Design and performance of the multiplexing spectrometer CAMEA

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The cold neutron multiplexing secondary spectrometer CAMEA (Continuous Angle Multiple Energy Analysis) was commissioned at the Swiss spallation neutron source SINQ at the Paul Scherrer Institut at the end of 2018. The spectrometer is optimised for an efficient data collection in the horizontal scattering plane, allowing for detailed and rapid mapping of excitations under extreme conditions. The novel design consists of consecutive, upward scattering analyzer arcs underneath an array of position sensitive detectors mounted inside a low permeability stainless-steel vacuum vessel. The construction of the world’s first continuous angle multiple energy analysis instrument required novel solutions to many technical challenges, including analyzer mounting, vacuum connectors, and instrument movement. These were solved by extensive prototype experiments and in-house developments. Here we present a technical overview of the spectrometer describing in detail the engineering solutions and present our first experimental data taken during the commissioning. Our results demonstrate the tremendous gains in data collection rate for this novel type of spectrometer design.

Keywords: Neutron Scattering Instrument, Spectroscopy, Massive Multiplexing Instrument, Inelastic Neutron Scattering

I. INTRODUCTION

Triple-axis spectrometers are workhorses of modern neutron scattering experiments. They allow mapping of both the static correlations and the elemental excitations in condensed matter materials, which provide fundamental insight into the microscopic interactions of the measured systems. Neutron scattering experiments are usually flux limited, which leads to continuous efforts to improve the experimental setup. These consists of increasing the number of neutrons created at the source, improving the number of neutrons that reach the sample, and optimizing the detection efficiency of scattered neutrons.

In this publication we report on the design and commissioning of the new multiplexing spectrometer CAMEA[1], replacing the secondary spectrometer part of RITA-II at SINQ. CAMEA possesses 104 position sensitive detectors, which are collecting scattered neutrons from 600 analyzer crystals enabling a coverage of a large part of reciprocal space within the horizontal scattering plane. This setup is ideal for experiments that require extreme environments, such as high magnetic field and pressure. The concomitant increase in data requiring reconsideration of the instrument control system, the data processing procedure and data handling. These obstacles were overcome with the new software package MJOLNIR[2]. Finally, we report first experimental results obtained with the new spectrometer, demonstrating the enormous capacity of the CAMEA concept. Being the first instrument to utilise the prismatic analyzer concept[3] and due to the similarities with the upcoming BIFROST spectrometer, currently under development, at the European Spallation Source[4], CAMEA will pave the way for the next generation of massively multiplexing secondary triple axis spectrometers.

It is of importance to state that the introduction of massive multiplexing mapping instruments does not remove the raison d'être for standard triple axis instruments, as these still allow for a more detailed parameter studies where overview maps of $Q$ and $\Delta E$ are less important.

II. IMPLEMENTATION

CAMEA has replaced the RITA-2 multiplexing instrument located at the neutron guide port RNR13 at SINQ. During 2019 and 2020 SINQ undergoes a major upgrade program of its neutron guide system. The primary spectrometer of CAMEA will consist of new guides with converging elliptical sections reaching $m$ values up to a factor of 4, focusing the neutrons on a virtual source placed 1.6 m upstream of a double-focusing monochromator. This upgrade will result in a flux gain of up to a factor of 5 at the relevant energies, while undesired neutrons are suppressed. The basic concept of the secondary spectrometer has been described in detail by Groitl et al.[1].
In this publication we will give an account of key features and focus on the technical implementation of the CAMEA concept.

A. Cross-sectional overview of the secondary spectrometer

Fig. 1 shows a cross section view into the stainless steel vacuum vessel of the secondary spectrometer. It consists of 8 identical analyzer modules that cover 61 degrees in scattering angle. Each module consists of 8 focusing analyzers angled to scatter neutrons at fixed final energies ranging from 3.2 meV to 5 meV, see table I. A beryllium (Be) filter with a build-in radial collimation of 1’ is installed before the analyzer array[5]. This unit is cooled to temperatures below 80 K by a Gifford McMahon cryocooler. At this temperature the transmission of the Be is close to 100 % for neutron energies below 5.2 meV. The low temperature ensures suppression of Be phonons allowing a cleaner filtering. The upwards scattered neutrons are detected by a radial layout of 104 position sensitive $^3$He detectors tubes, all 1/2 inch in diameter. Due to their radial placement they are arranged in a stack of two staggered layers. Cross talk is prevented by Boralcan shielding separating individual wedges and analyzers within the wedges. All components are mounted within a shielded non-magnetic stainless steel vacuum tank. In the following sections we give an in-depth description of the main components.

