Polarized ^{3}He for the Fundamental and Applied Neutron Research

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The polarized ^{3}He nuclei are widely used in many fields of applied and fundamental researches, both as polarizer and/or analyzer of neutron polarization. Basically there are two methods of ^{3}He polarization: low pressure optical pumping through the metastable stage (MEOP) [1], and spin exchange optical pumping (SEOP) [2,3]. The last technique assumes the optical pumping of Rb vapor with production of atomic shell polarization, then this polarization is transformed to the ^{3}He nuclei via hyperfine interaction during collisions. Usually, MEOP is applied for multiuser facilities and assumes one separate installation which produces many cells with polarized ^{3}He simultaneously. Then, these cells are transported to the particular sites of application [4]. This way is very efficient, but quite expensive if the number of users is limited. The SEOP method is more individual and in some sense simpler. The pumping facility may be installed as a part of installation right on a beam line. This is traditional way of SEOP usage before.

We have build a mobile pumping device which provides ^{3}He polarization outside of application site in a convenient place. Then it transported to a desired location. Thus, we have created device which joins the advantages of SEOP and MEOP methods. Such type of devices may be reasonable when the number of users is not many.

Design of mobile ^{3}He polarization device

When SEOP polarization device is used as in-line part of installation on a neutron beam line there is no problem with real-time control of polarization. The well known way of neutron transmission difference measurement through a polarized and unpolarized ^{3}He cell provides quick and adequate information about ^{3}He polarization. Besides, an in-line device is always kept in a steady magnetic environment. Thus, if one polarize ^{3}He cell outside of neutron beam, the other way for polarization control is necessary, and some magnetic storage unit should preserve polarization from decay during transportation of a cell. We have decided to join these requirements in a same design. Figure 1 shows the sketch of our off-line pumping facility.

The cell with ^{3}He is placed inside of aluminum oven with build-in RF- and pick-up coils for the NMR measurement of ^{3}He polarization. The oven is fixed in a solenoid, which provides uniform longitudinal magnetic field along the direction laser light. The hot gun (not shown on sketch) blows a hot air through an oven to keep desired temperature for production of optimal Rb vapor number density. The optical part includes OptiGrate volume Bragg grating diode laser with output power up to 35W and wavelength maximum spectrum near 795 nm. The cube splits the laser beam into two linearly polarized components. One of them is then converted to a circularly polarized one by $\lambda/4$ plate, and guided by a mirror to ^{3}He cell. The oven with cell and a solenoid forms a single unit which is used both for pumping and transportation. After achievement of a maximum degree of ^{3}He polarization, the hot gun is turned off. When the cell temperature become less than Rb evaporation one, the solenoid supply is switched to a battery and the laser is turned off. Then, the unit is disconnected from all supply lines, placed in a car and transported to a desired location.

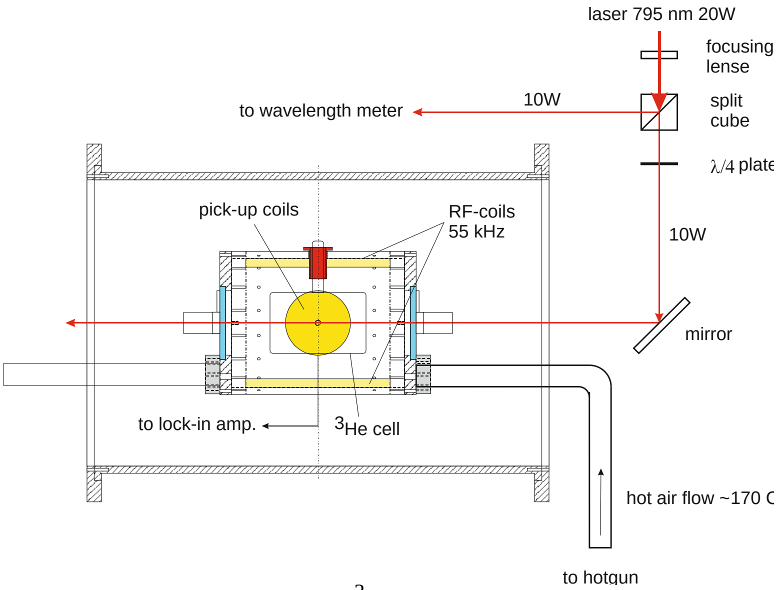

Figure 1. The sketch of ^{3}He optical pumping facility.

