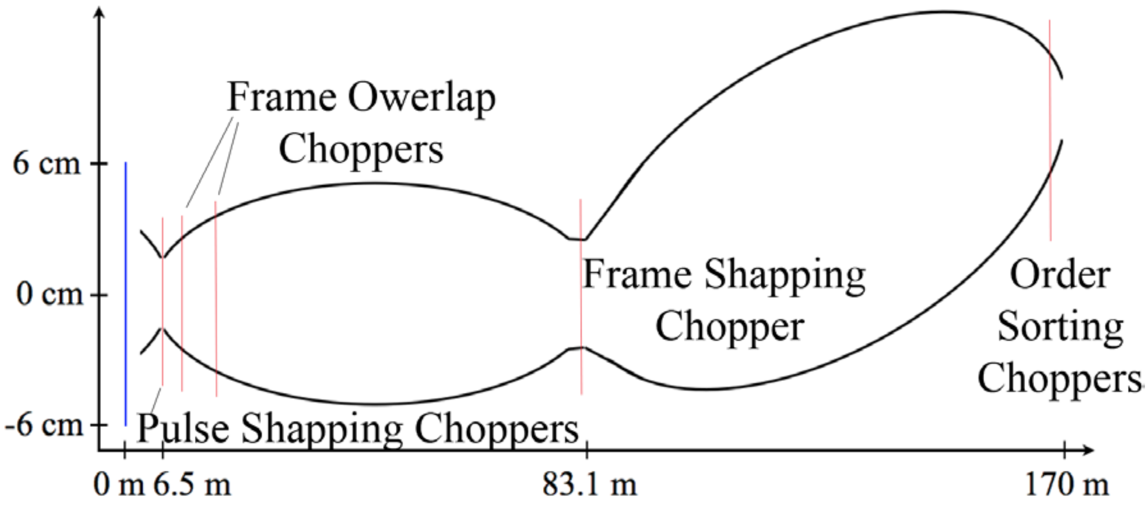

Figure 2: Sketch of guide and chopper system.

For the beam extraction system, CAMEA uses a pinhole with a "feeder" guide piece close to the moderator [bertelsen13a] 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 beam spot is 15 x 15 mm^2 and that the desired divergence is ± 1.0 degrees vertical and ± 0.75 degree horizontal. A combination of analytical calculations, McStas simulations, and automated optimizations [bertelsen13b] lead us to choose a 30 mm wide pinhole, after the gap for the pulse shaping chopper which starts at 6.5 m and ends at 6.6 m. The guide opening is 98 mm tall at 6.6 m (see also next section).

The guides are here chosen to be elliptical, although parabolic-straight-parabolic combinations may perform equally well [klenø12] and could be seen as an alternative guide option. The guides have a maximum width of 0.23 m for the vertical part and 0.15 m for the horizontal. The guide sections are kinked with respect to each other by 0.056 degrees 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 only small flux cost (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 typically run in the same direction and run at a small multiple of the source frequency. The chopper diameter is 700 mm and is has an opening angle of 170 degrees. This makes it possible to use the entire ESS pulse in a high flux mode or reduce the opening to increase the resolution. We foresee that 0.2 ms will be needed to achieve good resolution at the highest energy (20 meV), matching the resolution contribution of the 5 meV analyser (0.06 meV). To achieve the short opening times with a good pulse shape it is necessary to increase the chopper frequency to up to 210 Hz.

Both frame overlap and the extra pulses generated when running the pulse shaping faster than 14 Hz 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 band defining chopper, of same size but 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.

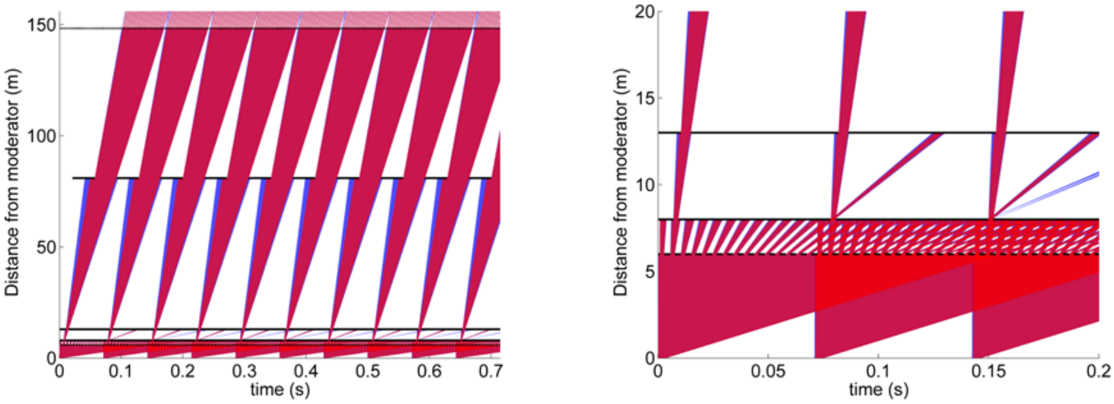

Figure 3: Left: time-distance diagram of the CAMEA guide system, right: zoom of the first 20 m. The pulse is shaped by the first chopper pair at 6.5 m, while the next two choppers are eliminating frame overlap and the shaping of the wavelength band is done by the last chopper. The chopper close to the sample is an "order sorting chopper" to be detailed in fig. 4.

At 1.7 m before the sample is placed a so-called ''order-sorting chopper''. This optional double chopper has an opening of 160 degrees and spins with 360Hz. 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.

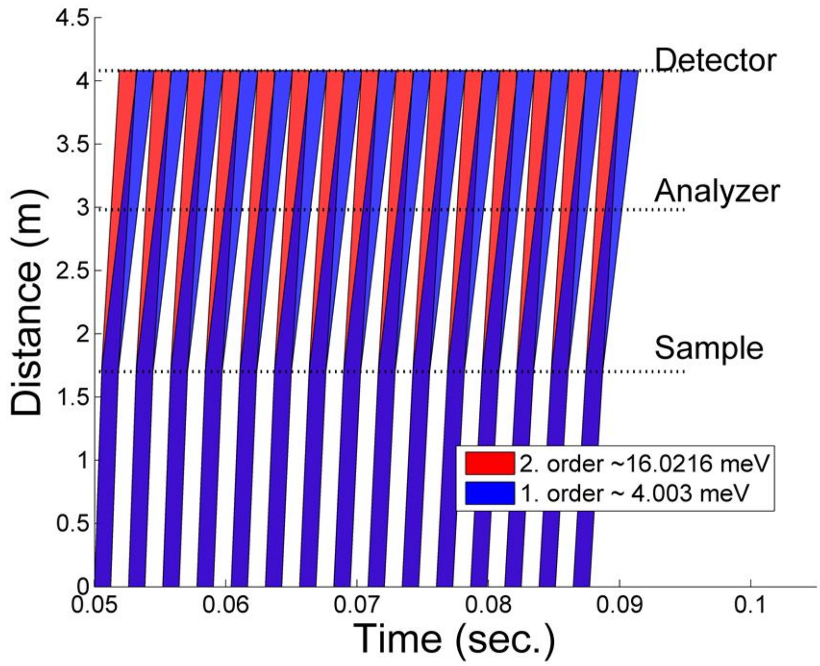

Figure 4: Time-of-flight diagram of the order sorting chopper. The figure shows a Time of Flight diagram of the signal after an order sorting chopper set to separate first and second order scattering by time of flight. The Time of Flight diagrams are different for each analyser, here the 5th is displayed.

