Approaching the theoretical limit for ^{129}Xe hyperpolarisation with continuous-flow spin-exchange optical pumping

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Target audience: spin-exchange optical pumping polarisers; hyperpolarised noble gases community.

Purpose: Hyperpolarised ^{129}Xe gas can be inhaled to non-invasively study lung structure and function with MRI [1,2]. The nuclei of ^{129}Xe gas atoms are polarised by spin-exchange optical pumping (SEOP), whereby Rb valence electrons are optically pumped with circularly polarised laser light resonant on the D_1 transition line (794.77 nm), resulting in a highly polarised electron spin Zeeman ground state. In this study, a 50 W volume holographic grating laser diode array (VHG-LDA) was integrated with a continuous-flow SEOP ^{129}Xe polariser operating at 2 bars. The polarisations obtained approach the theoretical limit predicted by previous models[3] and the results compare favourably with those obtained previously with an external cavity laser (ECDL) [3]. With this relatively simple and robust system the routine generation of highly polarised volumes of gases needed for diagnostic clinical lung imaging is made possible.

Methods: *^{129}Xe polarisations vs. flow rate*: for both laser designs (see Fig 1 for VHG-LDA hardware details and ref [3] for ECDL details) 3% xenon was collected directly from the cell (T = 373 K) at different flow rates into a Tedlar plastic bag, and 10 ml samples were decanted into a plastic syringe. An FID from the syringe sample was recorded following a 10° pulse-acquire at 1.5 T (GE HDx) with a small saddle coil. The ^{129}Xe polarisation was calibrated by comparing signals from 10 ml HP to a 100 acquisition-average on a 10 ml thermal xenon sample containing 50 % O_2 (T_1 ~ 6 s). A least-squares fit was performed on the experimental ^{129}Xe polarisation data points, using the relationship

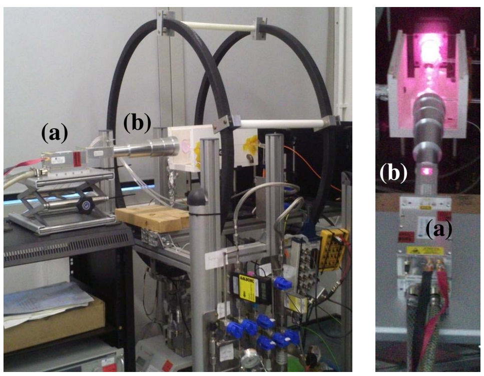

Figure 1: (a) Volume holographic grating laser diode array (VGA-LDA) (BrightLase, Ultra-200, QPC, California, USA) with (b) optical train (OT) apparatus (QPC, California, USA). Power incident on cell 50 W, FWHM ~ 0.3 nm and beam diameter of 5 cm. The optical train provides superior beam homogeneity over the length of the 25 cm optical cell compared to the ECDL.

$$P_{Xe} = P_{\infty}(1-\exp(-(\gamma+\Gamma)t_{res})) \quad (1)$$

where γ is the spin exchange rate, Γ is the ^{129}Xe spin relaxation rate and $t_{res} = V[G]/Q$ is the gas residency time in the cell, where V = cell volume (500 cc), [G] = gas density (1.44 amg) and Q is mass flow rate measured in standard cubic cm per minute. The gas mixture in the cell was kept constant throughout as 3 % Xe (86 % ^{129}Xe enrichment), 87% He and 10 % N_2. Details of the theoretical ^{129}Xe polarisation modeling can be found in ref. [3].

Results and Discussion: *ECDL*: maximum static ^{129}Xe polarisation (no gas flow) measurement of 30 %; and a maximum flow measurement 14 % at 100 sccm. *VHG-LDA*: maximum static ^{129}Xe polarisation measurement of ~ 80 %, approaching the theoretically calculated limit of 86%; and a maximum flow measurement of 65 %. As shown in Fig. 3, the agre ement between the experimental polarisations using the ECDL and theory breaks down at low flow rates, whereas the VHG-LDA agrees well over the whole gas flow rate range. We believe this to be attributed to improved beam homogeneity of the VHG-LDA and the integrated optics over the length of the cell with compared to the ECDL, which would act to increase the average rubidium polarisation over the cell length, thus increasing the Rb-^{129}Xe spin-exchange efficiency.

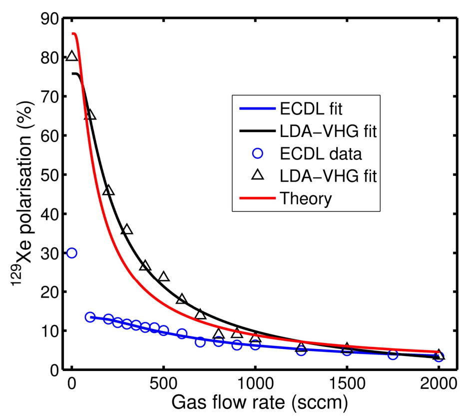

Figure 2: ^{129}Xe polarisation as a function of gas flow rate through the SEOP cell. The open blue circles and black triangles represent polarisation measurements when using the ECDL and VHG-LDA as optical inputs, respectively. The black and blue lines are fits to the data using Eq. 1. The red line shows theoretical ^{129}Xe polarisation vs. flow rate.

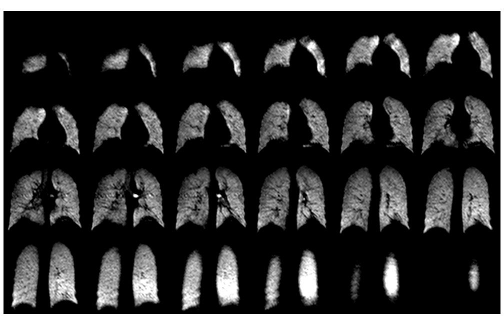

Figure 3: In vivo ^{129}Xe images of the lung at 3 T with 1 L natural abundance xenon hyperpolarised using the VHG-LDA

Conclusions: In this study we have demonstrated very good agreement between the calculated theoretical ^{129}Xe polarisation limit of 86% and ^{129}Xe polarisations measured on a 2 bar SEOP system using a 50 W VHG-LDA (80 %) with an optical train as an optical input. Gas collected from this system is routinely providing high quality lung images and provides sufficient polarisation for imaging with natural abundance xenon (see Fig. 3).

References: [1] Patz et al,. New J Phys, 015009, 2011. [2] Stewart et al., MRM doi: 10.1002/mrm.25400, 2014. [3]Norquay et al., J. Appl. Phys, 113, 044908, 2013.

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