in-situ ^{3}He SEOP polarizer for Thermal neutrons

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Abstract.

In this article we describe the neutron polarizer for a new time-of-flight neutron spectrometer with polarization analysis TOPAS. This instrument will use the convergent focused incoming beam of thermal neutrons with energies up to 150 meV (wavelength down to 0.74Å). The polarizer employs a high opacity ^{3}He neutron spin filter with continuous ^{3}He polarization provided by two laser array bars frequency narrowed by an ultra-compact volume Bragg grating. The system was successfully prototyped, and tested. In the course of first experimental test at the polarized hot neutron diffractometer POLI at MLZ, neutron polarization of 97.6% was achieved for 0.895Å neutrons and kept constant during 30 days.

1. Introduction

In recent years we operate successfully a continuously SEOP [1] pumped ^{3}He filter cell as an analyzer on the cold neutron reflectometer MARIA [2]. Similar to this application it is requested here to polarize a rather divergent beam in the focusing section of the TOPAS [3] neutron guide. The beam size is here somewhat smaller, but the wavelength of the neutrons is significantly shorter, therefore requesting a larger opacity compared to the MARIA setup [2]. Gaining this experience, we have developed the in-situ SEOP polarizer for TOPAS [3]. The main difference between these two setups is in the working wavelength range: TOPAS employs thermal neutrons with energies up to 150 meV (wavelength λ down to 0.74Å) [3], in contrast to cold neutrons with λ>4.5Å used at MARIA.

The system is placed inside a closed box cooled by the roof mounted chiller to keep the working temperature stable at 35˚C for the optical pumping lasers and optics despite the high temperature, 210˚C, inside the oven. The box also satisfies safety conditions for powerful lasers. An automated guide changer will be used to move the system in and out of the beam to allow the unpolarized neutron option as shown in figure 1.

In the following we present the details of an optimized design for thermal neutrons and the first use of the system as a polarizer on the hot neutron diffractometer POLI [4].

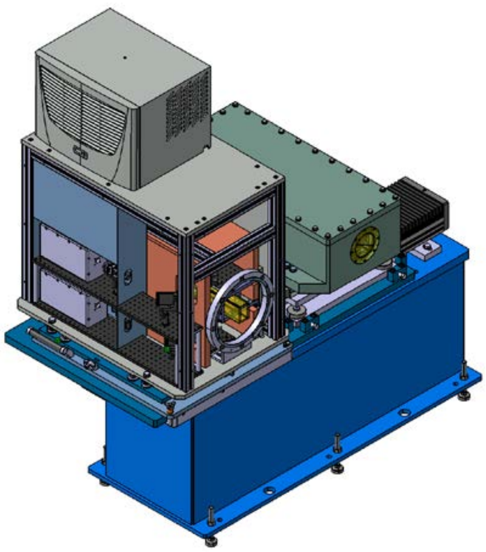

***Figure 1**. CAD model of the guide changer with one stage for the neutron guide and one stage for the SEOP polarizer box including the oven, the laser system, and a chiller box on top of the housing.*

2. AFP and NMR Control system

NMR free induction decay (FID) and adiabatic fast passage (AFP) flipping are both available on this system [5] as shown in figure 2. The FID allows one to monitor the ^{3}He polarization over time and characterize the optical pumping parameters such as the spin-up time constant and cell lifetime. Our FID system conserves the phase information of the ^{3}He precession and thus also allows us to probe whether the ^{3}He is in the up or down state. It is a single-coil pulse and receive system using in-house developed analogue switch and signal conditioning amplifier [6,7]. The AFP adds the function of a high performance spin flipper to the spin filter. The AFP program uses an all digitally generated pulse that is then amplified using a house built power amplifier with a 120 Vpp output from 5 kHz up to 100 kHz [7,8]. For the case of in-situ optical pumping via SEOP, the handedness of the circular polarization, and therefore the alkali-metal polarization, must be in phase with the direction of the ^{3}He spin. For this purpose, we use liquid crystal variable wave retarders to switch between left and right polarization by applying a TTL pulse to a house built analogue liquid crystal (LC) wave plate driver. All the NMR devices and the switching of the LC retarders are accomplished with a program written in Python which has a web-browser interface that can be accessed remotely over a web server or via IP protocols. The program controls a 1.25 MHz Lab-view DAQ card using the legacy National Instruments DAQmx 8.0 driver library which runs in either Linux or Windows.