1.2.1.3 Sample and sample environment

The samples are foreseen to be mostly single crystals. The sample is placed on a sample table of the type known from most 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. sufficiently solid to sustain the weight of the magnet and with no own 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 already the case presently, e.g. for 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 the standard cryostat will be equipped with standard variable temperature inserts for 2-350K temperatures, and with dilution refrigerator inserts for temperatures down to 30mK.

Sample sticks will be available to provide an additional electrical field up to 10 MV/m. 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 (>10T) 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 sample transport cylinder, similar style as used for transportation of fuel rods. The transport cylinder is positioned at the sample environment top during sample change, and the cylinder stays around the lower part of the sample stick during transport to a cool-down area by a crane. See the Technical Solutions report for details [Technical Design].

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 132 degrees scattering angle to 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, as sketched in figure 1.

The analyser-detector module inside the tank is positioned on rails so that is 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^o degrees with a 6^o active area. The first segment will be a special half size segment to get as close as possible to the direct beam.

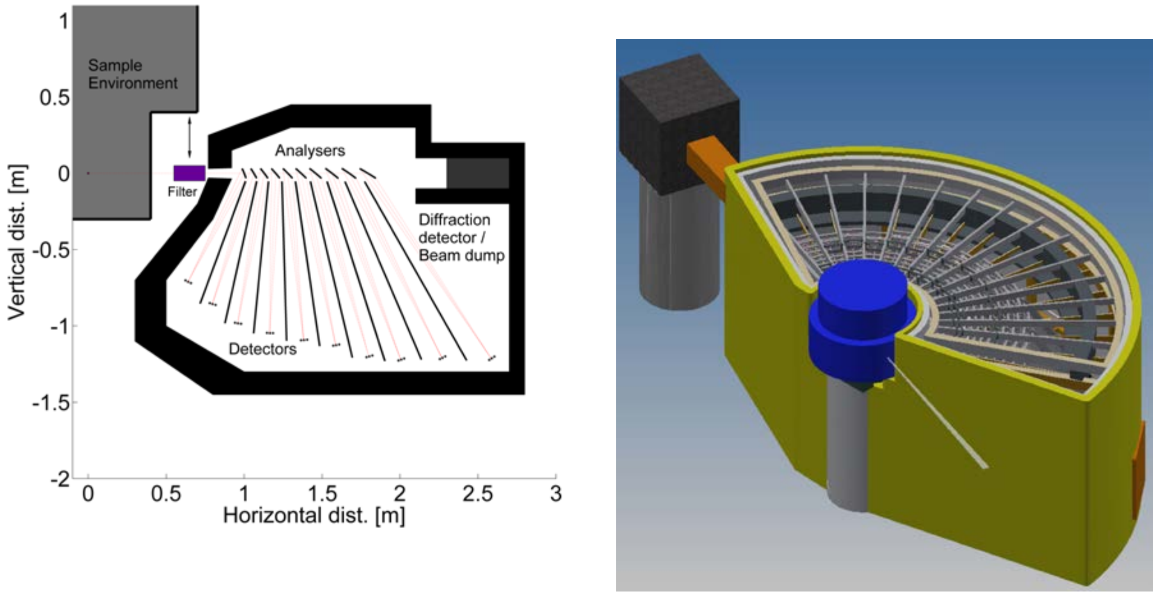

Figure 5: Left: A vertical cut of the secondary spectrometer tank. The sample is at the left, and the neutrons travel from there through the filter. Then the neutrons pass through (possibly) several single-focusing analyser arrays, until scattered towards the detectors. Right Technical drawing of the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

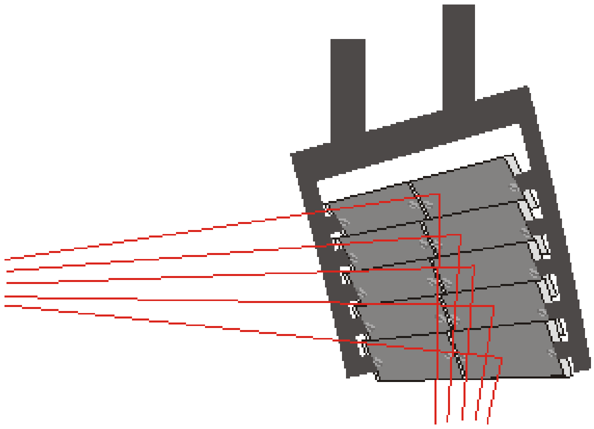

Figure 6: Illustration of analyser layout. The analysers are screwed into Si wafers that are mounted in an Al frame. Each Si wafer can be rotated manually. The individual PG crystals are aligned to the Si beforehand width small Al spacers if needed. The actual analysers will have between 7 and 11 wafers with each 3 to 5 analyser crystals depending on E_f.

1.2.1.5 Analyser-detector geometry

The truly novel part of the CAMEA spectrometer is the analyser-detector arrangement. We use thin (1 mm) pyrolytic graphite (PG) of low 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 banks 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 Rowland focusing much like on a backscattering spectrometer (See figure 6). The PG is held in place by aluminium holders that ensures the focusing condition for each particular energy.

The detectors are 1/2 inch 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. The positional resolution along the focusing direction can be used 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.), and the extended mosaic of the PG causes neutrons with slightly different energies to be scattered at different Bragg angles – and in turn be detected in different detector tubes [birk13]. This effect is illustrated in Fig. 7.

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 secondary analyser tank by a few degrees. With 3 settings all angles can be covered twice as all analyser rings have at least 67% angular coverage.

Each of the analyser modules is aligned prior to installation. The module can in turn be aligned after installation by a movable motor inside the tank, rotating the module around a horizontal axis. After the analyser modules are aligned inside the tank, the alignments of the modules are fixed, and the motor removed.

In total, one secondary spectrometer tank will use up to 3 m^2 detectors and 2 m^2 PG crystals.

