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Babcock, E.; Salhi, Z.; Feoktystov, A.; Bannenberg, L. J.; Parnell, S. R.; Alba Venero, D.; Hutanu, V.; Thoma, H.; Xu, J.; More Authors

DOI
10.1088/1742-6596/2481/1/012009

Publication date
2023

Document Version
Final published version

Published in
Journal of Physics: Conference Series

Journal of Physics: Conference Series

PAPER • OPEN ACCESS

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To cite this article: E. Babcock *et al* 2023 *J. Phys.: Conf. Ser.* **2481** 012009

in-situ ^{3}He neutron spin filters at JCNS, status and updates

E. Babcock[1], Z. Salhi[1], A. Feoktystov[1], L.J. Bannenberg[2] S.R. Parnell[2], D. Alba Venero[3], V Hutanu[4], 5, H. Thoma[4], J. Xu[4], P. Pistel[6], J. Damean[6], A. Ioffe[1], S. Mattauch[1]

[1] Jülich Centre for Neutron Science (JCNS) at Heinz Maier-Leibnitz Zentrum (MLZ), Forschungszentrum Jülich GmbH, 85747 Garching, Germany
[2] Faculty of Applied Sciences, Delft University of Technology, Mekelweg 15, 2629 JB, Delft, The Netherlands
[3] ISIS Neutron and Muon Source, Rutherford Appleton Laboratory, Didcot, OX11 0QX, United Kingdom
[4] Institute of Crystallography, RWTH Aachen University and Jülich Centre for Neutron Science at Heinz Maier-Leibnitz Zentrum (MLZ), 85748 Garching, Germany
[5] Fakultät für Physik, Technical University Munich, 85748 Garching Germany
[6] Zentralinstitut für Engineering und Technologie (ZEA-1), Forschungszentrum Jülich GmbH, 52425 Jülich, Germany

E-mail: `e.babcock@fz-juelich.de`

Abstract. The JCNS has been developing and using in-situ polarized neutron spin filters for many applications. The system used for analysis on MARIA and polarization for TOPAS were completed about 10 years ago with the MARIA system in standard operation for users and the TOPAS system employed for a long measurement on the POLI instrument. In the meantime we are progressing on several new in-situ polarizers based on these first two but with additional innovations. The KWS-1 analyzer device which was recently used in tests at TU Delft and ISIS is essentially a 50%-sized copy of the MARIA device. The two devices in construction for polarization and analysis on POLI for hot neutrons feature magic-boxes with angled plates on both the entrance and exit sides to minimize overal length and the polarizer device will employ an additional passive magnetic shield of soft iron so that it can operate inside the stray field area of a 8-T vertical (compensated) sample magnet. We will summarize the current status of our ^{3}He neutron spin filters and provide extra focus on the technical aspects and measured performance characteristics of the new devices for KWS-1 and POLI in particular.

1. Introduction

The JCNS has been committed to using neutron polarization for complex instrumentation since its beginning. Of the 19 instruments operated or constructed by the JCNS at the FRM2 in Garching Germany, the ILL in Grenoble France and the SNS in Oak Ridge TN [1], 13 employ neutron polarization. Additionally the 3 instruments being contributed to the ESS employ neutron polarization as an option. This paper will focus on a subset of these instruments, namely the ones using ^{3}He spin filters, most of which are in-situ polarized via spin-exchange optical pumping SEOP[2].

The in-situ ^{3}He neutron polarization analyzer on MARIA has been used reliably in each reactor/user cycle since 2013 for both reflectometry and GiSANS [3, 4]. Despite various limits to cycles performed, recently there have been several publications using this device to provide full polarization analysis e.g [5, 6]. Additionally the TOPAS [7] analyzer was used for a 30-day measurement of the effect of rotation (ROT) in the angular distribution of prompt γ rays from the fission of ^{238}U [8]. The performance of the device exceeded expectations providing neutron polarization in excess of 99.1% at 22% transmission (with respect to the unpolarized flux) for 1.17 Å $\simeq$ 60 meV neutrons. As such two new in-situ polarized ^{3}He devices for polarization and analysis on POLI are in the works which will be described later in this paper. Before construction of the in-situ polarization elements, the components of the KWS-1 analyzer were used for two user experiments, one on magnetic nano-particles and the other on skymions both leading to publications [9, 10].

