

Measurements in the Hyperpolarized Helium-3 for Medical Applications

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Abstract –Hyperpolarized helium-3 (³He) gas, is a new contrast agent for lung imaging diagnostic in functional Magnetic Resonance Imaging (fMRI) becoming an important technique to diagnose diseases and abnormalities in the respiratory tract. In this paper is described a new modular production method of ³He gas, hyperpolarized using the Metastability Exchange Optical Pumping Technique (MEOP). A standard set of measurements has been collected considering a prototype developed by ITEL Telecomunicazioni srl, able to produce one litre of ³He polarized gas at the pressure of 1000 mbar. A 27% of polarization at a pressure of 1 mbar is obtained in the optical pumping cell in a single run, while a time of about 20 minutes is needed to pump the gas at a final pressure of 1000 mbar in the storage cell.

I. INTRODUCTION

In the last years, several research groups have taken an entirely different approach to lung magnetic resonance imaging (MRI). Rather than imaging the lung tissue, MR techniques are applied to gas within the lung to obtain the images of the airspace. During this imaging modality, nuclear-spin polarized ³He is inhaled and acts as a contrast agent in the ventilated regions of the lungs. For these reasons the use of hyperpolarized ³He gas is growing as an important contrast agent for lungs MRI [1-3]. MRI offers the benefits of computer tomography without the risks of ionizing radiation but it is not suitable for imaging the lungs due to the low fraction of polarized protons (5 in 106 at 1.5 T). The density of protons in the lungs is very low and the differences in susceptibility between air and lung tissue generate magnetic field inhomogeneities which lead to signal loss and image distortion. These susceptibility effects increase with the field strength of the magnet.

With hyperpolarized MRI diagnostic good signal to noise ratios can be obtained even at low static magnetic

field [4–6], thanks to the high polarization level of ³He nuclear spins, obtained using optical pumping. In fact, the optical pumping in combination with polarized laser increases the nuclear magnetic resonance signal up to five orders of magnitude. The hyperpolarization is obtained by means of the optical pumping technique that allows the alignment of spins by transferring angular momentum from polarized light [7]. In the following sections of this work, a prototype developed by ITEL Telecomunicazioni s.r.l. is described, afterwards a comparison with a traditional fixed gas production system is made. Finally, some measurements, demonstrating the advantages of the proposed method, are reported.

II. MEOP TECHNIQUE TO HYPERPOLARIZE ³HE

Recently most authors agree that to hyperpolarize ³He for MRI, instead of the optical pumping of an alkali metal transition (e.g. rubidium) used in spin-exchange optical pumping technique, a metastable electronic state of the ³He itself is pumped, which then transfers its electronic polarization to nuclear ³He spin polarization [6, 8]. Before the ³He gas can be optically pumped, a small portion of the gas must first be excited from the ground electronic state into the metastable state. This is achieved by applying a weak RF discharge to the optical pumping cell at room temperature and at low pressure, in the order of a few mbars. Metastable atoms can then be optically pumped by absorbing circularly polarized laser light at $\lambda = 1083$ nm. By collisional mixing of the excited states and isotropic reemission into the different hyperfine states, the population is driven into the states with positive quantum number. The entire MEOP process can be obtained using a homogeneous static low magnetic field, which is necessary in order to establish the quantization axis. The main characteristic of the MEOP technique is the use of ³He gas with high chemical purity, without any intermediate medium to transfer the angular momentum from photon to ³He atom at a very low

pressure. Moreover the time necessary to hyperpolarize the ^3He gas in the MEOP technique is in the order of seconds, instead of several hours necessary for the SEOP technique, while using the same laser power for both MEOP and SEOP. In our work we have produced hyperpolarized ^3He gas by means of MEOP, using a 10 W Keopsys optical fiber laser with a wavelength of 1083 nm.

III. HYPERPOLARIZED ^3He SYSTEM

A schematic layout of the gas production system is shown in Fig. 1. To obtain the magnetic field which surrounds the entire MEOP production system, we have used a source with 25 spatially modulated coaxial coils of 2.5 m of diameter, which produces a homogeneous field (about 120 ppm) of the order of 25 G in a large volume. The coils surround the tubes where ^3He flows, which are made in glass in order to reduce the impurities that are largely responsible for the ^3He depolarization. As shown in Fig. 1, our MEOP system is characterized by two cylindrical optical pumping cells (OPC), each one having a length of 150 cm and a diameter of 6 cm. The new design of this system makes possible to use one or both OPCs, each one able to produce up to 50 L/day of hyperpolarized ^3He .

