Construction of a compact $^3$He polarizing facility

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Abstract. In this paper we present concepts, developed to construct a compact $^3$He polarizing facility as well as first results of their realization. The apparatus, which is currently in the state of construction, is based on the method of metastability exchange optical pumping (MEOP). Contrary to the present apparatus at the university of Mainz, which serves as central polarizing facility, the compact polarizer is designed to serve as local polarizing facility in both basic research and medical application. With the new polarizer we aim to reach polarization degrees of $P > 65\%$ at a flux of several standard liters per hour.

1. Introduction

Applications of hyperpolarized $^3$He are various. The strongly spin-dependent absorption of neutrons in polarized $^3$He opens up the possibility of polarizing neutrons over the full kinematical range of cold, thermal and hot neutrons [1]. Hyperpolarized $^3$He nuclei are as well used as kind of polarized neutron target in medium energy physics [2] and in precision magnetometry [3]. In 1994 it was discovered, that hyperpolarized gases can serve as contrast agent in medical imaging in order to display lungs in vivo [4]. The wide interest in this new medical diagnostic tool made it necessary to produce large quantities of hyperpolarized $^3$He. Therefore a polarizing facility has been developed at the university of Mainz a decade ago, designed for centralized polarization of $^3$He. The concept of remote production of hyperpolarized $^3$He requires means for shipping the polarized gas safely to the customer. To that end glass vessels have been blown from a special melt of He-diffusion tight glass, showing little wall relaxation [5]. For storage and transport they are packed in specially developed spin boxes with a homogeneous magnetic field inside, that maintains the polarization of the gas [6]. The residual relaxation rate is typically about $1/(100\, \text{h})$.

The design of the compact polarizing facility currently under construction facilitates local polarization. As it will be possible to install the polarizer directly at an experiment in order to perform on-line polarization, experiments that require the highest possible degree of polarization can benefit from the compact facility. On the other hand, users needing huge amounts of polarized $^3$He e.g. for clinical applications can gain independence from gas-deliveries, when using the compact polarizer at their own facility.

2. The current polarizing facility

The current polarizing facility is based on the method of metastability exchange optical pumping (MEOP) [7]. $^3$He gas at a pressure of about $1\, \text{mbar}$ is polarized in a weak gas discharge by two
Figure 1. Sketch of the current MEOP polarizing facility at Mainz. It is located in a homogeneous magnetic field of 1 mT provided by a set of large air coils which occupy a volume of 2.6 m in length and 1.6 m in diameter. Shown are two of the five optical pumping cells with a total volume of 36 l. [8][9][10]

fiber-lasers at 1083 nm. The whole apparatus is located in a homogeneous magnetic field of 1 mT (relative field gradients \( \frac{dB_r}{dr}/B_0 \) in the order of \( 10^{-4} \text{ cm}^{-1} \)), which serves as quantization axis and holding field for the \(^3\)He-spins. The polarizer consists of three parts.

The first part (upper part in fig. 1) consists of the reservoir for the unpolarized gas and getters for gas purification. These are necessary as gas impurities exceeding the ppm level reduce the density of metastable atoms in the gas discharge and hence the degree of polarization, that can be reached in the optical pumping.

The second part (middle part in fig. 1) contains the optical pumping volume with typical pressure values of about 1 mbar. A weak gas discharge excites Helium atoms into the metastable \(^2S_1\) ground state. Optical pumping is performed with two 15 W fiber lasers at 1083 nm. After having passed a polarizer cube and a \( \lambda/4 \) plate the light is circular polarized and gets absorbed by the metastable atoms. In this absorption process angular momentum of the photons is transferred to the electron shell of the atom. By hyperfine-coupling the angular momentum gets transferred to the nucleus. Via metastability exchange collisions the \(^3\)He atoms get back to their ground state.

The third part (lower part in fig. 1) contains a mechanical, polarization-conserving piston compressor driven by hydraulics in order to achieve gas pressures up to 5-6 bar. In a first step the gas is compressed into a buffer cell of \( V = 61 \). After having polarized the desired amount, the polarized gas from the buffer cell is compressed in a second step into a detachable transport cell.