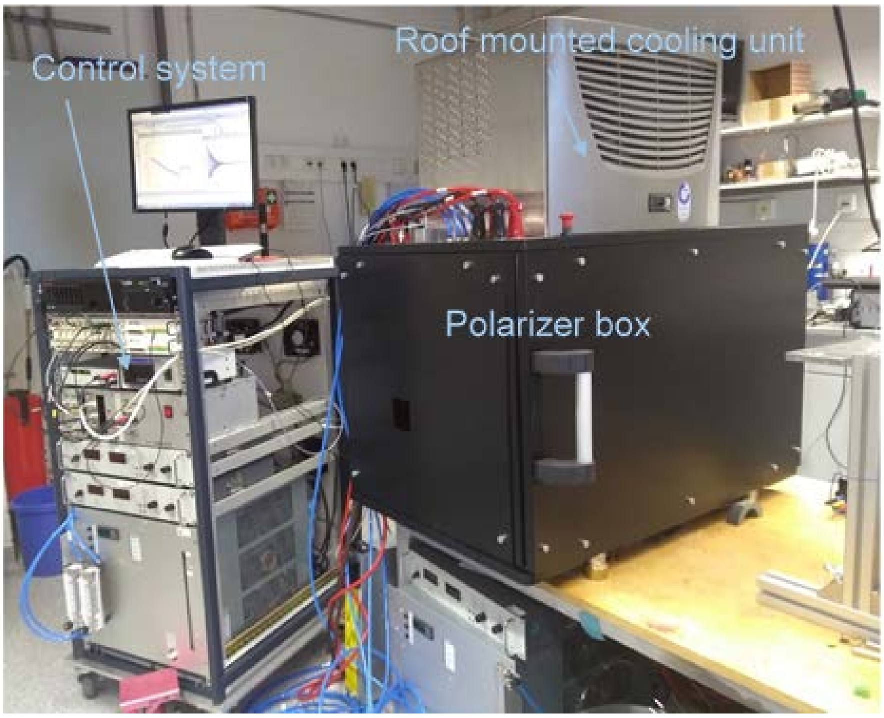

Figure 2. *The polarizer box with roof mounted cooling unit and the control system*

3. Magnetic cavity

A simple rectangular SEOP magic-box style magnetic cavity similar to those in [9-11] is used. The magic-box design is resized for the smaller beam diameter required for an incident beam of about D=6 cm. The resulting cavity is 40 cm tall by 20 cm wide and 62 cm long. The magnetic field is along the 40 cm direction and co-linear with the guide fields of TOPAS to prevent depolarization of the fastest neutrons with wavelength λ=0.7Å to be used there.
The magnetic cavity has been constructed and tested for the polarized ^{3}He magnetic lifetime (Figure 3-a). Detailed description of *permanent magnet and current driven magnetic cavities using mu-metal to create highly homogeneous magnetic field is described in a separate paper in this proceeding* [12]. Initial experimental optimization has been performed with the 3-axis Hall probe moved along the 40 cm direction to map the 1D longitudinal magnetic field in the cavity.
As the next step we have used a 5 cm in diameter and 15 cm long SEOP cell filled with ^{3}He at pressure of 3 bar. It has been polarized externally in the JCNS ^{3}He lab and placed in the centre

of the magnetic cavity for measurements of the ^{3}He lifetime by observing the decay of the relative polarisation using the NMR system. The free induction decay (FID) of the longitudinal magnetization is periodically monitored, typically every hour: ^{3}He polarisation is proportional to the amplitude of the FID signal. The exponential decay fit of the time dependence of amplitude of the FID signal gives a value of T_1. Figure 3-b shows the result of the measured ^{3}He relaxation time, resulting in T_1 =185 h.
After subtracting of the contribution for the intrinsic lifetime of the cell which includes ^{3}He dipole-dipole relaxation [13] and the wall relaxation of this cell [14] taking into account the T_1 of 220 h measured for the same cell in perfect magnetic field, we obtain the measured ^{3}He magnetic lifetime of 1395 hours for 3 bar pressure or a cell averaged equivalent magnetic field gradient of about 5×10^{-4} cm^{-1}.