B. Vacuum tank

Several recursions were taken to minimize sources of background. As such, the entire CAMEA unit has been enclosed in a vacuum tank that minimizes air scattering. The vacuum tank is made out of stainless steel, for which individual pieces were carefully selected with regard to their magnetic permeability. Only pieces with $\mu < 1.05 \times 10^{-7}$ H/m were chosen in the manufacturing process. Specialised welding material was used to ensure that the tank retained its non-magnetic state. High magnetic field tests using an external vertical magnetic field of up to 13.5 T were performed during commissioning confirming similar conditions as for the replaced RITA-2 instrument. No changes are expected up to 15 T, which is currently the maximum field available at SINQ. The tank wa evacuated at room temperature to a pressure of $10^{-4}$ mbar. At this pressure, the cryocoller was switched on to cool the Be filter to its base temperature of 65 K. At this stage, a pressure of $3 \times 10^{-7}$ mbar was reached inside the vacuum tank.

C. Shielding

The Pb target of SINQ produces fast neutrons with energies up to the proton beam energy of 570 MeV. Despite shielding around the target structure, some of these may enter the detector tank, if no additional shielding is used. We, this added 200 mm thick polyethylene blocks were added. Right: The CAMEA instrument in operation using the MA15 cryomagnet at a vertical field of 13.5 T.

FIG. 2. Left: The stainless steal vacuum tank on top of the support structure made of Aluminium before the 200 mm thick polyethylene blocks were added. Right: The CAMEA instrument in operation using the MA15 cryomagnet at a vertical field of 13.5 T.
analyzers. This guarantees that only neutrons scattered at a particular analyzer segments reach the designated part of the detectors. In addition, the whole tank is covered with boron. Our combined shielding provisions result in a low background of about 0.3 counts per minute per detector when the main shutter is closed. This number, thus, includes dark currents and background from the environment. During operation, after the neutrons enter through the aluminium windows they pass through our Beryllium filter, which acts to remove neutrons with energies above 5.2 meV. These scattered neutrons are absorbed by Cadmium in the filter, generating gamma radiation. To suppress these, a Pb shielding has been added on top of the filter. Similarly, neutrons not scattered by the analyzer array end up in the beam stops located behind all of the analyzers. Here, gamma radiation is also generated due to neutron absorption and a Pb shielding has been put in place.

**FIG. 3.** Left: Cross-talk shielding between analyzers and wedges prevent contamination of signals from the different energy and angular channels. Right: Cross-talk shielding inside the vacuum tank.

### D. Air bearing

Conventional triple-axis instruments are moved often during experiments. This is necessary due to change of incident energy affecting the scattering geometry. In most cases this is achieved via pressurised air-pads that allow instrument to glide over a polished marble floor. CAMEA is based on the same principle and an efficiently method to reposition the vacuum tank is needed. The enormous weight of CAMEA requires the development of a new suspension system, distributing the weight evenly across the large tank, while ensuring a smooth movement with high precision. We used an assembly of air-pads from AeroLas as shown in Fig. 4. Vibrations were prevented by the use of large cushion elements made out of steel wool inserted between the air-pad and its mounting.

**FIG. 4.** Left: Close up of air pad with steel wool used as a damping element. Right: 3D rendering of air bearing solution.

### E. Be-filter, cooling and performance

The Be filter between sample and analyzer is a necessary requirement to reduce parasitic scattering as well as higher order scattering in sample and monochromator. Since the scattered neutron should be collimated directly after the sample and due to spacial restrictions, a combined radial collimator and Be filter [5] was designed and manufactured. The optimal design consists of placing thin Be slices mounted between 0.3 mm thick glass lamellas coated with $^{10}$B. The spacing of the lamellas was chosen to provide a collimation of 1 degree. The filter-collimator combination was mounted within the vacuum vessel and dry cooled with a cryo cooler providing a cooling power of 175 W at 77 K. We reached a cooling rate of about 5 K per hour, resulting in a cooling time of less than 2 days. After reaching a base temperature of 65 K the temperature slowly increased at a rate of about 1 K/day. The loss in cooling power is believed to be caused by residual gas on the large surface of the collimator, resulting in a reduced emissivity. This problem can be solved by installing a sorbitol pump next to the cold head.

**FIG. 5.** Left: The combined Be filter collimator unit consisting of 8 different segments. Right: Cold copper head of the Be filter.