Fig.s 2 and 3 show the performance of the current polarizer. The build up of the nuclear polarization is shown in fig. 2. In steady state a maximum polarization of \( (84 \pm 2)\% \) can be achieved with the facility. Fig. 3 shows the polarization of the gas in dependency from the throughput of hyperpolarized \(^3\)He. For medical applications, where high production rate counts more than ultimate polarization, a working point around 65\% polarization and 3 standard liters per hour throughput is adequate. Basic research, on the other hand often requires the highest
3. The new compact polarizing facility

The new compact facility follows the same design principles and aims at the same performance data as its predecessor (see figs 1 - 3). However, a decisive reduction in size is achieved by embedding the critical components shown in fig. 1 into a magnetic shield with a homogeneous field inside. Moreover, we have tested and will implement a more efficient concept for the various optical components which allows - amongst others - saving of one of the two high power pump lasers. Also the cumbersome hydraulic compressor drive will be replaced by a neat linear motor.

3.1. Magnetic field and shielding

In order to keep the relaxation of the polarization due to a magnetic field gradient small, a sufficiently homogeneous magnetic field has to be provided. $T_{\text{grad}}$, the time constant of relaxation induced by diffusive motion of the gas atoms through an inhomogeneous magnetic field, is given by

$$\frac{1}{T_{\text{grad}}} = D \cdot G_r^2$$

where $D$ is the diffusion coefficient and $G_r$ the relative transverse field gradient

$$G_r = \sqrt{\left(\nabla B_x\right)^2 + \left(\nabla B_y\right)^2} / B$$

Using the known diffusion coefficient at room temperature one can write $T_{\text{grad}}$ as [6]

$$T_{\text{grad}} \text{[h]} = \frac{1}{6900 \frac{p \text{[bar]}}{G_r^2 \text{[cm}^{-2}\text{]}}}$$

With a desired $T_{\text{grad}} \geq 1 \text{h}$ the radial field gradient has to be $G_r < 3.8 \cdot 10^{-4} \text{ cm}^{-1}$ at 1 mbar. Such a homogeneous magnetic field can be provided by a solenoid. To construct a compact apparatus it is imperative to use the volume of such a solenoid efficiently. The concept of creating a homogeneous field all over the solenoid’s volume consists of covering it at both ends with flat polefaces and returning the flux through a mantle around the windings [6] (see fig.
This closed cylinder, built from material with high magnetic permeability [11], provides also an efficient shielding of magnetic stray fields which allows to place any electronics, motors, steel constructions etc. close by. One of the endplates has an opening in order to feed in a support structure from aluminum as well as supply lines for helium, vacuum, pneumatics, electronic signals etc. to the assembly inside the solenoid. As the field homogeneity inside would be disturbed by this opening, a chimney with a correction coil is attached to the opening. The correction coil is continuing the homogeneous field into the chimney. The endplate on the opposite side is designed as a door in order to be able to remove a transport cell, after it has been filled with polarized gas.

Two-dimensional simulations using the fast FEM program *femm 4.0* ©1998-2003 by D. Meeker show, that this design yields the desired field-homogeneity within almost the total 80 cm.

![Diagram](image1)

**Figure 4.** Solenoid enclosed in soft magnetic material.

![Diagram](image2)

**Figure 5.** Simulation of the magnetic field inside the shielded solenoid. One colour step comprises a relative field interval of $2.5 \cdot 10^{-4}$.

![Diagram](image3)

**Figure 6.** Measurement of the relative radial field gradient. The data is taken on an axis where OPC 2 is located (see fig. 8), starting at the maintenance door and proceeding to the endplate with the chimney.
wide and 200 cm long cylinder (see fig. 5). Fig. 6 displays measured data in the realized object. The measurements show that the required field homogeneity is being reached everywhere in the solenoid but the first 25 cm next to the endplates, which results in a 1.5 m long cylindrical volume of 80 cm in diameter for assembling the decisive components of the polarizer shown in fig. 1. Measurements of the total relaxation time in a long optical pumping cell resulted in $T_1 = 330$ s, which is the same as in the cells of the present polarizer (see fig. 2), where sufficient conditions for polarizing are found.