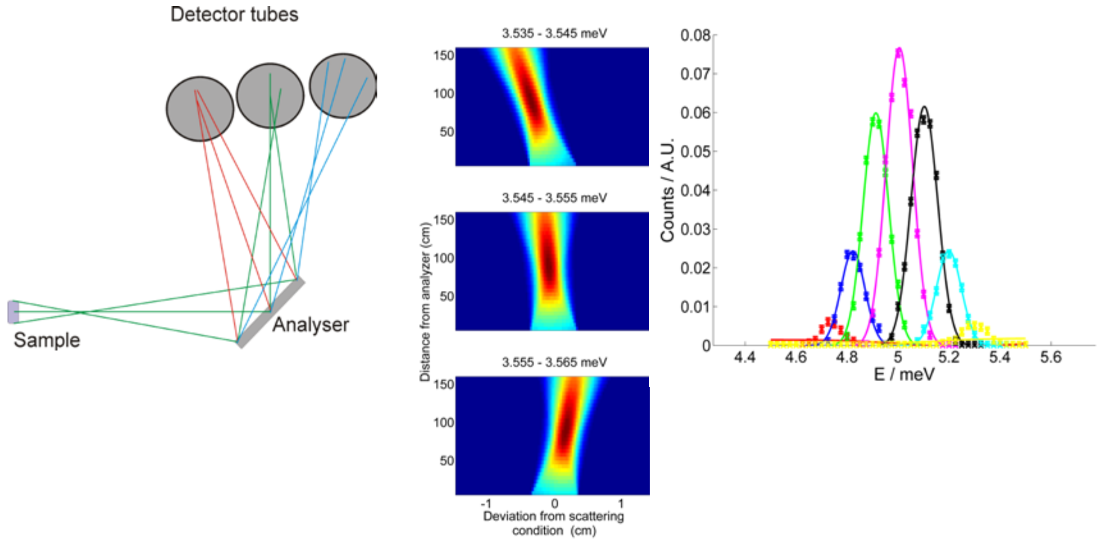

Figure: 7: An analyser crystal with relaxed mosaicity will reflect a band of different energies in slightly different directions. The left panel illustrates the principle for a single analyser crystal. Middle panels show simulations of the beam profiles of 3 narrow energy bands reflecting from the same crystal as shown to the left. Right panel shows a simulation of how the principle works if the single crystal is replaced by a focusing analyser in Rowland Geometry. The detector consists of a system of seven 1/2 inch detector tubes. The simulations shows that several energies from the same analyser crystal can be separated; thus improving resolution compared to a big-detector scheme, but without losing intensity. We chose only to use the 3 high intensity tubes since the remaining would have lower ratio of detected neutrons to detector cost, and often would have too different count statistics from the others to be fully useful in mapping.

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 remove background from unwanted neutrons at the sample position, the guide is designed to transport as few unwanted neutrons as possible early in the guide. In addition, to remove unwanted neutrons at the end of the guide, 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 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 it 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 component inside the tank – and by placing absorbing walls between analyser modules, as well radially as vertically. Such a type of shielding, albeit on a smaller scale, was found to reduce the background level of the RITA-2 spectrometer at PSI significantly [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 covered 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 that works in transmission geometry. This will give a highly stable time-independent polarized neutron beam. The flipping of the incoming beaming 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 there are 2 solutions:

a) A wide angle polarized ^{3}He cell can be placed around the sample to analyse the scattered neutron polarization. However, two problems exist: (1) Any stray fields from cryomagnets will depolarize the ^{3}He; (2) The diameter of the sample space is highly limited due to the quantity of ^{3}He required on increasing the cells diameter.

b) Polarized mirrors can be used to select one neutron polarization, and the 10 PG analyser arcs placed behind the supermirror can be used to analyze the energy of the scattered neutrons. This can work when using cryomagnets but will have a lower efficiency and will take up 15 cm usually used for the Be filter. We can however run without filter by using the order sorting choppers.

Option b) is preferred, but because of the large cost, 3.25 M€, to polarize fully the analyzed beam, it is not foreseen as a day-1 part of CAMEA. We emphasize, however, that polarization analysis is a high-priority upgrade possibility, and note that a compromise solution is a build-up of polarization analysis capabilities, by gradually adding more and more polarized mirrors.

1.2.2. Instrument performance

1.2.2.1 Working 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]. By these methods, we have investigated a standard working model (See table 1) to allow for comparison of results. The final instrument may differ from the working model in the detail. However, the working model does reflect the main features of the proposed back-end, like choices of distances and scattering angles.

$E_{Analyser}$ (meV)	2.5	2.8	3.1	3.5	4.0	4.5	5.0	5.5	6.5	8.0
$D_{Sample\text{-}Analyser}$ (m)	1.00	1.06	1.13	1.20	1.28	1.37	1.46	1.56	1.67	1.79
$D_{Analyser\text{–}Detector}$ (m)	0.80	0.90	1.00	1.05	1.10	1.15	1.25	1.30	1.35	1.45

Table 1: The main numbers of the working model for which the simulations, calculations and experiments were performed.

1.2.2.2 Flux and Coverage

At the high flux mode the instrument will receive a (simulated) flux of 1.26×10^{10} $n/s/cm^2$ on the sample (above 8×10^9 $n/s/cm^2/Å$ for the 2.5 -3.3 Å interval), for the specified guide delivering a divergence of 1.5×2.0 degrees^2. 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 1.6 Å, where a triple-axis would integrate over 0.05 Å. This matches well with the 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.