### F. Analyzer Design

The analyzer arrangement consists of 8 identical modules with a total angular spread of 61 degrees. Technical details of the design are described by Groitl et al. [1]. The analyzer arcs are composed of 600 highly oriented pyrolytic graphite (HOPG) crystals (Panasonic PGCX07SP). The quality of all crystals was examined by neutron diffraction on the thermal time-of-flight neutron diffractometer POLDI. Among different mounting possibilities [6], we chose a purely mechanical option
based on clips and stoppers simply holding the crystals in place. These are made out of Anticorodal AC110, a stiffer aluminium alloy, that can be cut precisely. This allows manufacturing of holders and clips with high precision as to circumvent the cumbersome and error prone process of crystal aligning either through laser reflection or neutron diffraction. The 3D design of clip solution used at CAMEA is shown in Fig. 6 together with a picture of a showcase example of Cu mounted like the graphite piece. The height of the clip and stopper were chosen to exert sufficient force onto the HOPG crystals and the Si wafer to ensure that they do not slide during tank movement. Moreover, the force needed to be low enough, such that the crystals were not bend, changing their properties. Two clips of 2 mm in width were combined with the clamp at the end of the clip further ensuring that the HOPG does not tilt or move during experiments.

\[ \text{FIG. 6. Left: 3D rendering of the analyzer mounting solution, consisting of clips and stoppers to attach the HOPG crystals to Si wafers. Middle: Clip and holder design used to secure the HOPG crystals onto the Si wafers and these to the aluminium frame. Right: Showcase of Cu mounted like the HOPG crystals of the analyzers.} \]

G. Detectors and Plugs

The detector system of CAMEA consists of 104 position sensitive half-inch detector tubes (Reuter Stokes) with a length of 1 m. Each tube is filled to a total pressure of 9.27 atm which includes 7.1 atm of \(^3\)He. A radial arrangement in two planes was used resembling a ‘W’ pattern as can be seen in Fig. 7. The configuration is designed to cover as much area above the analyzers as possible while minimising gaps between the tubes. This choice results in detector tubes from the two layers overlapping towards the sample position, which affects the sensitivity of neutron detection for the upper layer. This is to be taken into account in the normalisation procedure described in section IIIA. Despite the optimisation, gaps between detector wedges are unavoidable leading to an angular coverage between 50% and 70% for low and high final energies, respectively[1].

CAMEA is designed in a modular fashion by 8 almost identical wedges, each consisting of 13 detector tubes located above 8 analyzer arcs. The ‘W’ configuration is realised by alternating 7 and 6 detector tubes in the upper and lower layer, respectively, see Fig. 7.

\[ \text{FIG. 7. Left: Radially arranged detectors tubes. Right: In-plane detector arrangement of two nearby segments, showing the ‘W’ configuration.} \]

The radial arrangement of the detector tubes requires a very compact design of transition pieces and plugs less than 0.5 inches and could thus not be used for our detector design. Our newly designed connectors are coaxial and are based on the standard Lemo plug, which can be operated up to a voltage of 2 kV. Further, these do not suffer from leakage currents for the measurement.

The spacial sensitivity of the detector tubes is achieved by recording the relative charge distribution reaching each end of the tube. Connectors and coaxial cable lengths are identical on each side end of the detector, which guarantees a homogeneous impedance which is easier to handle by the electronics. Coaxial conductors also posses substantial shielding and an insulation jacket, which offer ideal conditions for preventing cross-talk between adjacent conductors. Kapton (orange colour in Fig. 7) was chosen as insulating material, since it does not degrade noticeably in vacuum.

With the chosen design, the detectors are fully functional at the operation pressure of 10\(^{-7}\) mbars. However, if the pressure increases above 10\(^{-3}\) mbar, the detectors HV supply needs to be shut down due to the Paschen regime[7].

H. Detector electronics

Neutron events along the tube axis are measured using a resistive charge division readout concept. Each tube is read out at both ends, requiring 208 analogue acquisition channels for the CAMEA instrument. A new generation of readout electronics was designed to achieve a high integration density. The key components for this development are highly integrated multi-channel Analogue-to-Digital Converters (ADCs), serialised high-speed data interfaces, and Field Programmable Gate Arrays (FPGAs).