Figure 2 shows the photo of RF-coils were incorporated into an oven and the 55 kHz field distribution inside the oven. The winding of RF-coils consists of 8 line parts in series, and forms the sine-shape circuit [5]. That means the number of turns in each individual line circuit follows the sine function, as it is shown on Figure 2b. It is easy to see, this design of RF-coil provides uniform field transverse to a cylinder axis.

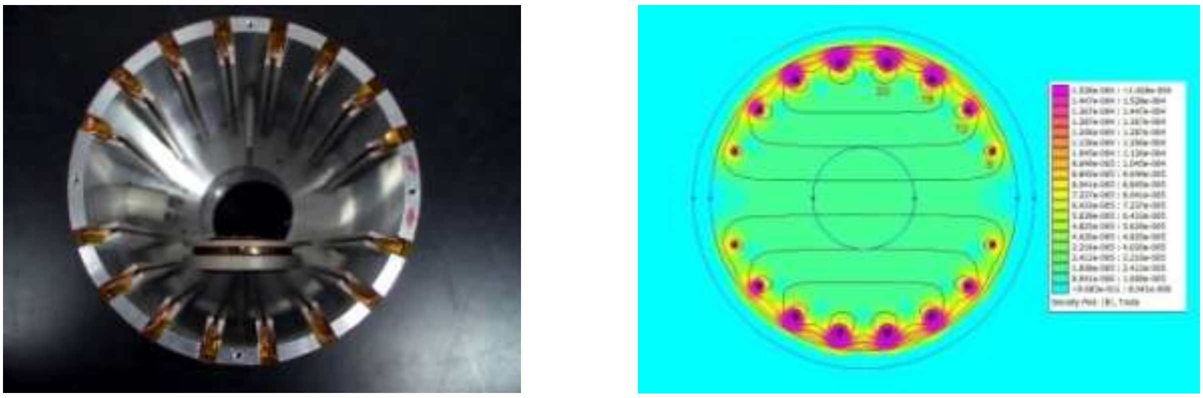

Figure 2. Construction of RF-coils (a) and RF-field distribution inside it (b). The coils for pick-up of NMR signal is shown on left image too.

The rails for every line circuit, pick-up coil body together with fixation screws were made of PEEK since they must sustain a high temperature continuously. The laser light is transmitted inside an oven through a 0.5 mm fused silica windows with anti-reflection coating.

The cylindrical cell was made in KEK from aluminosilicate glass GE-180. It had 40 mm in diameter and 60 mm in length. A cell contained 5.74 bar·cm of ^{3}He gas. The preliminary test had showed a ^{3}He polarization decay time about 200 hours for this cell.

NMR circuit and measurement procedure

The NMR measurement circuit was based on widely-used technique of adiabatic fast passage (AFP) with a guide field sweep. Its sketch is shown on Figure 3. A current for the solenoid was provided by a high speed amplifier/bipolar power supply (NF4025). The current was controlled by a function generator (HP33120A) and swept for AFP-NMR. The solenoid power supply provided output current 1.3 A without modulation. The function generator was used as the burst mode that provided a single triangle signal for the solenoid current modulation, and the corresponding modulated current was 1.3 A to 1.8 A to 1.3 A. The RF-coil was resonated at ~55 kHz with a capacitance of 0.02μF connected in series to maximize the solenoid current at the resonance frequency. The pick-up coil was also resonated at the same frequency with a capacitor of 0.02μF connected in parallel to maximize the voltage produced in the pick-up coil. The fact that both coils were in resonance with the same capacitance is just coincidence; usually, they come in different values. Since gyro-magnetic moment of the ^{3}He nucleus is -2.03789×10^8 [rad/s/T], the resonance magnetic field becomes 17.957 G at a Larmor frequency of 55 kHz for ^{3}He. The corresponding solenoid current was ~1.6 A. Since, the solenoid was short - 30 cm in length and 21 cm in diameter, we supplied it with ends correction coils to provide a more uniform field along the cell.