In this way this system is a flexible solution to produce the gas quantity necessary for a single or more MRI lung exams in the hospital environment. In detail, if we operate our MEOP closing the valves 1 and 4 (see Fig. 1) and opening at the same time the valves 2, 3 and 5, we produce hyperpolarized gas using only the optical pumping cell 1 (OPC1).

Instead if we operate opening the valves 1 and 4 and closing at the same time the valves 2, 3 and 5, we produce hyperpolarized gas using both the optical pumping cells (OPC1 and OPC2).

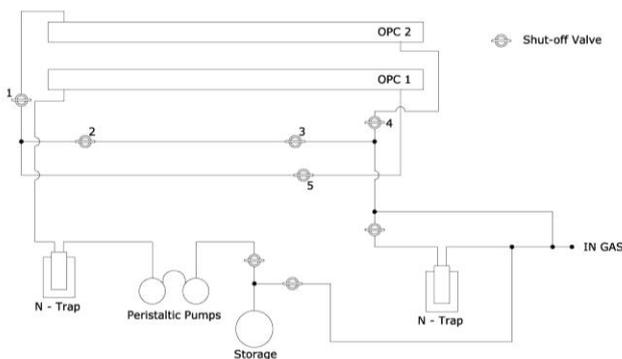


Fig. 1. Layout of a MEOP System with two modular optical cells (OP).

The hyperpolarized gas can fill a storage cell (ST) that in our system can accumulate up to 1 L of gas at the

atmospheric pressure.

To minimize the interactions of spin-polarized ^3He atoms with the paramagnetic centers on the inner surface of the containers walls, which leads to the so-called wall relaxation [11], we have used a borosilicate glass for the entire system. The first step to start the MEOP is a standard cleaning procedure, which uses a strong discharge to remove all impurities from the cell walls and then create a high vacuum in the system.

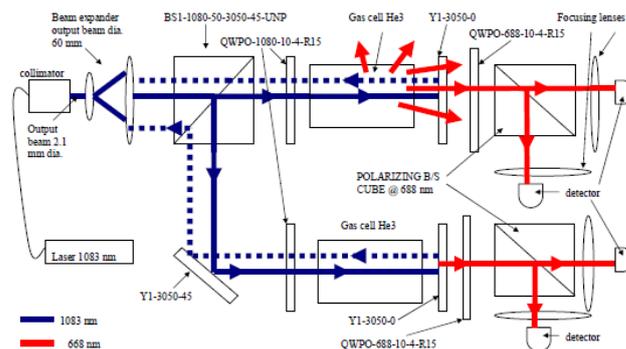


Fig. 2. Optical system of OP cells designed for the two ^3He emission lines $\lambda = 1083$ nm (blu line) and $\lambda = 668$ nm (red line).

A SAES getter (rare gas purifier, PS2-GC50-R) is used to purify ^3He gas before it is admitted to the glassware section of the MEOP station [10]. The getter reduces contaminants other than noble gases, to less than 10 ppb. After the first cleaning procedure with SAES getter an N-traps were used in the gas input line (see Fig. 1) to further clean the gas obtaining a 99.999% pure ^3He gas. [10]

The high vacuum was obtained considering a turbo molecular Edward pump able to obtain a vacuum in the order of $10\text{E-}9$ mbar. An initial quantity of ^3He atoms in the 2^3S metastable state was obtained by a weak RF discharge, created by an E-H balanced antenna dipole wrapped along the OP cells. A Keopsys fiber laser, with output power up to 10 W, is the starting point of the system used for optical pumping, as shown in Fig. 2.

The laser light, expanded by a couple of lens and divided by a 50/50 beam-splitter, passes through the two cells once and at the end of the cells is reflected back by a dielectric mirror to increase the efficiency of the optical pumping process.

To verify the nuclear polarization of the ^3He , an optical polarimeter is mounted after the cells in the same direction of the laser light, as shown in Fig. 2.