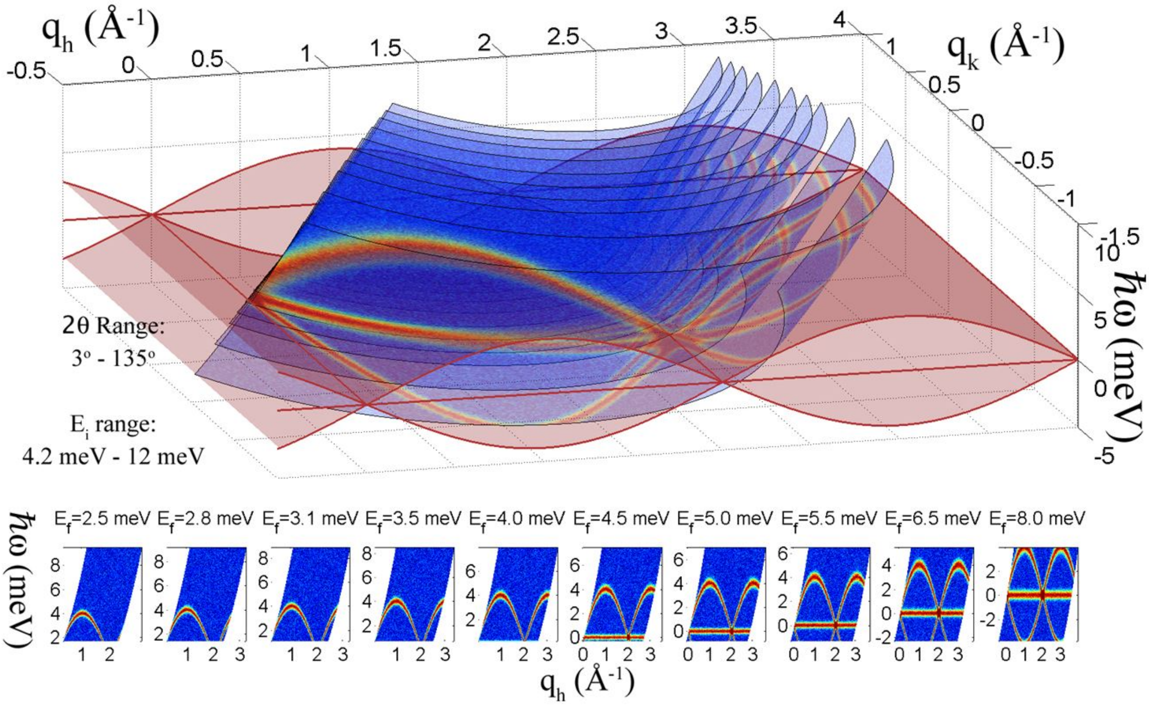

Figure 8: Simulation of data from a single CAMEA data acquisition, using a system with an elastic line and a magnon. The simulation is done for the high flux mode so only 10 surfaces, corresponding to 10 analyser-detector groups is shown and displayed below. When including the 3 energies from each analyser,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

The graphite has a reflectivity of about 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 modification that the counts would come pulsed. Hence, the instantaneous count rate is potentially a factor 30 higher on CAMEA, a fact that should be considered for the detailed specifications of the detectors.

The many angles and energies means that CAMEA will give 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 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.

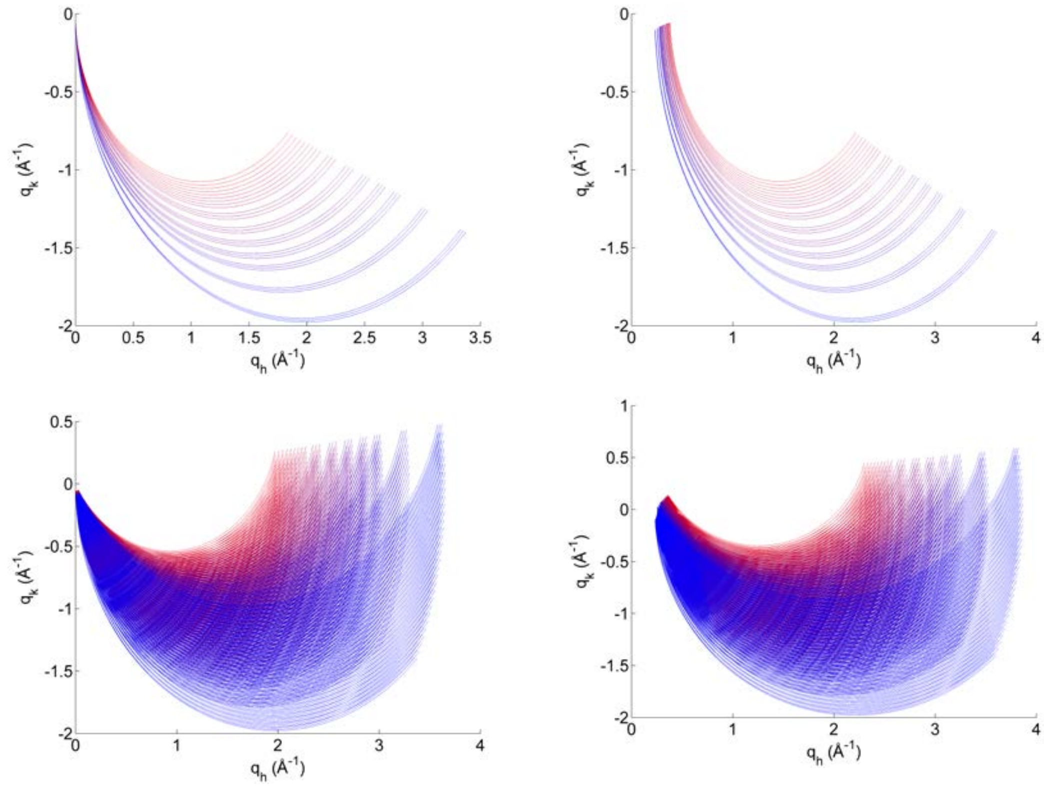

Figure 9: Schematic diagram of constant ħϖ coverage with ħϖ = 0 at left and ħω = 2meV at right. On the top a single scan step is shown and below 31 steps of 1⁰. The shape of the q-coverage will depend on the chosen incoming wavelength band.

1.2.2.3 Resolution

The energy resolution will consist of a variable resolution of the incoming neutrons and a fixed outgoing resolution for each analyser. Our set-up uses distance collimation and 3 thin detectors for each analyser. Hence, we achieve an outgoing energy resolution of dE/E=1.2% (FWHM) at E=5 meV. Summing the 3 detectors (or replacing with one thick) would result in the same summed flux, but a 2.0% energy resolution. 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 low limit comes from the flight time uncertainties in the secondary spectrometer. Combining the two one gets elastic resolutions between 4.2% and 1.2%. However, the instrument will perform best with 1.7 % where primary and secondary resolutions are matched. The latter gives a vanadium linewidth of a 85 μeV at 5 meV, twice as good as a standard TAS at that energy (See figure 10).

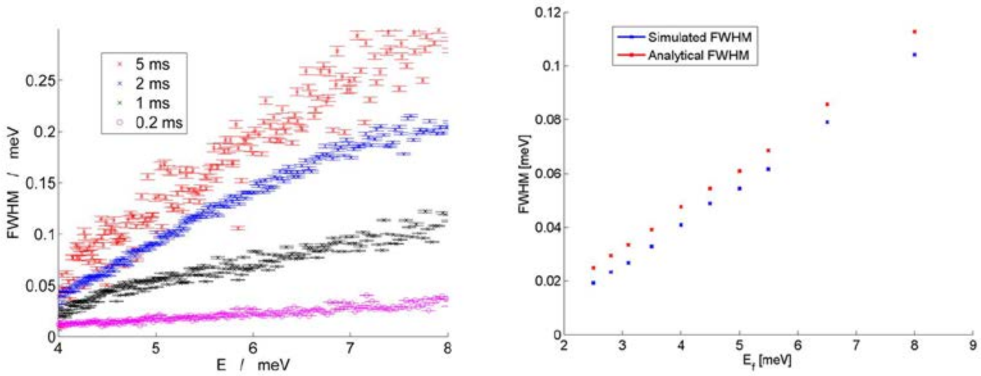

Figure 10: Left: Simulated incoming energy resolution with varying opening time of the pulse shaping choppers, running at up to 210 Hz. Right: Simulated and calculated outgoing energy resolutions for the 10 analysers.