^{3}He in-situ polarizers currently in construction or planning include the polarization and polariztion analysis for hot neutrons on POLI, polarization analysis for cold neutron SANS on KWS-1 using a magic-box geometry for implementation in conjunction with a high field sample magnet (3 T horizontal and longitudinal) and also KWS-2 using a solenoid geometry for ambient external fields, *i.e.* no/low sample field, in soft matter applications [11]. Further a thermal beam polarizer is in the planning for the ESS [12] for the T-REX instrument [13] and a similar device for a cold beam polarizer option, funded externally by a Röntgen Ångstrom cluster grant, for the DREAM instrument [14, 15]. This paper will elaborate further on the two current projects for POLI and KWS-1 and end with a summary or recent SEOP cells.

2. KWS-1 analyzer and commissioning

A polarization analyser designed for KWS-1 has largely been completed. Before completing the in-situ components, the components were tested and several user experiments where even conducted with off-line polarized cells on KWS-1. The 38 cm long magic box magnetic cavity [16] provides a ^{3}He magnetic lifetime of 300 hours with the cell centred in the device. When used in conjunction with the KWS-1 HTS-110, New Zealand sample magnet [17] and a 3T horizontal (towards the ^{3}He cell) field this magnetic lifetime was reduced to 163 hours. This level of performance is more than adequate, especially for an in-situ polarized system where spin-exchange rates on the order of 10 hours or less can be obtained [18]. Some of the μ-metal components in the device are not fully to geometric specifications resulting in unwanted gaps between μ-metal plates in the assembly, this led to a smaller than designed homogeneous magnetic field region and the resulting cell T_1 to be sensitive to position in the cavity. We expect some improvement in the overall field homogeneity when those components are replaced. Unfortunately when the cell oven required for in-situ pumping is installed, the final design placed the stainless steel cartridge heater too close to the ^{3}He cell, here only about 4 cm, and the cell position became a few cm below the vertical center of the magic box. Conversely the area of lowest magnetic field gradients will be in the geometric center of any (symmetric) magnetic cavity and when the cartridge heaters are about 10 cm from the edges of the ^{3}He cell we have obtained over 80% ^{3}He polarization in the TOPAS device [8]. Thus in this configuration the overall T_1 is reduced to only 20 hours measured in the lab, however with in-situ pumping a spin-up time constant of 5.5 hours is obtained (corresponding to about a 8.7 hour spin-exchange rate) and thus 63.5% ^{3}He polarization can be expected in saturation for a nominal 0.3 X-factor [23]. This value of polarization was indeed confirmed in commissioning tests using TOF transmission [19] on the ROG instrument at TU-Delft (65%) [20] and in scattering measurements at on the ZOOM instrument at ISIS (62%) [21] within measurement errors. One of our standard chirped volume brag grating lasers [11, 7] is used and run at a nominal 40-50W output power. All of the control electronics for temperature control, and NMR FID and AFP are JCNS standard as described previously [7]. A photo of the KWS-1 analyser as installed on Zoom [21] is shown in Fig. 2. The total length of the enclosure along the neutron beam is 45 cm with a height and width of about 40 cm. During those tests the optical pumping and ^{3}He performance were stable

