High-Volume Output Hybrid-SEOP Helium-3 Polarizer

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Need and Design

- Large scale helium-3 polarizer can be used as a central production facility to serve multiple users by shipping smaller quantities when needed, or in places where high volumes (MRI-clinical trials) or a continuous supply of highly polarized helium-3 is needed (nuclear physics).
- Helium-3 can be polarized by MEOP or SEOP. MEOP is faster, but more expensive, with low production output and large footprint required. SEOP is slower, however all the gas is available for use when ready, and it can be preserved at highest polarization under pumping condition.
- SEOP volumes have been limited by the cell size (typically under 300cc internal volume and thick glass affecting laser beam) in order to withstand high pressures (up to 10 atm) optimum for operating.
- Novel laser diode progress with kilowatt power opened new opportunities for SEOP, if the cell volume, pressure limitations, and heat transfer could be overcome.
- We designed a large scale SEOP system which met all these challenges (fig 1):

- Our design uses a thin-wall and flat end windows cell with a fixed diameter (10cm) that can have a length depending on its application/ output: from 2 liters to 8 liters internal volume.
- Cell is clamped within aluminum shells in close thermal contact. For larger cells, we designed two separate thermal regions for further improving heat transfer and gas homogeneity within the cell.
- The cell, shells, insulation, and magnetic field solenoid are all hermetically closed inside a heavy duty vessel capable to withstand very high pressures. The pressure inside the vessel is in equilibrium with the cell, thus eliminating mechanical stress on the cell.
- Novel laser technology with spectrum narrowing maximizes laser use efficiency and allows for uniform laser deposition and SEOP processes within the cell.

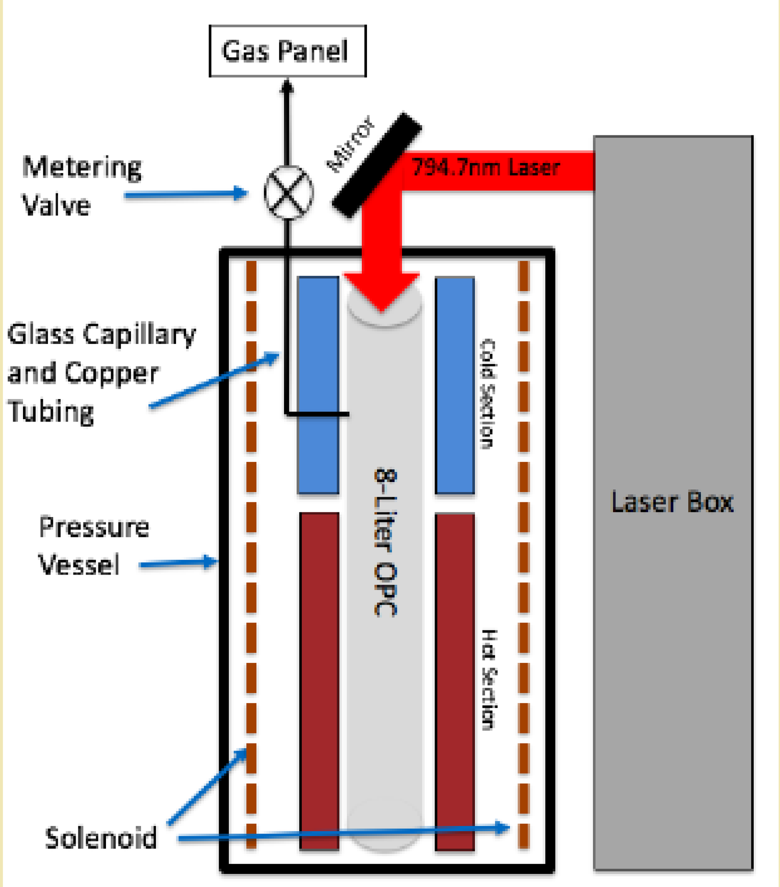

Figure 1: Schematic of the high volume hybrid SEOP helium-3 polarizer.