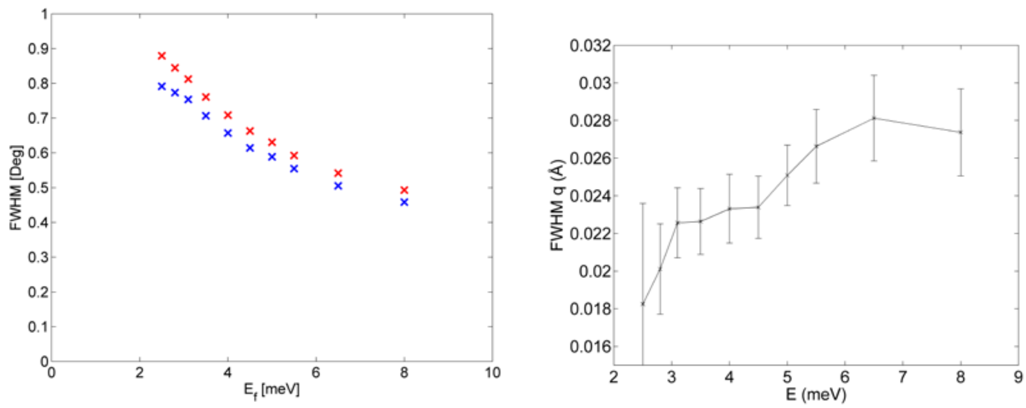

Figure 11: Left: Simulated (blue) and calculated (red) angular resolution of the secondary spectrometer. Right: momentum-resolution at the elastic line for 1 ms pulse shaping and $2\theta = 60^{\circ}$

The angular resolution at 5 meV is about 0.6 degrees outgoing (See figure 11), corresponding to a decent 40’ collimation on a Triple Axis Spectrometer. 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 degrees. 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.

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 table 2.

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

Analyser #	1	2	3	4	5	6	7	8	9	10
Energy (meV)	2.5	2.8	3.1	3.5	4	4.5	5	5.5	6.5	8
Time Resolution (μs)	37	28	23	22	22	22	21	22	21	19

Table 2: Calculated time resolutions for the different analysers of CAMEA.

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 energies in the 1 GeV range. 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 accordance with the present thinking at ESS. 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 from the kink position. 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 5%, 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.

We imagine here 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 The prototype and performance verification

We have built and tested the performance of a prototype of CAMEA [Prototype report]. The prototype was designed and build at DTU and installed at PSI in the tank of MARS backscattering spectrometer (See figure 12). MARS has a time of flight front end. The master-chopper sample distance is 38.4m. The front end can work with 50 Hz and 14 Hz base frequency, the wavelength bandwidths are 0.69 and 2.45 Å respectively.

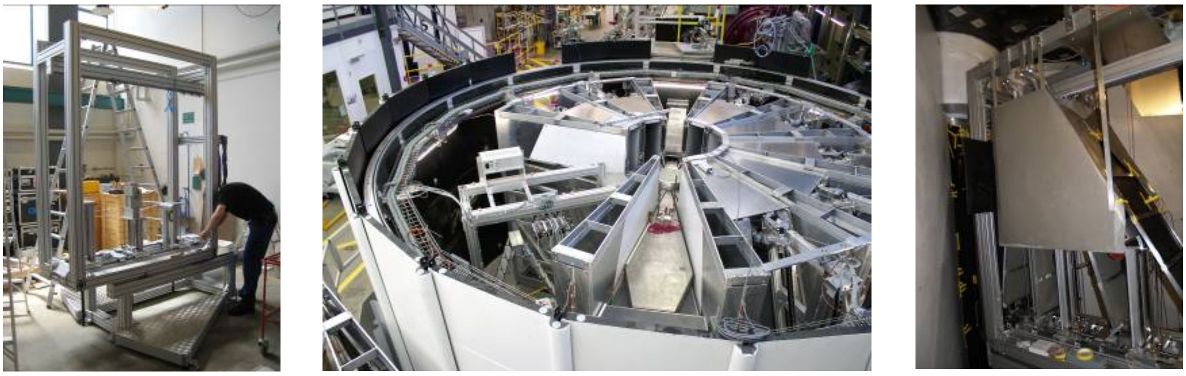

Figure 12: the prototype before (left) and after (middle) installation in the MARS tank. In the right panel all of the shielding elements are mounted (side walls, walls between the banks, slits between analysers and detectors, and a slit between the sample and the first analyser.

The prototype has three vertically focusing analyser banks, scattering the neutrons downwards to the detectors. Each bank has three linear position-sensitive tubes perpendicular to the scattering plane of the analysers. The analysers and the detectors have many degrees of freedom to be able to test different geometries.

During the test measurements we checked the basic idea of CAMEA: multiple analysers, whether we can measure many different energies from one analyser, varied the geometry, and verified the results of the analytical calculations and Monte Carlo simulations. We also measured the background conditions and the effect of different shielding.

1.2.2.5.1 Crystal alignment

We found that a careful cleaning of every part of the analyser bank reduces the misorientation of the different PG crystals during mounting. We checked the orientations of the mounted crystals both optically and with neutrons. The differences in the measured orientations were less than 0.1 degree. We used laser reflection for the final alignment (See figure 13).

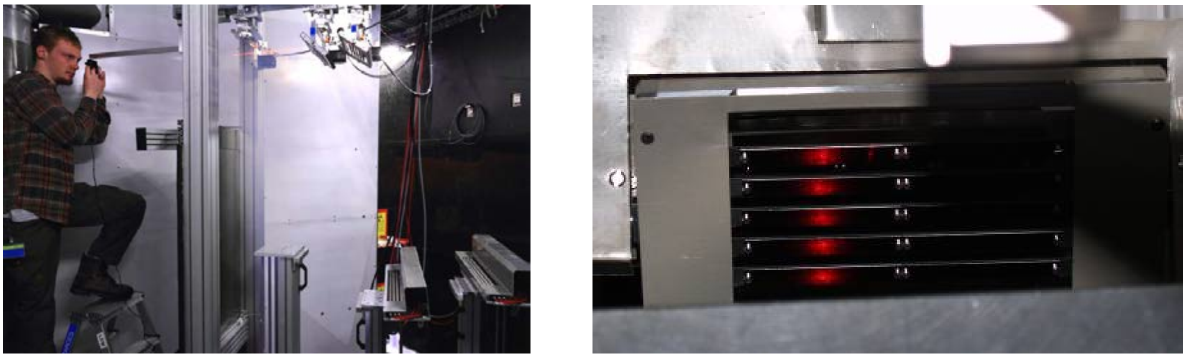

Figure 13: Optical alignment for a given Rowland geometry. Left: the laser is at the sample position, right: well aligned analyser. The laser is positioned at the sample position and pointed at the 3rd analyser blade. This creates a red dot on the central detector tube and the reflection of this dot can now be seen in all 5 analyser blades by the camera just next to the sample position.