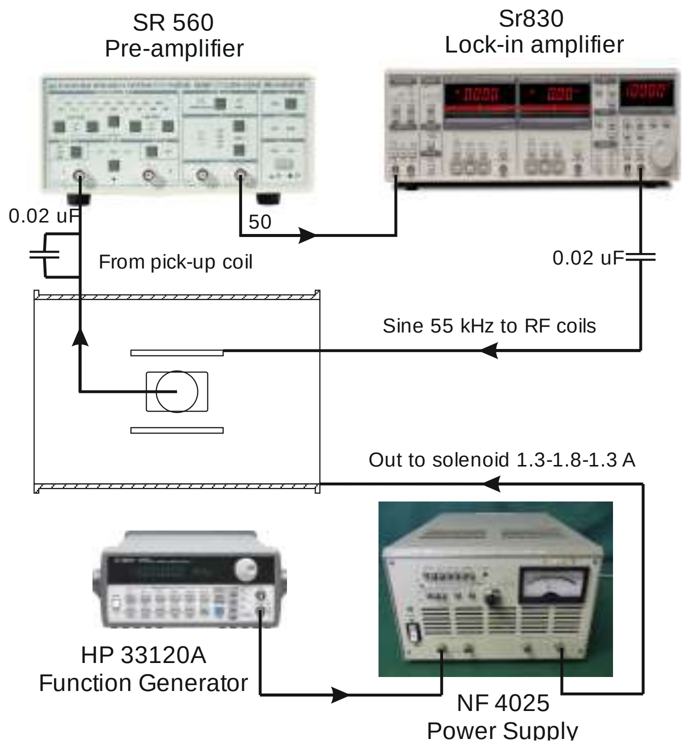

Figure 3. NMR signal measurement circuit.

The NMR signal detected by the pick-up coil was pre-amplified (SR560), and then provided to a lock-in amplifier (SR830), for phase-lock detection.

An alternating current for the RF-coil was provided by the sine out of lock-in amplifier. The RF-coil was directly driven by this output. Lock-in amplifier has internal memory for storing the X and Y output data. During every NMR measurement, 1024 data points for each

X and Y outputs were stored at a sampling rate of 512 Hz, corresponding to two seconds of output data. The phase of the internal oscillator was tuned so that NMR signals (peaks) were only observed in the X output.

AFP-NMR measurements were performed using LabVIEW. The AFP-NMR program measures and stores the NMR data on HDD. The program automatically turns on and off the RF current and gives start trigger signals to both the function generator (magnetic field sweep) and the lock-in amplifier (data taking).

Observed NMR signals are shown in Figure 4 after subtraction of the cross-talk linear component, which comes from RF-magnetic field detected by the pick-up coil. The last arises owing small vibrations which came to pick-up coil from hot gun through the air guide pipe.

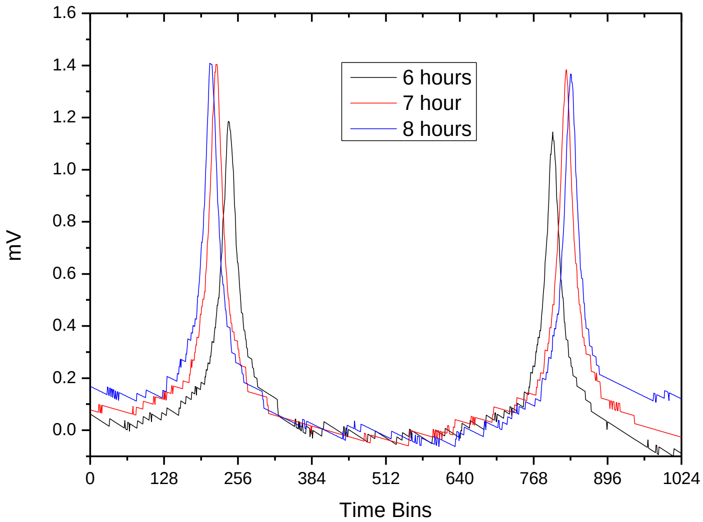

Figure 4. Typical NMR signal from polarized ^{3}He as a function of pumping time.