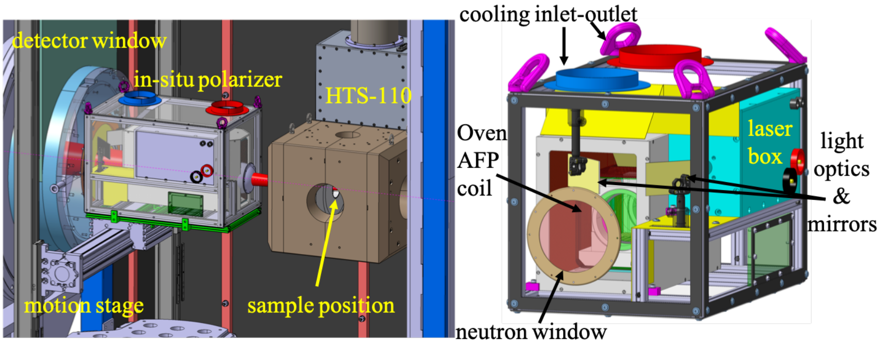

Figure 1. A CAD drawing of the KWS-1 analyzer on the instrument (left) and a detailed drawing of the polarization analyzer (right). In the left drawing, the sample magnet and sample are to the right with the neutron beam path between it and the ^{3}He polarizer to the left indicated in red. The right drawing shows the inside of the polarizer box with a view from the detector facing side. This geometry is very similar to the MARIA analyzer at 50% size. Due to the smaller size a smaller up to 7 cm diameter cell is used and polarization is performed with one laser, however a relatively large angular coverage providing up to a ± 0.07 Å^{-1} scattering vector at 4.5 $\AA$ is possible due to its close proximity to the sample and sample magnet shown on the right hand side of the first diagram.

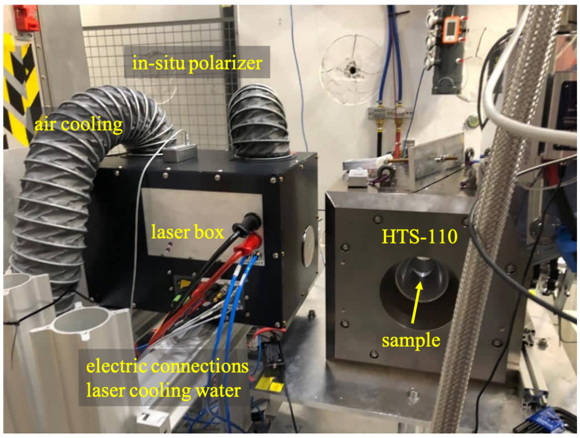

Figure 2. A photo of the KWS-1 analyzser installed on ZOOM at ISIS. The orientation is the same as in Fig. 2 with the sample magnet on the right and the $in-situ$ polarized ^{3}He polarization analyzer on the left. The sample area has ample space for the analyzer and the sample magnet is identical to that used on KWS-1, so ZOOM makes an optimal "sister-instrument" to KWS-1 for development work.

and it is desired to continue with more experiments. In the meantime we have prepared a new oven design to move the heaters approximately to 9-10 cm away from the cell such that the cell-heater distance is comparable to [7] and replacement μ-metal plates have been procured for the out-of-spec ones to improve the magic box geometry. We hope to be able to install these new components and thus improve the ultimate ^{3}He polarization performance of this device. In the meantime we hope to continue collaborating with the ISIS team during the extended down-time of the FRM2 reactor and cold source.

3. POLI polarizer and analyser

The POLI polariser and analyser designs have been recently finalized and production has begun, with the analyzer nearing completion. The analyzer is the simpler installation as it is not intended to be operated in large stray magnetic fields from sample environment so it is very similar to the TOPAS polarizer [7]. The polarizer on the other hand will be required to work with the 8 T vertical (compensated) sample magnet, as a result this device will have an additional 2-layer (each layer separated by 10mm) soft iron shell around the sample facing portions to help decouple the polarizer's magic box magnetic field from the sample magnet. This 8 T magnet has been calculated to create fields of up to 100 G at the front of the ^{3}He polarizer where it will be installed about 60 cm from the sample position. A CAD drawing of the two polarizers as designed for POLI is shown in Fig. 3. The geometry on POLI must remain compact because of the double-focusing monochromator and the relatively short distance of about 2 m between the exit of the monocromator shielding and reactor wall and the sample position. Except for this additional iron shielding, the POLI polarizer and analyzer will share the identical design for all other components such as the magic box, cell, and oven. Because of the compact geometry on POLI, care was taken to minimize the overall length while retaining the ability to accept a cell up to 18 cm long so that we can eventually provide polarization/analysis of even the 0.3 Å minimum neutron wavelength on POLI. The resulting magic box uses the concept of angled end plates that is employed already on MARIA and KWS-1, but applies it to both ends of the device to minimize the length as is it not required to accept a neutron beam or scattering larger than the size of the focused incident beam. These magic boxes are 46 cm long with over a 18cm long central homogenous region suitable for the 3-6 bar cells expected to be employed. The total length of the polarizer and analyzer is 64 and 61 cm respectively, they are approximately 55 cm wide and high. the extra length for the polarizer due to the extra thickness of the double layer iron shielding not present for the analyzer. The oven geometry containing the heaters is very similar to that of TOPAS [7] with the heaters on long copper plates on either side of the cell, employs transverse optical pumping, and has an AFP coil wound directly on the oven [22]. Compared to the TOPAS design this oven has been slightly shortened by about 4 cm overall due to the very short length of these boxes, placing the heaters 8cm away from the end of a 15cm long cell. Drawings of this angled cavity with hinge and expanded drawing of the oven detail is show in Fig. 4.