A simplified block diagram of the readout electronics is shown in Fig. 8. The electric charge collected at the detector tube ends is amplified by means of transimpedance amplifiers, one for each end of the tube. The amplified signals are low-pass filtered and driven into an ADC. The ADC operates at a sampling rate of 50 Mega-Samples...
Per Second (MSPS) per channel and with a resolution of 14 bits. The digitised sample data flows into an FPGA, which extracts the pulse event information from the continuous ADC data stream. A data packet is generated for each pulse event, containing a source identifier, a timestamp, the actual position information, and the charge content of the event, i.e., the summed sample values above the trigger threshold. Finally, the event packets are collected into User Datagram Protocol (UDP) frames and sent to the generic computing infrastructure via an optical Small Form-factor Pluggable transceiver (SFP) module.

Commanding and updating of the readout system take place through the same SFP module, except that the Transmission Control Protocol (TCP) is used to ensure higher reliability. Many system parameters, e.g., the signal-trigger threshold and the gamma rejection level, are mapped to programmable registers in the FPGA. In addition, a test pulser is included for debug purposes, which was helpful in the early stages of instrument commissioning. It allowed us to provide a well-defined input to the data collection, histogramming and data display algorithms before the startup of the full instrument. A further debug feature is the extraction of raw ADC waveform data for neutron events, enabling checks of stimulus and response verification of the trigger, peak detection, and position calculation functions.

The actual hardware, denoted the CAMEA Front-end Box, is shown in Fig. 9. We chose a modular design in which transimpedance amplifiers are self-contained plug-in modules with connector interfaces to the ADC Printed Circuit Board (PCB). This design further allow for reuse of parts of the system for future instruments. The ADC PCB carries 16 amplifier modules (8 on each side) providing a similar amount of analogue input channels. The module also contains a high voltage bias injection with an appropriate conductor clearance to prevent arcing. Most of the digital functionality is contained on the data concentrator board, namely the FPGA, the clock source, the configuration logic, and the digital interfaces. High-speed serialised data lanes connect the ADCs to the FPGA. The continuous data generation rate of the two ADCs amounts to 22.8 Gbit/s. We chose a Gigabit Ethernet connection for the outgoing data link. It is, however, noted that up to 24 Gbit/s could be implemented using a Quad SFP (QSFP) module.

Prior to the installation of the electronics boxes at CAMEA, the design was tested at MORPHEUS at SINQ. MORPHEUS allows a narrow beam of neutrons to be directed onto well-defined tube positions which is not possible in the final CAMEA instrument assembly. Here, the detector tubes are always out of the direct beam. Fig. 10 shows the results of the test campaign. The positional resolution expressed in terms of the Full-Width at Half Maximum (FWHM) of the pulse position histogram is below 5 mm in the central tube area of the tube, and below 10 mm towards the endpoints. A degradation of the resolution towards the two ends of the tube is expected for a charge division readout system as most of the charge flows to the near end whereas a close-to-threshold signal is detected at the far end with a correspondingly low Signal-to-Noise Ratio (SNR). These results allow estimation of a lower limit for individual pixel size along the detector tube. We chose a minimal pixel size of about
∼1 mm as to ensure dense enough coverage while avoiding a smearing of any signals. Observing an active tube length of 0.9 m, a total of 900 pixels is reached. This number is changed to 1024 pixels as to comply with a full power of 2.

The results in Fig. 10 further demonstrate the capability of the readout system, allowing measuring the pulse height spectra of the individual detector tubes. It is noted that since the pulse position and height are measured for every neutron event, the creation of these spectra is possible for all detector tubes during normal user operation. This can be used as a diagnostic tool to detect drifts in tube parameters, such as a gas leak.

III. DATA TREATMENT AND REDUCTION

In this section we discuss the treatment of the raw data and the process of converting the detector counts from the 1024 different pixels of each of the 104 position sensitive detector tubes into scattering intensity as function of momentum transfer $Q$ and energy transfer $\Delta E$. The process requires determination of the scattering angle $\alpha_4$ (the angle between incident and scattered neutron beam) and the energy transfer (the energy loss or gained during the scattering process). In the latter case, we note that the incoming energy is defined by the monochromator setting, while the final energy at a given pixel position needs to be determined from the detector-analyzer setup.

A sensible data treatment also requires construction of a normalization matrix, correcting for inhomogeneities in detection efficiency among all 1024 x 104 pixels.

A. Normalization energy scans with Vanadium

One efficient way to normalize all analyzer-detector pairs is to measure a strong incoherent scatterer such as Vanadium. Measuring the scattering intensities as a function of incoming energy allows determining the energy dependence of the detector pixels and their relative sensitivity. The upwards scattering analyzer arcs are designed to measure 8 different final energies ranging from 3.2 to 5.0 meV[1]. Because the corresponding eight analyzers are geometrically fixed, incoherently scattered neutrons of a given energy will be confined to 8 well-defined pixel areas on each individual tube detector (see Fig. 11).