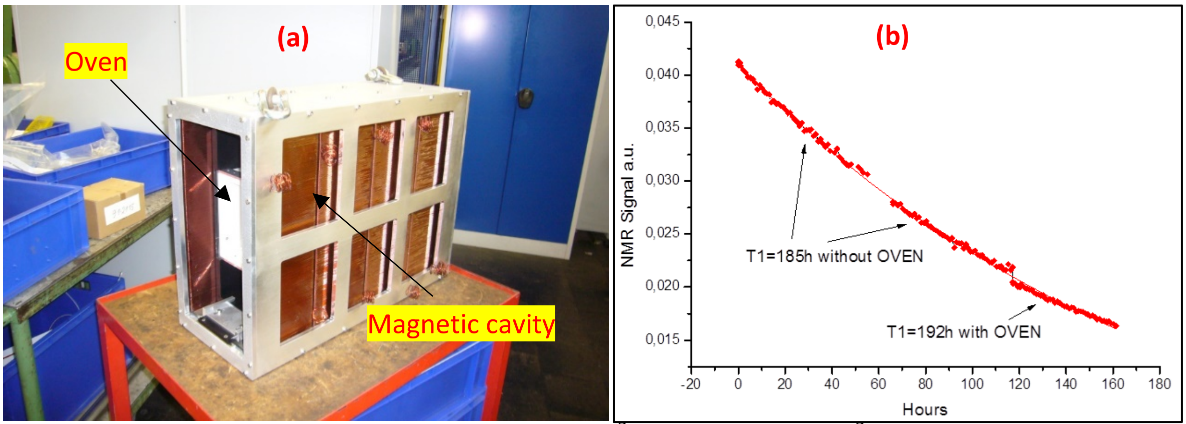

Figure 3. *a- The magnetic cavity with oven and ^{3}He cell inside. b- ^{3}He cell relaxation time. Measured ^{3}He relaxation time of 185 hours for 3 bar ^{3}He cell placed inside the magnetic cavity. Subtraction of the cells self-relaxation time yields a cell averaged equivalent gradient of 5×10^{-4}cm^{-1}.*

4. New oven concept

As shown in figure 4, the oven is designed to host a 15 cm long and 5 cm diameter ^{3}He cell, and to fit inside the magic cavity described before. The heating system uses static air heated by electric cartridge heaters mounted in copper heat sinks. These stainless steel electric cartridge heaters (220 V CSS-series from Omega Engineering) have not been found to decrease expected ^{3}He polarization, or room temperature T_1 lifetime. There is indeed some magnetic components to these heaters, namely the nickel plated lead wires, however in our installation, the heater is placed inside the before mentioned copper heat-sinks, about 10 cm away from the cell (see figure 4), with the wires exiting away from the cell position.

Figure 4. *The new oven with ^{3}He cell inside the magnetic cavity*

The copper heat sink is grounded to limit pickup of electrical noise by the NMR FID system [5]. To meet the requirement of temperature accuracy and stability needed for optical pumping the system was tested over the course of one week. A PID control system is used to control the heaters and regulate the oven temperature and several temperature sensors were placed at the surface of the cell and at different position inside the oven. After only 25 minutes of heating, the system could reach the temperature of 250˚C at the heat sink position and 210˚C at the cell position; the temperature was stable to within 0.5˚C over the whole time of the test experiment, as shown in figure 5.

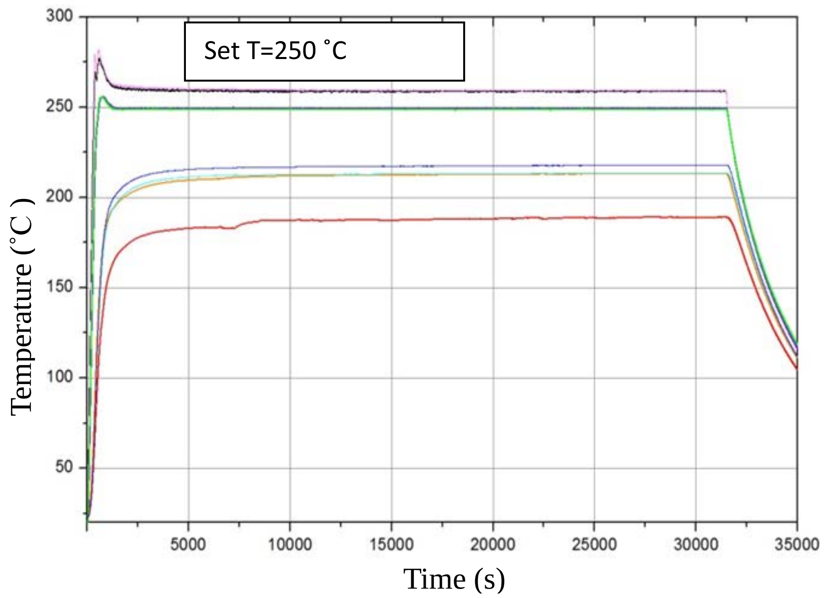

Figure 5. *Test of the oven temperature stability, the different colors represent the readout from different sensors mounted in the oven. The cell reaches a stable temperature after ~2000 s and remains then stable for the rest of the test.*