The magic boxes have been constructed and the fields were mapped using a Hall-probe robot. Overall the measurements of the magnetic fields match the calculations very well. Plots of magnetic field maps for the 2 planes in the center of the box are shown in fig. 5. Inspection of these maps implies a field gradient orthogonal to the B_0 field on the order of $< 8 \times 10^{-4}$ cm^{-1} for up to a 180 mm long by 70 mm diameter voulme of the ^{3}He cells planned for POLI when operated at the nominal 12.56 gauss field of the boxes for these measurements. The actual ^{3}He decay time, T_1, was also measured with NMR FID using a 5 cm diameter 15 cm long cell with a 220 hour lifetime and 2.8 bar of ^{3}He called TOPAS1[7]. The results were a total measured T_1 of 200 hours, implying a magnetic relaxation rate of 750 hours at 1 bar pressure, i.e. about a 4×10^{-4} cm^{-1} field gradient averaged over the cell volume in agreement with the field maps. This result verifies that even with the hinged ends for accessing the inner volume, good lifetimes can be achieved. Given these polarizers will be used with cells ranging from about 3 to 5.5 bar and the inversely proportional dependence of the ^{3}He relaxation on pressure [24], the magnetic field gradients of the magic boxes themselves will pose no practical limits on the eventual performance of these two devices. Next additional tests using the SEOP oven will be conducted, followed by laboratory tests of the magic box with the additional soft-iron shielding in the vicinity of the 8T sample magnet in laboratory conditions. When all continues according to specifications, we expect both the polarizer and analyzer to be available on POLI for the next FRM2 reactor cycles, foreseen in 2024.

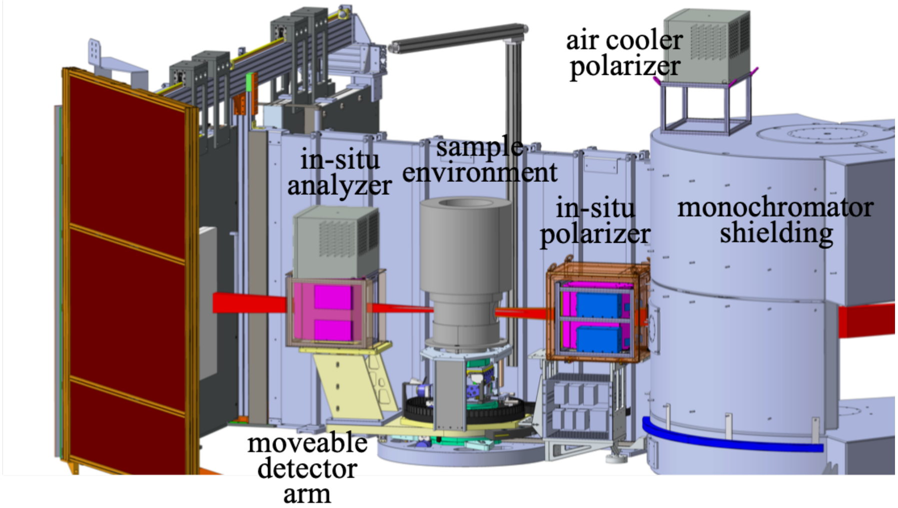

Figure 3. A CAD drawing of the two polarizers designed for POLI on the instrument. One can see the limited space between the reactor wall on the right and the sample position in the center. The polarizer device on the right has an additional 2-layer soft iron magnetic shield (orange outer cover) so that this device can also operate with the 8T compensated sample magnet (not shown). Both devices are air cooled, the cooler for the analyzer is mounted on the device cover as it is for TOPAS, the flexible cooling ducts from the polarizer air cooler to the polarizer (similar to KWS-1) are not shown.