![FIG. 10. Top: Position measurement histogram of a spot beam scan. The translation from leftmost to rightmost position is 825 mm, with a step size of 55 mm. Bottom: Pulse height spectra of the 13 detector tubes attached to one front-end box.](image)

![FIG. 11. Comparison between Top: Vanadium normalisation scan. and Bottom: simulated McStas model.](image)
energy from 2.9 meV and 5.5 meV. Considering the incident wavelength spread, reproducibility of monochromator angle and the amount of data points required on the detector, an optimum of 250 to 500 scan points was found (cf. Figs. [12] and [13]).

The resulting data is a 3D scattering intensity matrix with the axis being incoming energy (i.e. scan step), detector number, and location along detector. Summing over incoming energy, one of the normalization scans is shown in Fig. [11]. The neutron scattering intensity per pixel is shown in a 2D plot of pixel versus detector number. We also show the calculated intensity determined by a McStas[9] simulation. Note the very satisfactory agreement between experimental and simulated data confirms the geometrical accuracy of our analyser-detector setup. The fixed design of the secondary spectrometer also promises a long term stability of the intensity distribution on the detectors.

Depending on the integration limits of the incoming energy, different parts of the detector tubes have high intensity.

Fig. [12] shows that each detector tube has 8 high intensity areas, separated 7 low intensity regions. They correspond to neutrons scattered from the eight focusing analysers underneath the tubes and the regions between the analysers, respectively. We denote the prior as detector segment. The excellent separation between the individual segments confirms the quality of the cross-talk shielding. The intensity distribution along each detector tube is be fitted by eight. As a representative example we show the result to such a fit to the data in detector 41 in Fig. [12].

The red points correspond to an acceptance width of ±3σ. The low intensity regions are displayed in black. A 3σ acceptance region results in a suitable compromise between maximal signal and background. During data processing the low intensity areas are masked to reduce noise and background not originating from the sample.

Finally, the individual pixels are assigned to final energies. The normalization scan has a dimensionality of 501 (scan steps) × 104 (detectors) × 1024 (detector pixels). The previous consideration allows rebinning the data for each detector into eight segment, resulting in a data set of size 501 × 104 × 8. For each segment the intensity is now known with respect to the incoming energy (Fig. [13] for the eight segments of detector 41). Each peak is fitted by a Gaussian distribution extracting the nominal energy, resolution, sensitivity, and background level.

![FIG. 12. Intensity in detector tube 41 summed across incoming energy. Red dots denote pixels within an acceptance area of ±3σ.](image)

![FIG. 13. Binned neutron count in the active detector areas as function of incoming energy for detector 41 in the Vanadium scan.](image)

We note that the derived nominal energies and widths are stored in the data files together with the background, amplitude, and pixel edges. This facilitates the data treatment for users of the instrument. It also ensures that the required instrument parameters are included in every single data file, such that they can be analysed independently and without the need of a specific Vanadium normalization scan.

### B. Scattering angle

The calibration of the momentum transfer requires the scattering angle for every pixel for all the detector tubes with respect to the incoming beam direction. The tubes have both a relative scattering angle among themselves, denoted $A_4$, and an absolute angle depending on the detector tank rotation, $2\theta$.

In strong contrast to standard TAS, the scattering angle at CAMEA needs to be determined on a pixel by pixel basis. This is due to the out-of-plane scattering combined with flat analyzers and detector tubes placed radially above these. A determination can be achieved either experimentally through a set of measurements or by a calculation based on the geometry of the analyser-detector system. The former method requires 8 angular scans for each of the 8 final energies on a sample with large lattice parameters. The latter relies on an accurate description of the instrument.

During the commissioning phase we relied on calculations, but checked their validity with two energy scans at
the highest and lowest final energy. We used a high-quality Pr$_2$Hf$_2$O$_7$ single crystal for which we found excellent agreement with our calculations, less than 1 deg.

IV. INSTRUMENT PERFORMANCE

A. Energy and A4 resolution

A summary of calculated and observed instrument parameters is shown in table I.

A comparison to the measured parameters, given in table II, to the design specifications for the secondary spectrometer alone is tabulated in table III. Here a discrepancy is clear. While the final energies are within the expected range, their resolutions are on average 40% worse than our calculations for the back-end. This difference has been further investigated by a McStas simulation with a 1 cm high and 1 cm diameter cylindrical Vanadium sample in the current experimental setup. The energy resolution was found to agree within 4% and it is concluded that the primary spectrometer is the main source of energy broadening.