To test the influence of the oven components on the relaxation time the same test has been performed, this time with a cell placed inside the oven as in the real optical pumping procedure. The results are shown in the same plot (Figure 3-b); we can see that the oven does not affect the decay of the ^{3}He polarization.

5. Laser systems upgrade

Our laser systems have also been upgraded. Formerly diode array bars (DAB) with external cavities using Littrow-type configuration were used [15] as narrow-band optical pumping light has been shown to provide the best SEOP performance. However, it was found later that a new compact method using chirped volume Bragg gratings, CVBG, provides a higher absolute ^{3}He polarization [16]. Additionally, CVBG narrowed lasers give higher laser intensity output for laser diodes of the same power, and contain much fewer optical elements making the cavity more compact, stable and robust for long term operations required for in-situ ^{3}He polarizer applications. A photo of the new laser cavity is shown in figure 6, where the laser mounted inside a newly designed compact box for mounting the laser and cavity optics is shown, as well as external connections to the power cables and cooling water. This box also provides environmental protection and increased laser security. Two such lasers are used to pump the 15 cm long ^{3}He NSF cell used here for this in-situ polarizer by illuminating it from opposite sides.

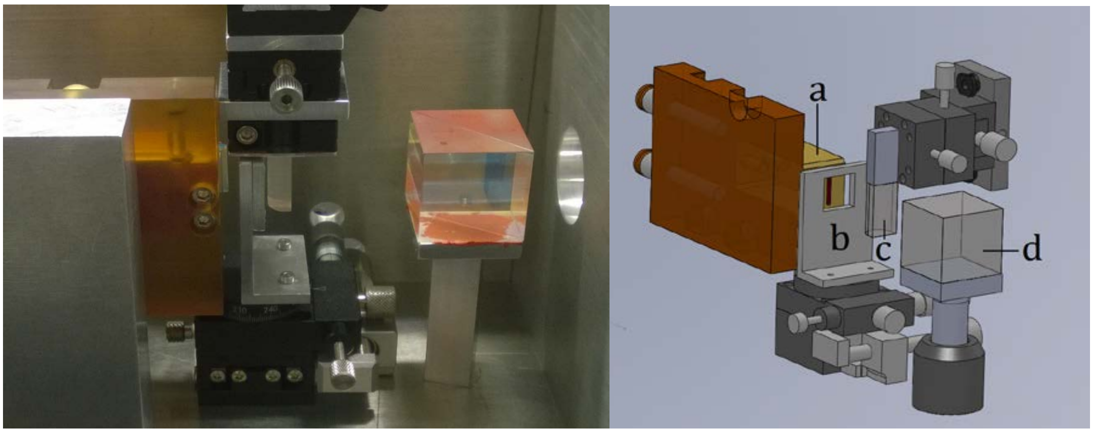

Figure 6. *A picture the laser-box (left) of the current volume Bragg grating narrowed laser configuration, CAD drawing (right); a) laser diode, b) support for the optical grating, c) cylindrical lens, d) beam splitter.*