1.2.2.5.2 Several energies from each analyser

We checked the idea of measuring several energies reflected from one analyser. The simulated and measured data are shown in figure 14. The data clearly show that we can measure 3 different energy bands in the 3 parallel tubes. Measurements and simulations are in almost perfect agreement.

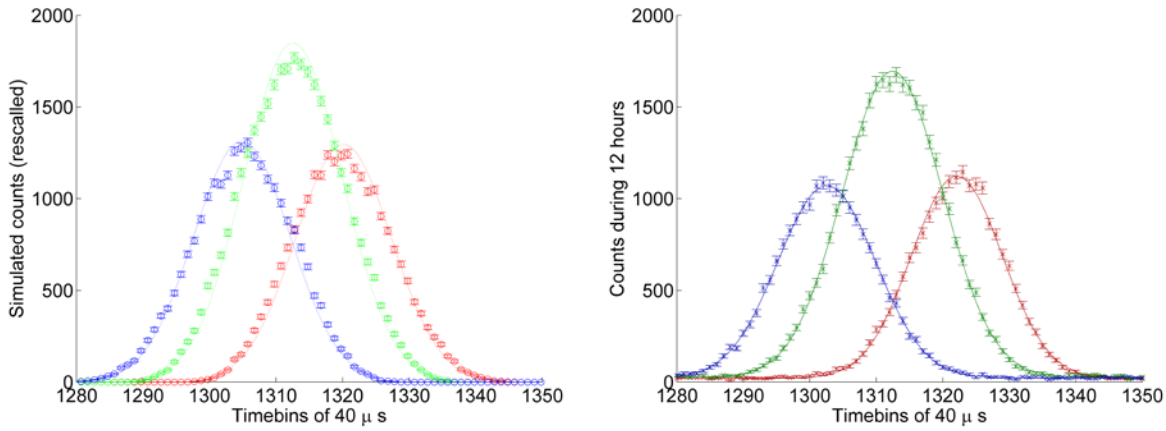

Figure 14: Measured intensity as a function of time-of-flight in three parallel detector tubes facing the same analyser. Left: McStas simulation. Right: Prototype measurement.

1.2.2.5.3 Resolution function

We have tested the energy resolution of the prototype at different sample sizes, and different primary resolutions. The measurements were compared with the results of analytical calculations [Resolution Calculations]. During these measurements we used two vanadium samples (with radii 3cm and 1cm, respectively). The final energies of the analysers were set to 4.0 meV, 5.1 meV, and 7.0 meV. The measured and calculated energy resolutions are in good agreement (See figure 15). In addition, our results prove that the resolution as expected is almost independent of the graphite mosaicity, since the distance collimation dominates the available graphite mosaicities.

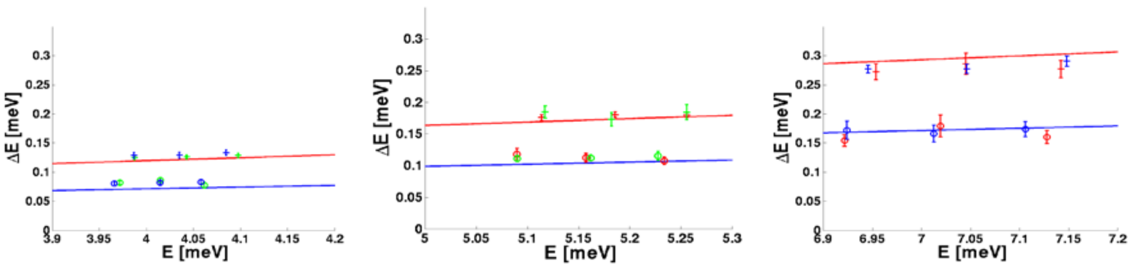

Figure 15: Energy resolutions measured with different sample sizes with different graphite qualities. The symbols show the measurements, the mosaicities: 40’ (green), 60’ (blue) and 80’(red). The lines show the result of analytical calculations, where the sample heights are 1cm (blue line), 3cm (red line). The offsets in the final energies are due to the non-perfect sample height.

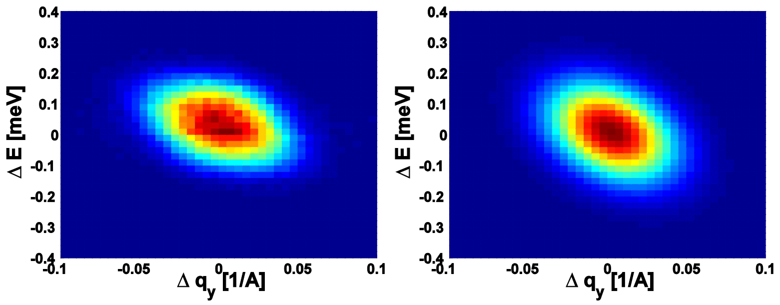

Figure 16: Projection of the resolution ellipsoid measured by an omega-scan around the (002) peak of a Pyrolytic Graphite sample. q_y is in the (100) direction. Left: measurement, right: analytical calculation.

We also checked the three dimensional resolution function (in the space spanned by the horizontal q-plane and the energy) by measuring the Bragg peak of a PG sample. One projection of the resolution function and the result of analytical calculation are seen in the figure 16. Despite slight deviation on the orientation of the resolution ellipsoid, the results are in good general agreement.

1.2.2.5.4 Crystal field excitations in $LiHoF_4$

We have performed an inelastic measurement on a $LiHoF_4$ sample at four different temperatures. $LiHoF_4$ is known to have strong crystal field excitations at low temperatures. The sample consisted of 5 plate-like large single crystals stacked together. The data is obtained at 14Hz base frequency, with low primary resolution within approx. 3 hours at each temperature. Figure 17 shows the measurements at four different temperatures. The inelastic crystal field signals are very clearly seen, proving that already the prototype can be used for scientific experiments.