The noted A4 checks of the secondary spectrometer reveal average FWHM of 0.5451 deg for 5 meV. This corresponds to an uncertainty of 0.014 reciprocal lattice units (rlu) using a cubic crystal with $a = 2\pi$. This is well within the performance requirements of triple-axis instruments.

B. Prismatic concept

The CAMEA concept allows a coverage of large parts of the reciprocal space positions in a single acquisition scan, but the position sensitivity of the detector tubes are also useful to improve the energy resolution. The prismatic concept[3] exploits the distance collimation of the secondary spectrometer. If cases where both the sample and the detector are small, the energy distribution on the detector is narrow, and the detection rate is low. By relaxing the mosaicity of the analyser crystals which results in a broadening of the detector energy resolution, the same as it is governed by distance collimation. This ultimately yields an increase in neutron count at minimal cost to the energy resolution.

The prismatic concept fully comes to live at CAMEA due to the position sensitive detectors used across the back-end. This allows a subdivision of the active area segments of the 8 energies into smaller segments. That is, the otherwise discarded energy distribution within the segments is used to improve the energy resolution. As an example choosing 5 sub-pixels is equivalent to placing 5 smaller detectors closely along the detector tube yielding 5 energies instead of one. This impacts the intensity as the total neutron count is of course unchanged. This subdivision modifies the normalization procedure in the step where the nominal energies are found and subsequently their normalizations. Here, the intensity of every energy segment is split into $n$ subpixels, which distributes the neutron counts over $1024/(8n)$ pixels. This is appreciably more sensitive compared to summing the intensity over 8 segments only. Thus, users can in principle choose the energies measured without compromising the total intensity.

It is here noted that a too aggressive subdivision can result in oversampling, for which systematic errors in the instrument resolution gain in importance. In this regime the energy resolution cannot be improved further, but the energy distribution is broadened. This discussion is intended to highlight the fact that the energy resolution cannot be improved further, but the energy distribution is broadened.

In Fig. 14 we show the prismatic concept by plotting the 5th energy segment of detector 41 with $n = 1, 3$ and 5. The sub-pixels are simply found by linearly splitting the active area of the segment. The resulting energy dependent signal for these three binnings is shown to the right in Fig. 14 and the nominal energy and width is tabulated in Table.

![Fig. 14](image)

**Fig. 14.** Left: Pixels used when binning into 1, 3, and 5 bins per segment for detector 41 and segment 5. Right: Measured and fitted energy dependency using the same bins.
A re-binning of the data using sub-pixels significantly impacts the energy resolution, see Table. II In Fig. 15 we show the energy dependence of the energy resolution for a single detector tube, using the FWHM of the Vanadium normalization scan.

The data are over-plotted with a McStas simulation, considering only the secondary spectrometer. It has been performed using a cubic 1 cm$^3$ source at the sample position with a divergence of 2 degrees. The simulation reveals the best possible resolution independent of the guide and monochromator. The results justify the need for an upgrade of the primary spectrometer to match the resolution of the secondary spectrometer. This upgrade is being performed in 2019/2020. It consists of a new guide with a scalable virtual source and a double focusing monochromator.

### C. Spin waves in MnF$_2$

The first commissioning phase allowed testing CAMEA under various setup, covering different scientific topics. Most results will be communicated in separate publications [10][11]. Here, we focus on an experiment using a MnF$_2$ single crystal of 6.2 g. The the spin waves for this spin 5/2 compound have been extensively studied[12], which makes this crystal an ideal calibration sample[13].

Our results also illustrate how an experiment is conducted on CAMEA-type instruments. The bandwidth of the magnetic excitations in MnF2 is roughly 6 meV. Since our analysers cover an energy range of 1.8 meV, four different incoming energies $E_i$ were used. In addition, the modular design of our analyser setup resulting in dark angles is to be considered. Thus, a full coverage of the scattering angles requires two different A4 settings, which are 4 degrees apart. For each $E_i$-A4 combination an A3 sample rotation scan ranging from 0 to 150 degrees is performed in steps of 1 degree. The 8 different scans lead the dispersion shown in the left part of Fig. 16 for which a binning of $n=8$ was used. In the left panel the 3D data of the dispersions above different Bragg peaks are shown. The right panel reveals a cut through the 3D data along the principal along the principle axes (h,0,0), (-1,0,1) and (h,0,-1).