3.2. New concept for the optics

The optical pumping requires a circularly polarized laser beam at a wavelength of $\lambda=1083$ nm. Unlike the current polarizing facility, which uses two fiber lasers, the compact apparatus will be equipped with only one pump laser. $^3$He gas is optical pumped in six 1.25 m long borosilicate glass tubes with a total volume of about 191. The beam from a 15 W fiber laser is magnified with a telescope to a diameter of about 35 mm and then guided through the six glass tubes. Polarizing beam splitters with attached $\lambda/4$-plates are put ahead of each glass cell to restore a perfect circular polarization of the incoming beam and to deflect the returning outgoing beam towards the next cell (see fig. 7). After each cell a dichroic mirror reflects the 1083 nm pumping-light back into the cell in order to maximize absorption in the gas. It transmits the 668 nm fluorescence light from the gas discharge whose circular polarization can be measured by a monitor behind the mirror. This polarization is directly correlated to that of the helium. A minimum laser power of about 5 W is required to achieve optimal performance in gas-polarization. Fig. 8 shows the arrangement of the six cells inside the solenoid. As a slightly imperfect circular polarization of the laser beam causes already huge losses in the final $^3$He polarization [12], birefrigerance has to be avoided. Therefore quartz-windows are glued to both sides of the glass tubes, as quartz does not show the effect of thermal birefrigerance caused by absorption of laser power inside the window.

Figure 7. Schematic drawing of the optics and the optical pumping cells. The laser beam passes each glass tube in both directions. The total length at which the beam polarizes gas is around 15 m. Each window is coated in order to reduce reflection power losses to < 1% per surface.

Figure 8. Arrangement of the six optical pumping cells mounted on an optical table inside the solenoid.
3.3. The drive for the piston compressor

The compact polarizer is equipped with an electrical linear motor, which drives the piston compressor. Contrary to the current hydraulic drive, this very compact linear drive can be attached directly to the compressor and needs about a factor of two less time for one compression cycle. That higher speed is required, as the compressor volume of the new apparatus is only half of that of the current machine. The linear motor allows a positioning of the piston with the accuracy of one micrometer, which is advantageous for minimizing the dead volume at the end of the compression phase. The maximum force, that can be generated by the motor is $F_{\text{max}} = 11600 \text{ N}$, which allows to compress the gas up to a pressure of $p_{\text{max}} = 7.5 \text{ bar}$.

3.4. Mechanical assembly of the new polarizer

The assembly inside the shielded solenoid, in which the gas is polarized is mounted to a pair of aluminum boards which stick out of the chimney at the rear pole face (see fig. 9). They rest on a mike boom whose foot is fixed to the base frame with some freedom for fine adjustment. The solenoid is mounted on telescope guide rails fixed to the base frame. They enable the solenoid to be shifted aside in order to allow easy access to the assembly inside. The base frame features space for vacuum pumps, electronics, $^3\text{He}$-supply etc. All major construction components outside the shielded solenoid are built from ordinary steel. The compact polarizer measures about 3 m in length, 90 cm in width and 1.8 m in height, which make it fit through a normal door.

3.5. Conclusion

The concepts and results, presented in this article show, that the physical and technical requirements for the construction of a compact polarizing facility are fulfilled. The apparatus, currently being in the final stage of assembling, is designed to provide a high flux of hyperpolarized $^3\text{He}$. The used 15 W fiber laser provides enough power to polarize the gas fast.
enough to reach a gas throughput of 1 standard liter per hour at $P = 75\%$, which is comparable to that of the currently used polarizing facility.

References
[1] Batz M, Baeßler S, Heil W, Otten, E.W, Rudersorf D, Schmiedeskamp J, Sobolev Y and Wolf M 2005 J. Res. Natl. Inst. Stand. Technol. B 110 293
[2] Krimmer J, Heil W, Karpuk S, Otten E.W and Salhi Z 2011 IOP journal of physics conference series, this volume
[3] Gemmel C et al 2010 Eur. Phys. J. D 57 303
[4] Albert M.S, Cates G.D, Driehuys B, Happer W, Saam B, Springer C.S Jr and Wishnia A 1994 Nature 370 199
[5] Schmiedeskamp J, Heil W, Otten E.W, Kremer R.K., Simon A and Zimmer J 2006 Eur. Phys. J. D 38 427
[6] Hiebel S, Großmann T, Kiselev D, Schmiedeskamp J, Gusev Y, Heil W, Karpuk S, Krimmer J, Otten E.W and Salhi Z 2010 Journal of Magnetic Resonance 204 37
[7] Colegrove F.D, Scheerer L.D and Walters G.K 1963 Phys. Rev. 132 2561
[8] Ebert M 2000 doctoral thesis Mainz University
[9] Schmiedeskamp J 2004 doctoral thesis Mainz University
[10] Deninger A, Ebert M, Hasse J, Heil W, Otten E.W, Schmiedeskamp J and Surkau R patent no.s DE 100 00 675 (2000) and [US] 09/758,006 (2001)
[11] The material used is NILOMAG; for specifications see www.specialmetals.com
[12] Wolf M 2004 doctoral thesis Mainz University