Implementation

Figure 2: Examples of 2-liter cell (~30cm) and 8-liter cell (~120cm), loaded with a 5:1 (by mass) K-Rb alkali mix, and with side glass valve.

Figure 3: "Packing" a 2-liter cell into an aluminum shell using copper-based thermal grease.

Figure 5: Zeppelin-4 helium-3 polarizer (4th generation) with the pressure vessel containing SEOP cell, tilted at 45 degrees. Left side of the frame contains gas panels, oil pumps, electrical, while the laser box (black) is located on the right side. The pressure vessel is made of steel and rated for up to 20.7 atm. An pressure interlock system automatically adjusts the pressure to match the cell. It includes a full length solenoid for B0 magnetic field. An additional mu-metal liner was added for increasing uniformity. Polarizer has casters and can be relocated.

Figure 4 (left): Following the cell "packing" in thermal jackets, the assembly is rigidly attached to the steel pressure vessel cap. The cap has a 6 cm thick fused silica window for allowing pumping laser entrance. Many bulkhead fittings allow for thermal stabilizing oil lines and electrical wiring to feed through the cap. A 1/8" OD copper tube allows the transfer of helium. Assembly is lifted using a hoist and lowered into the steel drum (right).

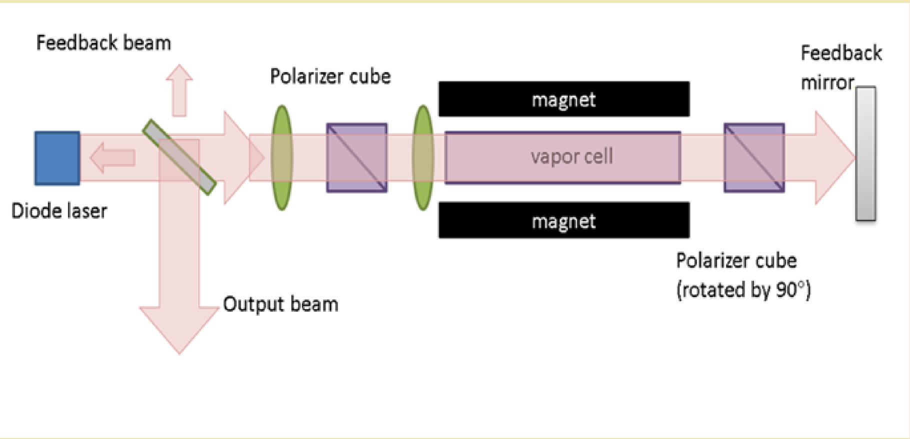

Figure 6: Design of new Atomic Line Filter for spectral narrowing for diode laser arrays using a reference birefringent Rb vapor cell [Hersman18].

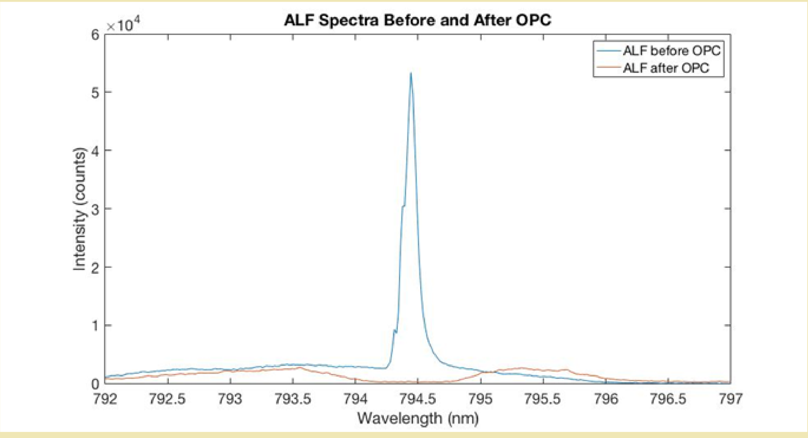

Figure 7: Example of ALF narrowed spectrum. Spectrum after the cell Optical Pumped Cell (OPC) shows all the narrowed peak is absorbed within the cell.