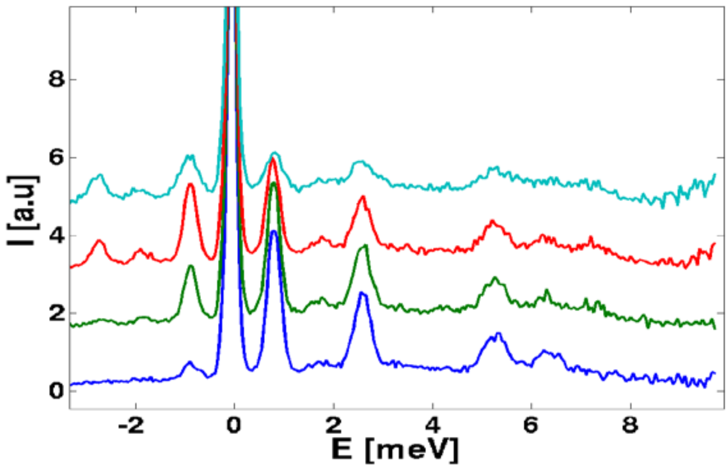

Figure 17: Inelastic measurement on LiHo4F sample at 4 K (blue), 10 K (green), 25 K (red), and 70 K (magenta). The base line of each data is shifted for the sake of visibility.

1.3 Technical Maturity

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 guide will however be very similar to most other long cold instruments at ESS, and also to e.g. 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. Further we have omitted the bispectral choice partly to ensure that we will still have a working instrument if the mirrors close to the moderator get damaged due to radiation.

1.3.2 Choppers

The proposed chopper system consists of 7 disc choppers. The 5 first will be standard solutions seen at many instruments today. The instrument can work if they run at 14 Hz but it will limit the efficiency of the high resolution modes if the two first choppers cannot run higher frequencies. The proposed 210 Hz limit is far below the 360 Hz that choppers at other instruments routinely reach.

The order sorting choppers do include a risk since they need to run at 360 Hz close to a strong magnetic field. This has not been tested before and should be tested before the instrument is constructed. If there are problems we see several fall back options:

A) The choppers can be moved further away from the sample to reduce the magnetic field. This will reduce the possible opening time and thus the flux on sample but only reduce transmittance with 0.02 per meter. As the magnet is not yet constructed the stray fields are not fully known but due to a more favourable geometry the stray field should be lower than the Berlin solenoid magnets field of 0.1T, 3 m away from the sample[Prokhnenko12].

B) The choppers can rotate slower but below 360 Hz the flux on sample will approximately be proportional to the chopper frequency.

C) The choppers have double the number of openings and rotate at 180 Hz. In this case the ramps of the transmission function of the choppers became 2 times longer and we lose 16% in intensity.

D) The choppers can be omitted and the instrument can rely on a Beryllium filter instead, limiting the energy of the secondary spectrometer to 5.0 meV. This will reduce the coverage and flexibility of the instrument significantly but not its performance in its primary focus area.

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.

1.3.3 Sample and Sample Environment

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 will undoubtedly be better than the 16 T, 1.5M EUR split coil magnet built is Switzerland and based at SNS. Because CAMEA is a largely superior spectrometer for use with split coil magnets, new science 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. Should this anyway become a problem one could free additional 20 cm radius by removing the Beryllium filter option when using the magnet. The distance between the end of the guide and sample is 60 cm, which would then be the upper limit for sample environment radius.

The limited volume inside pressure cells means that science today is both limited by technology and 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.

Both sample and environments will be exposed to strong radiation and will become active during and after the experiments. Calculations of the exact doses and decay times are on-going. ESS is considering using robotics for sample change. If that method is not used, we have suggested a simple mechanical solution for moving active samples and pressure vessels into a storage area for cooling. No calculations of needed shielding have been performed but since similar designs are used for transport of far more active fuel rods, necessary shielding levels should be achievable. For the magnets only the Aluminium rings should be exposed to high 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 (PG) analysers covering a large horizontal area. Mounting without possibilities for accurate alignment will decrease the background, but requires precisely manufactured holders. The size of graphite crystals is limited so in order to reduce dark angles by spanning more than 1.5^{o} several graphite crystals will be mounted on 1mm thick silicon (100) blades. These silicon blades will be mounted on aluminium frames. The only fine aligning possibility is the rotation of the frames around the horizontal axis. The criteria for the analysers are:

- Precise alignment
- Insensitive to mechanical vibrations
- Reduced phonon contamination

The silicon blades should have more than 1 degree off-plane cutting to avoid the detection of the PG(400) reflection which has roughly 6-times higher energy than the neutrons reflected by the graphite at the same scattering angle.

1.3.4.1 Alignment

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 degree (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 [PGreport]. So, the precise mounting needs an extra clean environment, careful cleaning of the PG crystals and the mounting device.

To keep misalignment below the 0.1 degree for the contacting aluminium-silicon surfaces the deviation from the optimal surface should be less than 17μm (assuming 1 cm wide blades).

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 will 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.

1.3.4.3 Extinction at higher energies:

The PG is polycrystalline around the c-direction, thus the (hkl) peaks (h and/or k ≠0) will scatter out the part of the beam. This extinction appears only above 5meV, and has a sharp edge at the lowest possible energy for a given peak at a given orientation [PGreport]. The energies of the analysers above will be chosen to avoid these sharp low transmission points.

1.3.5 Detectors

The design work so far has been 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 and that will somewhat reduce the ability to distinguish several energies from one analyser. But most neutrons will be detected in the first layers where this will still be possible and by aligning the plates inside the detector correctly it is believed that we will still get good energy separation.

A critical risk for detectors is the overloading. The time averaged intensity at the sample will be up to 1.26×10^{10} n/s/cm^2. A strong Bragg peak that gets reflected to a detector will not only risk overloading the detector but it can produce large amount of free ions causing decomposition of the stopping gas in the detector and also degradation of the gold coating of the wires.

Thus the detectors should avoid looking directly at strong Bragg peaks. It can be solved by thin attenuating foils between the sample and the vacuum tank that can be lifted in and out of the scattered beam by a pneumatic system. If a too high count rate is detected, the pneumatic system automatically lifts the corresponding attenuator strip. 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.

The monitor should have high dynamics. The presently achievable electronics can work until 50 kHz count rate meaning that the monitor should have the efficiency of ~10^{-5}. This efficiency is not enough for normalization in the case of strongly scattering samples, so we plan to use a second monitor with better (10^{-4}) efficiency for the high resolution measurements.

Several monitors will be needed to cover the wide possibilities for incoming wavelength band. These monitors will either be placed after each other or be automatically replaceable.

1.3.6 Vacuum Tank

The vacuum tank contains the analyser banks with the cooling system, the shielding between the banks, and the heat shield. The tank thus needs a row of very thin windows between the sample and analysers. Since the analyser holders will cause dark angles for every analyser, the part of the window in these directions can be thick decreasing the surface of the vacuum windows, and allow use of thinner material in the non-dark angle.

Due to the blind angles the analyser-detector module should be able to move on rails. The rails have to ensure the smooth movement (in order to protect the detectors and the analysers).

1.3.7 Electronics

The electronics has 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 environment, and the incoming flux will be high. All motors, encoders and other sensors at the secondary instrument should be designed to be able to work in a high magnetic field and to receive 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. Movement between two final states (Cd sheets for avoiding the Bragg-peaks, or the last beam shutter) should be solved by pneumatic actuators. Close to the sample environment mechanical encoders are preferable due to their insensitivity to high magnetic fields and radiation.