### TABLE I. Analyzer parameters for CAMEA as measured during the hot commissioning phase. $k_f$, $2\theta$ and resolution volume were calculated from $E_f$. Normalization factor is relative to channel 1.

| Channel | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---------|---|---|---|---|---|---|---|---|
| $E_f$ Calculated [meV] | 3.200 | 3.374 | 3.568 | 3.787 | 4.033 | 4.313 | 4.629 | 4.993 |
| $E_f$ Measured [meV] | 3.179 | 3.361 | 3.552 | 3.764 | 4.010 | 4.290 | 4.605 | 4.963 |
| $\Delta E_f$ FWHM Measured [$\mu$eV] | 147 | 159 | 171 | 186 | 203 | 227 | 253 | 291 |
| $k_f$ Measured [1/Å] | 1.239 | 1.273 | 1.309 | 1.348 | 1.391 | 1.439 | 1.491 | 1.548 |
| Take off angle 2$\theta$[degree] | 98.2 | 94.7 | 91.3 | 88.0 | 84.6 | 81.2 | 77.8 | 74.5 |
| $V_{resolution}$ Measured [1/Å$^3$] | 1.645 | 1.904 | 2.193 | 2.534 | 2.959 | 3.475 | 4.104 | 4.877 |
| Normalization factor Measured | 1.00 | 1.08 | 1.19 | 1.26 | 1.28 | 1.27 | 1.27 | 1.24 |

### TABLE II. Final energy and FWHM for segment 5 for detector 41 in commission.

| Segment | 1 |
|---------|---|
| $E_f$ [meV] | 4.006 |
| FWHM [$\mu$eV] | 202 |

| Segment | 1 2 3 |
|---------|-----|
| $E_f$ [meV] | 3.924 4.006 4.095 |
| FWHM [$\mu$eV] | 133 145 147 |

| Segment | 1 2 3 4 5 |
|---------|-----|
| $E_f$ [meV] | 3.893 3.949 4.009 4.064 4.134 |
| FWHM [$\mu$eV] | 126 128 134 137 146 |

FIG. 15. Mean FWHM for final energy at elastic line for $n$ equal 1, 3, and 5 over-plotted with McStas simulations considering only the secondary spectrometer. The linear fits are guides to the eye.
### TABLE III. Comparison of final energy and resolution between Vanadium scan and McStas simulation.

| E [meV] | Channel | 1    | 2    | 3    | 4    | 5    | 6    | 7    | 8    |
|---------|---------|------|------|------|------|------|------|------|------|
| Vanadium | Channel | 3.177| 3.370| 3.551| 3.757| 4.006| 4.292| 4.612| 4.963|
| Full Simulation | Channel | 3.199| 3.374| 3.570| 3.789| 4.037| 4.316| 4.634| 4.999|
| Back End Simulation | Channel | 3.203| 3.378| 3.573| 3.792| 4.040| 4.319| 4.638| 5.003|

| FWHM Prismatic 5 [µeV] | Channel | Vanadium | Channel | 96    | 109   | 116   | 121   | 134   | 150   | 174   | 198   |
|------------------------|---------|----------|---------|------|------|------|------|------|------|------|------|
| Full Simulation        | Channel | 98      | 106    | 119   | 132   | 146   | 166   | 186   | 209   |      |      |
| Back End Simulation    | Channel | 57      | 64     | 70    | 78    | 87    | 96    | 111   | 124   |      |      |

| FWHM Prismatic 3 [µeV] | Channel | Vanadium | Channel | 109   | 123   | 127   | 131   | 145   | 165   | 188   | 212   |
|------------------------|---------|----------|---------|------|------|------|------|------|------|------|------|
| Full Simulation        | Channel | 105     | 114    | 126   | 139   | 156   | 176   | 197   | 222   |      |      |
| Back End Simulation    | Channel | 69      | 78     | 84    | 93    | 101   | 113   | 128   | 145   |      |      |

| FWHM Prismatic 1 [µeV] | Channel | Vanadium | Channel | 142   | 162   | 174   | 186   | 202   | 230   | 258   | 292   |
|------------------------|---------|----------|---------|------|------|------|------|------|------|------|------|
| Full Simulation        | Channel | 132     | 144    | 160   | 177   | 198   | 224   | 253   | 286   |      |      |
| Back End Simulation    | Channel | 104     | 114    | 126   | 141   | 159   | 181   | 202   | 235   |      |      |

In just 28.5 hours the total data acquisition took place, measuring the spin wave dispersion in a large part of reciprocal space, covering all energies from 0.35 meV to 6.95 meV. Despite the rather large sample, this full mapping is not feasible with a standard TAS setup. Using the prismatic 8 pixels, a total of 9.5 mio individual data points are measured. If all of these points were to be measured on a standard TAS, only 0.01 s would be allowed per second, whereas on average each data point is measured for 73 seconds. A direct comparison is, however, not completely possible as sensitivity of neutron detection changes across CAMEA.