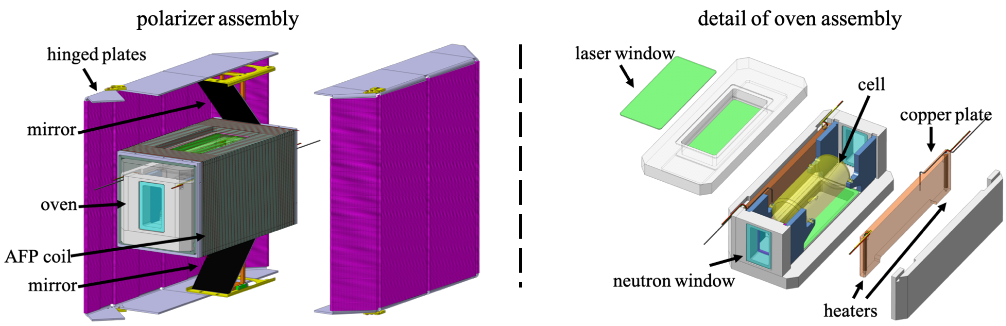

Figure 4. Expanded drawings showing detail of the new, double-angled opening+hinged magic box for POLI (left) and an expanded drawing of the oven detail which shows the heating plates to accommodate 4 stainless steel cartridge heaters and the up to 18 cm long ^{3}He cell.

4. Updates on cells

We have continued to produce high quality ^{3}He SEOP cells for our applications [24]. Several more cells, most with T_1's approaching the dipole-diopole relation limits have been produced. Most notably we produced a C-shaped cell for wide angle polarization analysis that had a 10 bar-cm neutron path length with a total pressure of 2 bar. This cell provided a very large angular coverage of around 240 degrees in the horizontal plane and more than 45 degrees in the vertical optimized for a $\lambda > 2.5$ Å neutron beam. It accepts a 40mm O.D. cryostat and in experiments at HZB on NEAT a maximum on-beam lifetime of 100 hours was obtained for experiments with the cryostat and sample installed [25]. The ultimate pressure-length product of these cells is

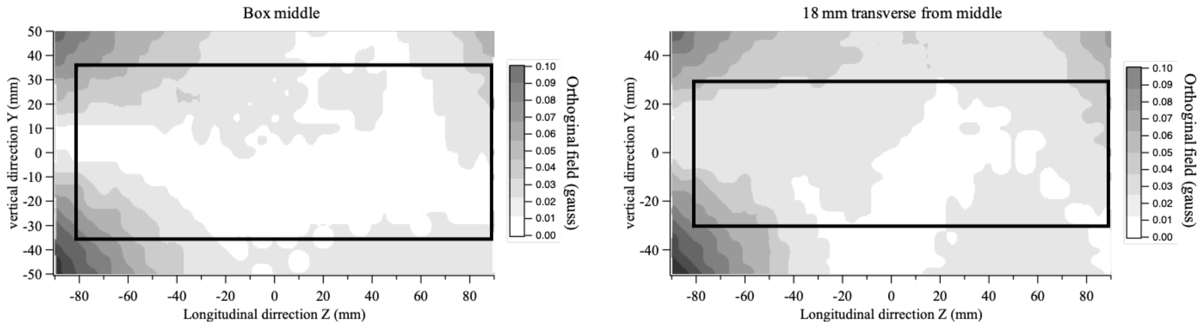

Figure 5. Plots of the Hall-probe measured orthogonal fields the new POLI magic boxes. The change in these transverse components normalized to the field strength per unit length are the transverse field gradient which is used to predict the ^{3}He magnetic lifetime [26, 16]. The plots show the quadrature sum of the fields transverse to the B_0 field at the longitudinal center (left) and 18 mm transverse to the longitudinal center (right) which was 12.56 G. The two maps are nearly identical and show that the possible gradients in the area of the cell are $< 1 \times 10^{-3}$ cm^{-1} even in the cell corners for a 180 mm cell with 70 mm diameter whose position is indicated by the boxes on the plots. Each gray-tone covers a 0.0125 G range of field at a 12.5 G nominal field, thus showing a $1{\times}10^{-3}$ relative field change. The gradients, or field change per unit length, on the right hand side of the box is lower because of the narrower 40 mm wide opening on that side of the box compared to an 80 mm opening on the left side. Because of this the optimal position for the cell would be asymmetric towards the side with narrower opening which will face the sample position for both boxes. This is logical given the converging nature of the focused beam on POLI.