1.3.8 Shielding

The shielding around the detector tank will be done with tested materials and methods. Open geometry instruments can achieve low background levels by using similar techniques. For example at Rita II at PSI, we were able to suppress the background in the inelastic range down to 0.1 counts per minute for a 5 by 1 inch detector area (plus a similar amount of electronic noise) [Lefmann 06]. Inside the detector tank shielding “chimneys” will ensure that detectors only “see” the relevant analysers. Finally a number of slits and collimators are needed.

1.3.9 Strategy and Uniqueness

The instrument we are proposing here fits into the strategy of the indirect spectroscopy to provide instrumentation that covers from ultrahigh 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].

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 analyzed 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 reciprocal space. When working with sample environments that have restricted neutron access only a fraction of the detectors of direct geometry chopper spectrometers are useful, so CAMEA’s in-plane optimization scans excitations at up to 22 times higher count rate. 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.

For studies in quantum magnetism, and the magnetism of strongly correlated systems this instrument demands availability of cryomagnets with the highest available fields, and pressure cells for extreme pressures. To utilize these sample conditions this instrument will demand specialist technical support laboraties for high magnetic fields, high pressures, low temperatures, and combinations of these conditions. For studying materials under high pressure the instrument will take advantage of a small beam mode for small samples.

This instrument concept incorporates a large sample space that is necessary for sample environments such as cryomagnets, the large space however provides an adaptability to accommodate complex sample environment for in-situ studies. The use of a collimated 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 range will be of great importance.

1.4 Costing

Here we give a brief overview of the costing and provide a breakdown of the costing between capital (construction) and personnel costs. More detailed information on the costing can be found in the separate costing report [Costing report], where we indicate the many sources of information that we have drawn upon in our costing process, such as technical and scientific staff at DTU and PSI, and ESS technical teams.

Categories: We divide the construction cost into three categories: (A) Guides and shielding; (B) The CAMEA spectrometer and (C) Sample environment. The division between "Guides and shielding" and "the CAMEA spectrometer " has been made to distinguish CAMEA-specific technical solutions from parts of the instrument which are less specific in the sense that all 170 m instruments at ESS will need fairly similar guides and consequently will have fairly similar shielding requirements. We include pieces of sample environment equipment that are considered integral parts of the CAMEA concept at ESS and key to its scientific success and output. Note, however, that while these sample environments are included in the present costing of CAMEA, they will be available to other ESS instruments as well.

Construction cost: We have attempted throughout to give conservative estimates, i.e. estimates which, after the more detailed examination that will take place in the first part (Design and Planning) of the construction phase, may likely turn out to be too high. In general, the costing estimates given should be regarded as preliminary estimates with significant uncertainties. The total cost of CAMEA (excluding salaries) as detailed in [Costing] is 18.239 M€. Divided between the categories indicated above, the breakdown looks as follows (We refer to table 3 of [Costing] for further details)

- Guides and shielding (Guides, guide Shielding, instrument cave, shutters and pumps for guides): 8.030 M€ (44% of total cost).
- The CAMEA spectrometer (Choppers, divergence jaws, sample table, vacuum tank, vacuum pumps, graphite analysers, Si wafers, cooling machines, detectors, Be-filter, radial collimator, electronics, polarization of incident beam): 6.399 M€ (35% of total cost).
- Sample environment (Magnets, pressure cells and auxiliary equipment): 3.810 M€ (21% of total cost).

The primary cost drivers in the two first categories are guides, shielding of guides, choppers, detectors, the vacuum analyser tank and the graphite crystals on Si wafers.

Personnel cost: We estimate that over the course of the 5 year construction phase of CAMEA, the personnel cost will correspond to 5 man years for the lead scientist, 5 man years for the lead engineer and 8 man years divided between various technical teams (For example the team responsible for the construction of the analyser tank, which is estimated to require up to 3 man years). In making these estimates, we assume that the hardware cost for major components, such as guides and shielding include installation. We also assume that electronic solutions are fully incorporated in the quotes for choppers and detectors. Should this not be the case, personnel costs will be higher.

Taking current Danish salaries for scientist and technical staff as a baseline for calculation of the personnel cost, we arrive at a total personnel cost for the construction phase of CAMEA of 1.28 M€.

Total cost: Adding the cost estimates for construction and personnel, the total cost of CAMEA becomes 19.519 M€. This should be considered an upper limit.

Schematic spending profile: In the following, 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, assuming a 5-year construction period starting when the lead Scientist and lead engineers, along with a technician have been recruited or subcontracted (e.g. from the proposing partner institutions).

Personnel costs: 3.6 man year per year over the 5 years, estimated at 256 k€ per year.

Constructions costs: 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 be expected to take place 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)

[bertelsen13a] 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) [bertelsen13b] M. Bertelsen and K. Lefmann, Optimizing neutron guides : the analytical minimalist concept and the program guide-bot, in preparation for J. Appl. Cryst. (2013)

[birk13] J.O. Birk et al, in preparation for Nucl. Instr. Meth. A (2013)

[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)

[Kempa06] M. Kempa M. et al. 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)

[Prokhnenko12] Personal communications with Oleksandr Prokhnenko

[Rodriguez08] J. A. Rodriguez, et. al., 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)

[zendler13] 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 (2013)

CAMEA Reports Available Online:

[Bench marking] http://www.psi.nbi.dk/~jonaso/ess/CAMEAProposal/Bench_Marking.pdf

[Guide Report] http://www.psi.nbi.dk/~jonaso/ess/CAMEAProposal/Guide_report.pdf

[Comparison to Cold Chopper]
http://www.psi.nbi.dk/~jonaso/ess/CAMEAProposal/Comparison_to_the_Cold_Chopper_Spectrometer.pdf

[Concept and science case]
http://www.psi.nbi.dk/~jonaso/ess/CAMEAProposal/Concept_and_Science_Case.pdf

[Scientific demand for CAMEA]
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[Technical Design]
http://www.psi.nbi.dk/~jonaso/ess/CAMEAProposal/Technical_Solutions.pdf

[Costing] http://www.psi.nbi.dk/~jonaso/ess/CAMEAProposal/Costing_Report.pdf

[PGreport]
http://www.psi.nbi.dk/~jonaso/ess/CAMEAProposal/Pyrolytic_Graphite_Experimental_Results.pdf

[Prototype Report]
http://www.psi.nbi.dk/~jonaso/ess/CAMEAProposal/Building_and_testing_prototype_for_CAMEA.pdf

[Resolution Calculations]
http://www.psi.nbi.dk/~jonaso/ess/CAMEAProposal/Analytical_Calculations_for_CAMEA.pdf

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**
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