The coaxial optical system used to measure the nuclear polarization is based on the analysis of the degree of circular polarization of the red (668 nm) light emitted by the discharge in the cell [12]. In detail, the circularly polarized light from the discharge is first passed through a rotating Quarter Wave Plate (QWP), where it is

converted to linearly polarized light. The direction of the linear polarization follows the optic axis of the QWP. This linearly polarized light is passed through a 670 nm interference filter, allowing passage of light within a 10 nm band centered at 670 nm, and finally comes in a polarizing beam splitting cube followed by two photodiodes which detect the two polarization components.

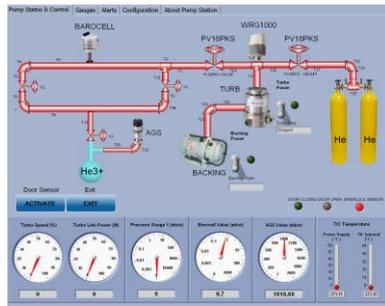
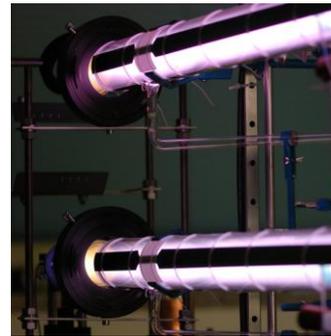


Fig. 3. LabView control of the MEOP ^3He hyperpolarized production system.

A lock-in technique developed in LabView environment is used to improve the sensitivity of the measure, applying a low frequency modulation to the RF discharge, with a modulation depth signal of 30% as reference. The ^3He gas, produced in the OP cells, is stored in the ST by a non-magnetic peristaltic compressor [13] driven by an air compressor motor so as not to produce a high depolarization of the gas. The value of the nuclear polarization inside the ST cell, was measured by a low frequency pulse NMR spectrometer able to monitor in the real time the trend of the ^3He polarizations. The scheme of the system and the LabView control system, developed by ITEL Telecomunicazioni srl, are shown in Fig. 3. The actual production system is shown in Fig. 4.



a)



b)

Fig. 4. a) MEOP ^3He system and b) a particular of the ^3He hyperpolarized production.

IV. EXPERIMENTAL MEASUREMENTS

We measured the system performance in different conditions. In Fig. 5 we have reported the optical spectrum of ^3He in the OP cells measured with an AvaSpec fiber optic spectrometer (75 mm, 2048x14 pixel CCD detector) after an interval of 10 s necessary to obtain hyperpolarized ^3He , with laser power 10 W and cell pressure 1 mbar. In Fig. 6 it is reported the Free Induction Decay (FID) signal of the hyperpolarized ^3He gas obtained using a magnetic field of 25 G and measured with an MRI sequence system emulator made by University of L'Aquila (Italy). Moreover in Fig. 7 we can see the NMR signal amplitude versus time at which the tipping pulse is applied. A fit to a decaying exponential allows one to extract the longitudinal relaxation time T1 of the hyperpolarized ^3He , which in our system was in the order of 25 min. Other important measures were made using a LabVIEW virtual lock-in amplifier, able to detect and measure very small AC signals, in order to evaluate how the level of the polarization changes when the pressure in the optical cells, the static magnetic field and the power of the laser are changed.

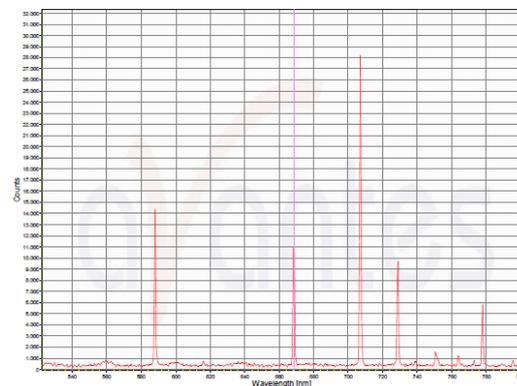


Fig. 5. Spectrum lines of MEOP technique after an interval of 10 s sufficient to obtain hyperpolarized ^3He gas, with laser power 10 W and cell pressure 1 mbar.