Results and Discussion

- After a series of system improvement (especially magnetic field gradients within the pressure vessel) we were able to identify and characterize cells of 2-liter (aluminasilicate) and 8-liter (sol-gel coated borosilicated) with decent relaxation times (70h and 30h), in-line with our numerical simulations for reaching polarizations in excess of 50%.
- New laser developments were used (fig.6,7), provided with an Atomic Line Filter spectral narrowing system [Hersman18], being capable of nominal power of 5kW, however for the 2-liter cells we found sufficient usage of only 350W.
- The 2-liter cell had an extraordinary T1 of 70h as measured in a high uniformity magnetic field outside the polarizer.
- All cells were filled with a mix of K-Rb, typically a mix ratio of 5:1 by mass.
- Operating temperature range of the cells were 220-250C.
- Maximum polarization measured was ~80% (externally), extrapolated to a saturation value of 85%.

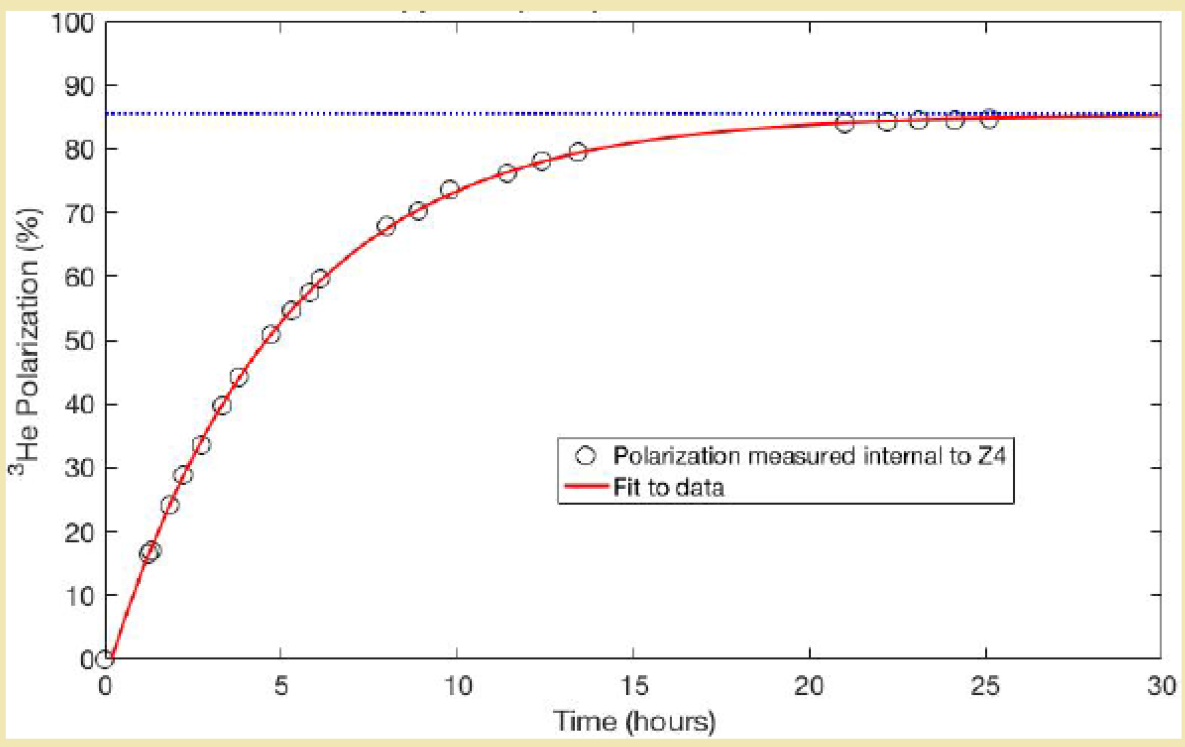

Figure 8: Build-up curve for our best 2-liter aluminasilicate cell acquired over a 24 hour pumping time. At the time of reaching this record polarization of 85% the cell was filled with 1.5 bar of He/N2 mix. Operating temperature for the cell for this run averaged 235C, and a t_{up} of ~5hours was fitted from the curve.