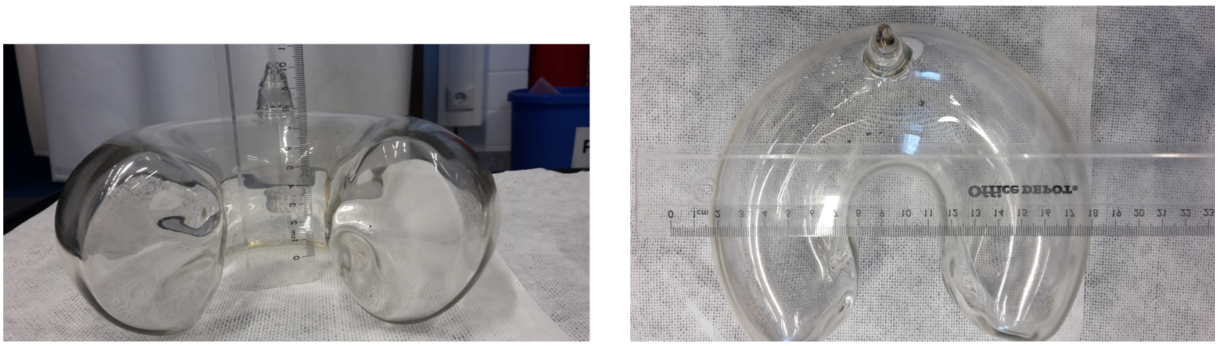

Figure 6. Photo of the PASTIS2 cell that was used for experiments on NEAT at HZB. This cell has a pressure of 1.5 bar and a 240 hour lifetime in laboratory conditions, it provided full polarization analysis coverage of the 240° horizontal and 40° vertical NEAT detector array.

still limited by the maximum outer diameters we can achieve, about 23 cm and the ability of the largest cells to survive pressure testing with a safety margin of 1 bar over the absolute pressure gradient the cell will be used at. This cell was pressure tested up to 4 bar in atmosphere before filling for example because it was used with 2 bar pressure in a vacuum. Larger inner diameters up to 80 mm are possible with the techniques used to make the cells. A photo of this very high performance C-shaped cells is shown in fig. 6. Additionally we produced a 0.5 bar hybrid K/Rd ^{3}He cell which obtained a measured T_1 lifetime of 1400 hours after corrections for NMR induced losses. Table 1 summarizes the characteristics of recently produced cells.

Cell name	diameter (cm)	length (cm)	pressure (bar)	lifetime (hours)	alkali used
PASTIS2	8 (high)	6 (thick)	1.5	240	Rb
Betty	5	5	2.1	290	Rb
Ulanda	6	5	0.5	1400	K-Rb
Jony	5	7	1	200	K-Rb
Jimmy	5	5	1.9	210	K-Rb
TOPAS-3	5	15	2.8	229	Rb
Ulasen	5	5	0.4	560	K-Rb

Table 1. Summary of the cells made recently at JCNS. The neutron path of the C-shaped cell is given, it was prepared from a 8cm long toroidal blank that was about 17 cm O.D. and has an inner diameter to accept a 4 cm cyrostat. All cells are reblown from 25mm diameter GE180 tubing in the FZ-Juelich glass shop.

5. Conclusions

We have reported on the status of several projects at the JCNS towards applications of ^{3}He neutron spin filters. In addition to the projects reported here, in the coming year we are working to contribute in-situ ^{3}He polarizers for the DREAM instrument incident cold neutron beam [15] and the thermal neutron incident beam on T-REX [13] with polarizers very similar in concept to the POLI analyzer or the TOPAS polarizer that we have already constructed [7].
We thank the contributors to the polarized ^{3}He work and its scientific use in neutron scattering who continually influence and drive this work. We especially thank the staff of the JCNS for work with the polarizers' consgtruction, and staff at ISIS and TU-Delft for all the help working with us for on-beam testing of the KWS1 device so far.

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