6. Result of the on-beam test at POLI

After several tests and off-line optimization, the compact cavity has been installed at POLI instrument at MLZ for absolute measurements of the ^{3}He polarization using the neutron transmission technique [17]. The cell was pre-polarized in the experimental hall near the POLI instrument, a temperature of 215°C was used in the oven to obtain a 7 hour ^{3}He polarization time constant (or "spin-up" time). The ^{3}He polarization reached saturation in one day. The polarizer box temperature remained very stable that in turn allows for stable temperature conditions for the optics and the magic box despite the oven temperature of 215°C thanks to the roof mounted chiller which cooled and stabilised the system to a temperature of about 35°C. Polarization has been held stable for three days at which point the polarizer setup has been moved into the incident beam of POLI (λ=0.895 Å) without shutting the polarizer down and neutron measurements have been started instantly. The polarizer is followed by a transmission monitor, the zero-field polarimeter Cryopad [18] with a single crystal sample and a MEOP [19] polarized analyser cell installed in Decpol - the standard POLI configuration for analysis of the reflected neutron beam polarization.
We use ^{3}He cell with the opacity of 41.5 bar·cm, and reached the maximum ^{3}He polarization of 78.5% determined from unpolarized neutron transmission measurements. The initial polarization after the transport to the POLI beam was 74%, but after the continuous optical pumping over 14 hours it built up to 78.5% and remain stable (figure 7). The total transmission through the polarizer for such ^{3}He polarization is 23.8% that results in the neutron polarizing power of 97.6% for λ=0.895 Å neutrons. A fresh analyzer cell HL2 from the FRM2 MEOP station Helios [20] was installed in the Decpol magnetostatic cavity for analysis of the polarization at a nuclear Bragg peak from a single crystal sample. The analyzer cell had an opacity of 37 bar·cm with ^{3}He polarization of 67.6% and neutron transmission of 20.5% measured 3.5 hours after the insertion into the Decpol, that results in the neutron polarization analyzing efficiency of 92.8%.
After optimisation of guiding magnetic fields the combined maximum flipping ratio of 17 is obtained (using the Decpol nutator flipper) that corresponds to the total neutron polarization

of 89.0%. This is only slightly lower than the product of the polarizer and analyser efficiency (97.6%*92.8%=90.6%) obtained from transmission measurements.

More recently the described in-situ polarizer has been used for a longer 30 day experiment on POLI. In this case, for neutrons with λ=1.15 Å the neutron transmission is 21% that corresponds to 80% ^{3}He polarization, in a good agreement with the results of the previous test. This level of transmission and polarization was highly stable over the whole 30 days of the experiment; more details on this experiment will be published elsewhere.

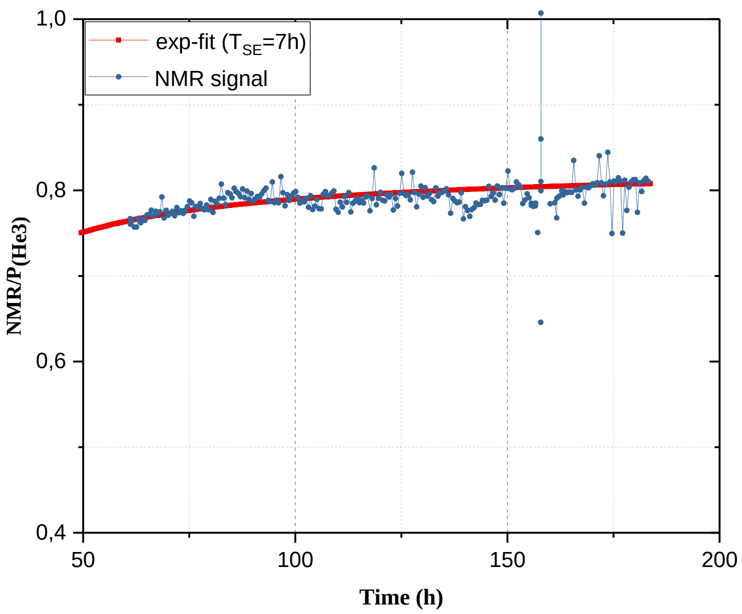

Figure 7. *The 3He polarization as function of time obtained during on-beam test at POLI*

7. Conclusions

We have designed, prototyped and successfully tested the in-situ SEOP ^{3}He polarizer for TOPAS spectrometer. The magnetic cavity design assures the relative field gradients of $5\cdot10^{-4}$ cm^{-1} over the whole cell of 5 cm in diameter and 15 cm length. All components easily achieved the desired goals, the first on-beam test gave maximal ^{3}He polarization of 78.5%. The total transmission through the polarizer was 23.8% resulting in the neutron polarizing power of 97.6% for 0.895 Å neutrons. Obtained results show not only the high performance of the TOPAS polarizer, but also demonstrate the feasibility of using in-situ SEOP ^{3}He spin filters, which up to now are mostly used on the cold neutron beam lines, also for the polarization of thermal and even hot neutron beams. A dedicated compact SEOP polarizer/analyser for the beam line POLI at MLZ will be targeted in the future.

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