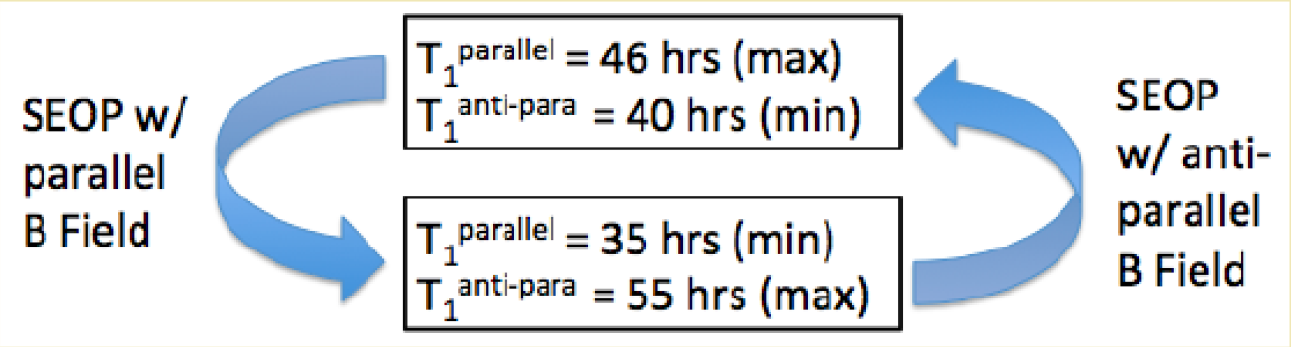

Figure 9: We observed different relaxation times for the two B0 magnetic fields orientations. Furthermore, if the cell was pumped for an extended period of time (over 10 hours), the T1 in that direction would lower to a minimum. E.g., in the schematic we show a reduction of $T_1^{parallel}$ from a maximum of 46h to a minimum of 35h, while $T_1^{ani-parallel}$ went from a minimum of 40h to a maximum of 55h. Reversing the magnetic field and pumping again for 10 hours restored he original values of T1. Intermediate values were measured for SEOP of shorter duration. Similar behavior were reported by others, with yet to be explained cause. Additionally, we observed also an irreversible decline of T1 after many SEOP cycles (>50).

Conclusions and Outlook

- New scale-up design for SEOP method of polarizing helium-3 in quantities of up to 50 liters/day.
- Polarization up to 85% achieved using a 2-liter cell and extracted into a sampling cell and measured externally.
- New Atomic Line Filter (ALF) laser spectral narrowing technology recently developed [Hersman18] allow for more efficient and uniform pumping at a wider range of pressures
- Central production facility concept demonstrated in deliveries of polarized helium-3, thereafter used in basic MRI testing.
- New observed phenomena of T1 hysteresis dependent on the orientation of the B0 magnetic field, and the possibility of correcting by reversing the magnetic field.
- While we tested 8-liter cell for feasibility and polarized successfully, we switched to smaller cells due to application (infant MRI), and are yet to reach record levels of T1 and polarization with a large cell.
- We are considering collaborators (MRI and/or nuclear physics) for utilizing this polarizer.

References

[Anderson20] - "A Path to Scaling Helium-3 Spin-Exchange Optical Pumping" Anderson A, Ruset IC, Watt D, et al. Journal of Applied Physics 127, 223103 (2020)

[Hersman18] – "System and method for high power diode laser wavelength spectrum narrowing" F.W. Hersman, M. Hersman, U.S. Patent US10348057B2 (2018).