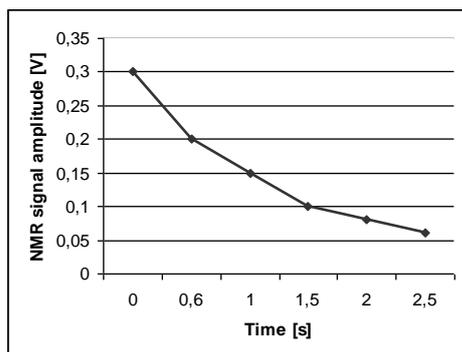


Fig. 6. Free induction decay (FID) signal from hyperpolarized ^3He obtained at a magnetic field of about 25 G and measured with an MRI sequence system emulator.

The results are shown in Figs. 8-10. By increasing the power of the laser for a fixed pressure of the optical cells and for a fixed static magnetic field we can obtain high values of polarization of the hyperpolarized ^3He , as we can see in Fig. 8. Instead the value of the polarization decreases as the static magnetic field increases, for a fixed pressure in the OPC, as reported in Fig. 9. A similar decreasing behavior is observed in Fig. 10 when the pressure of the optical cells increase, for a fixed static magnetic field.

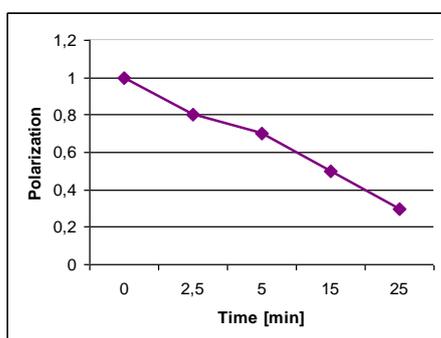


Fig. 7. T_1 measurement for pure ^3He at 1 mbar.

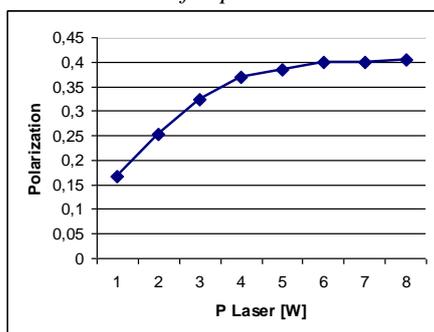


Fig. 8. Experimental measurement of the polarization versus laser power for an OPC pressure of 1 mbar and B_0 of 25 G.

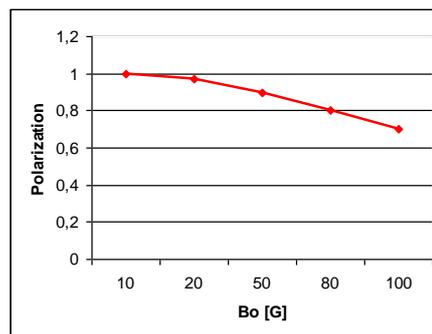


Fig. 9. Experimental measurement of the polarization versus static magnetic field for an OPC pressure of 1 mbar and a laser power of 9 W.

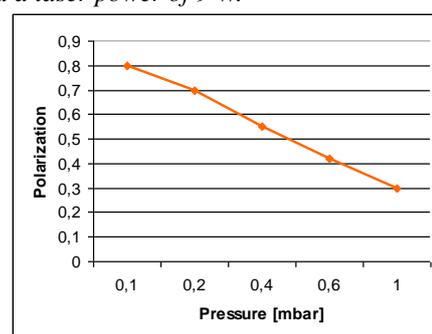


Fig. 10. Experimental measurement of the polarization versus pressure in the OPC for a power laser of 9 W and B_0 of 25 G.

V. CONCLUSION

In this paper we have described a new modular ^3He gas polarizer based on the MEOP technique. The entire system has been analyzed and has been proved able to produce 1 L of highly polarized ^3He gas at the pressure of 1000 mbar. Two most interesting system features are: *i*) the flexible use of two modular low-pressure optical pumping cells, each one having a capacity of 4 L, and *ii*) the fact that the hyperpolarized ^3He gas obtained is transferred into a ST through a non-magnetic peristaltic compressor. About 27% polarization at 1 mbar is achieved in the optical pumping cell in a single run, while a time of about 20 minutes is needed to pump the gas at a final pressure of 1000 mbar in the storage cell. Actually, further work will be aimed at finding the optimal design and the working conditions to increase the process efficiency for different gas pressures and magnetic field strengths.

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