The continuity and smoothness of the shown data confirms that the CAMEA is working very well. It is only possible to have a consistent intensity level of the dispersion and the background if all of the detector normalization steps work. Together with the regularity of the dispersion itself the use of geometry calculations to find A4 are deemed successful.

We further note that the 2D cuts show the instrument resolution of the inelastic signal, because it is known that the spin waves of MnF$_2$ are known to be resolution limited[12]. In particular we point out the in and out of focus sides of the dispersion are clearly seen around (-1,0,0). (h,0,0) is out of focus, making it wide and less intense than (-1,0,1).

The high data quality allowed an extraction of the coupling constants. Since complete form of the magnetic Hamiltonian is already known[12], it was directly applied to our data using the SpinW software package[14]. The results of these fits are plotted as red circles in Fig. 17. The obtained the exchange parameters are tabulated in table IV where $J_1$ and $J_2$ describe the Heisenberg interactions between same site Mn and different site Mn respectively. $D_{d_d}$ denotes the anisotropy term. Our findings are close to the reported values of Okazaki et. al[15].

**FIG. 16.** **Top:** 3D visualization of the measured dispersion relations of MnF$_2$. **Bottom:** Cut along a line from (h,0,0), (-1,0,1) and (h,0,-1). Points in a distance of 0.05 Å perpendicular to the cut were binned, while energies from 0.45 meV to 6.95 meV are binned into 66 equi-sized bins of 0.118 meV.
| Current Findings | $J_1$ [meV] | $J_2$ [meV] | $D_{d-d}$ [meV] |
|------------------|-------------|-------------|---------------|
| Tabulated Values | 0.028       | 0.152       | 0.091         |

TABLE IV. Resulting coupling constants for the Hamiltonian describing MnF$_2$.

D. Currat-Axe spurion

A triple axis spectrometer exploits Bragg scattering from the monochromator and analyzer crystals (typically pyrolytic graphite for cold neutron instruments) to determine the inelastic response of a single crystal. Together with the sample three scattering points are present. Whenever two out of the three crystals (sample, monochromator and analyser) are in Bragg condition, a weak signal from the third may be detected. This constitutes 3 different cases; A Bragg reflection in the monochromator and analyzer contributes to the elastic scattering. If the sample scattering angle accidentally corresponds to a Bragg reflection of the analyzer or the monochromator, incoherent scattering will result in a spurious peak known as a Currat-Axe spurion. Since CAMEA-type instruments cover a large range of scattering angles and energies transfers, Currat-Axe spurious are of widespread occurrence. Two spurious are produced above each sample Bragg peak. An example of these is shown in Fig. 18. We note that uncertainties are smaller than marker size.

We note that a prediction of where Currat-Axe spurious appear in reciprocal space is straight forward and is implemented in the MJOLNIR software. In Fig. 18 we calculated them for the (H,0,L) plane of MnF$_2$. The discontinuities in the monochromator Currat-Axe arise from the 4 different incoming energies.

V. CONCLUSION

The CAMEA secondary spectrometer has been installed at the continuous spallation neutron source SINQ of the Paul Scherrer Institut. The results obtained during the first commissioning phase substantiate our expectations of the spectrometer concept in terms of usability, stability, and detection efficiency. The novel multi-analyser-detector arrangement allows rapid mapping of excitations without sacrificing the energy- and q-resolution of modern triple axis instruments. The instrument will further benefit from an upgrade of the neutron guides and the replacement of the vertically focusing monochromator by a doubly focusing one. Comparing the instrument to the earlier RITA-2 instrument measuring 9 data points at a time, the CAMEA secondary spectrometer increases this capacity by more than a factor 700. We also report the energy resolution of all detector pixels. The energy and intensity calibration have been incorporated into the conversion algorithm of MJOLNIR transforming raw data into reciprocal space.

Raw data were generated at the Paul Scherrer Institut. Derived data supporting the findings of this study are available from the corresponding author upon reasonable request.
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