Neutron beam measurement

The device described above was designed, built and tested as R&D prototype for the use on cold neutron beam of HANARO nuclear reactor in KAERI (Daejeon, Republic of Korea). The polarized ^{3}He cell is aimed as an analyzer of neutron polarization in material science scattering experiments. The polarization of incoming neutron beam is provided by magnetic super-mirrors.

The pumping facility was allocated in optical laboratory of KAERI. After 8 hour of pumping and observing of NMR signal, a cell was cooled down, laser was turned off, and solenoid was switched to a commercial motorcycle battery (12 V, 10 AHr). Then the solenoid with polarized cell and a supply battery was placed into car and transported to HANARO test beam line. The whole procedure took about 30 minutes. General view of entire unit with polarized cell on a test beam line is shown on Figure 4.

The test beam line provides monoenergetic neutron beam with a wavelength 5 A (0.0032 eV). We have performed two measurements: neutron transmission of polarized cell N_p, then we have depolarized a ^{3}He with a permanent magnet and measured transmission N_u. Since the neutron beam was monoenergetic we did not measured the spectra, but the detector and beam monitor counts only. The duration of measurement was chosen to provide

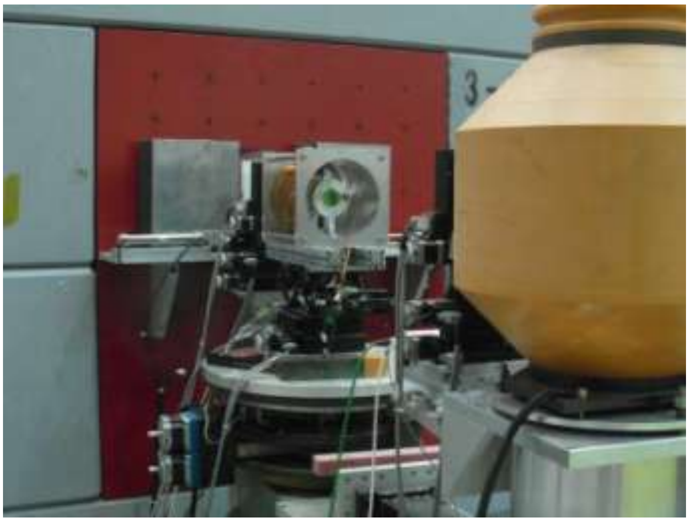

Figure 4. Polarized ^3He cell on HANARO beam line for cold neutrons.

an accuracy of ^3He polarization approximately to 1% at least. This two transmissions allowed us to obtain a neutron polarization p_n:

$$p_n = \sqrt{1-\left(\frac{N_u}{N_p}\right)^2} = 0.38 \pm 0.02.$$

The neutron polarization is connected directly with polarization of ^3He:

$$th(P_{He}\sigma nl) = p_n.$$

Here, σ is the polarization cross section of neutron - ^3He interaction which is 5333 barns, l is the thickness of a cell, n is ^3He number density. For our cell with a pressure of ^3He equal to nl = 5.74 bar·cm, the last equation gives P_{He} =0.18 ± 0.01.

According to KEK data of polarization decay for this cell, the maximum polarization of ^3He which may be achieved is 0.6 at least, if one provide typical time of pumping ~ 40 hours.

Conclusion

In a reported work, we have successfully demonstrated the functionality of a mobile device for SEOP production of polarized ^3He cells. The cells may be polarized off site and then transported to a desired location. The progress of polarization build-up during pumping is observed by AFP NMR.

The device we have designed has build-in parts both for pumping and transportation. It is light, compact, and may be used not just for neutron experiments, but for other applied and medical MRI purposes as well.

References

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