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SEOP Polarization of ^{3}He and ^{129}Xe at High Volumetric Rates

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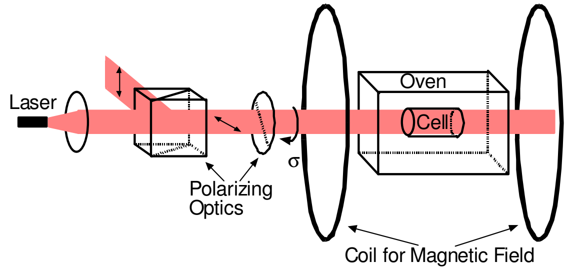
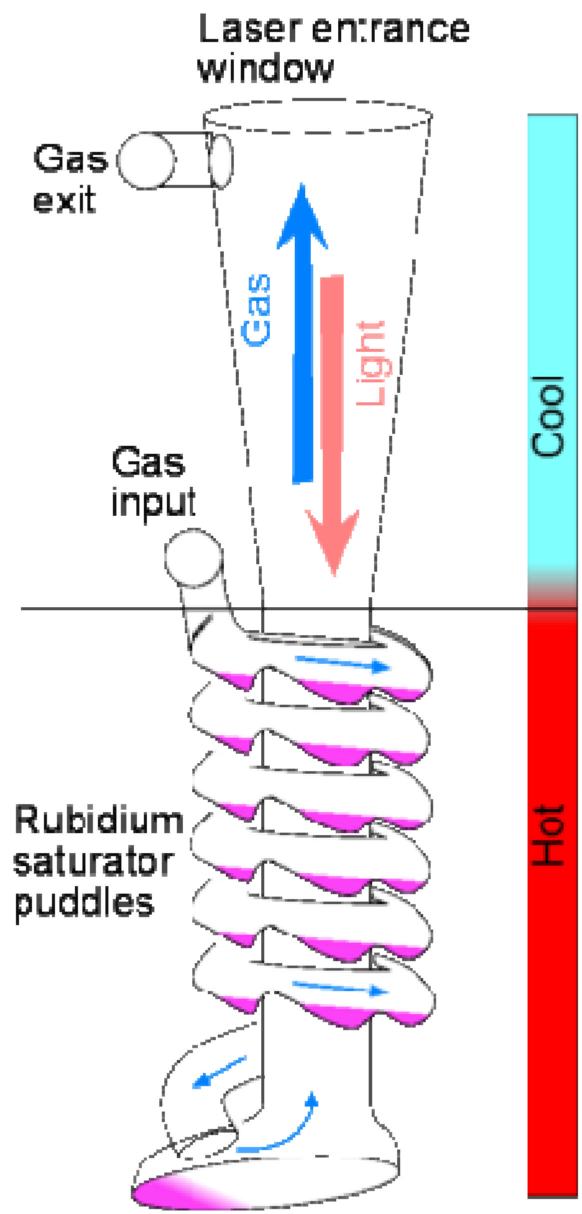
Xemed LLC

- Xemed: High technology spin-off company to commercialize hyperpolarized ^{129}Xe and ^{3}He
- Bill Hersman (CEO) is Professor of Physics at University of New Hampshire and inventor of the xenon counterflow SEOP polarizing system
- Started in 2004, presently ~10 employees (scientists, engineers, software)
- Xemed is funded from small business federal grants for polarization technology and hyperpolarized gas imaging applications
- Proceeding with US Food and Drug Administration for regulatory approval of diagnostic imaging with hyperpolarized gas products MagniXene™ and MagniLium™.
- Clinical product MagniXene™ passed Phase I trials, now in Phase II with Brigham and Women Hospital and Harvard Medical School.

Large Scale 129Xe Polarizer - Concept



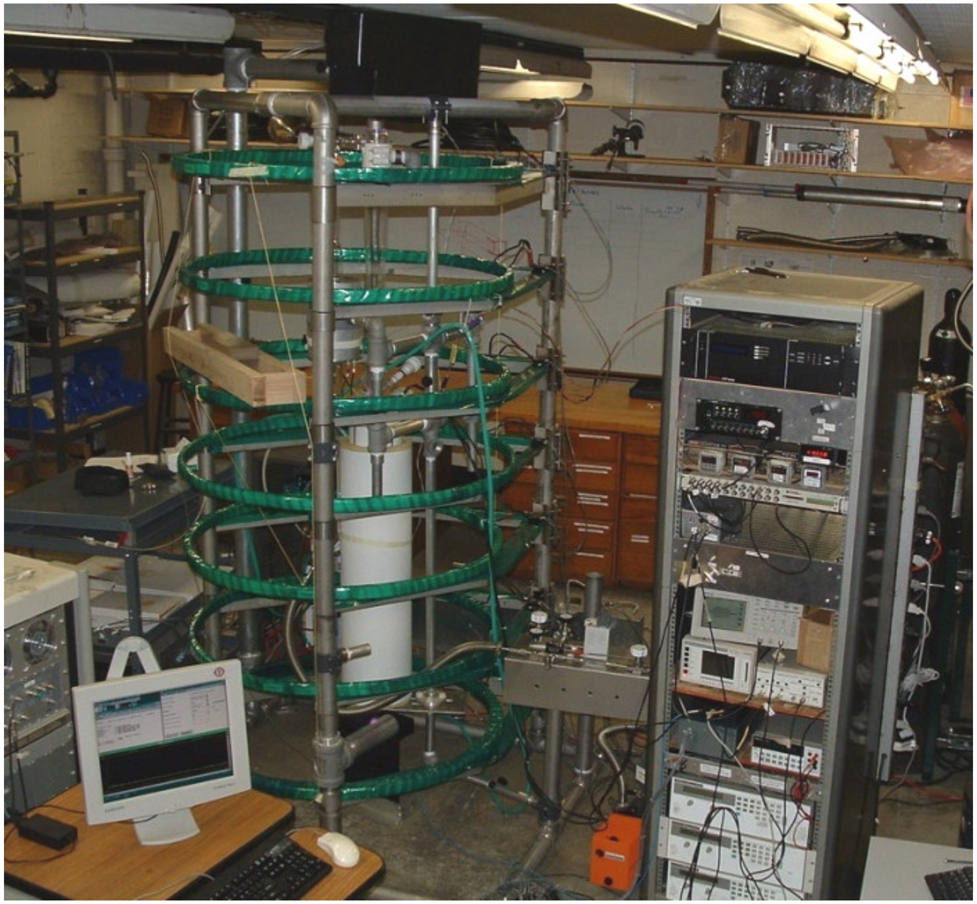
- Different functional regions: Rb vapor saturator (helix), SEOP hot region (lower side), Rb condensing region (top side)
- Meter-long column assures efficient laser absorption
- Counterflowing design with gas mixture flowing against the laser propagation
- Xenon accumulates polarization as it travels through the column
- Spin relaxation is minimized through fast Rb condensation under high laser illumination
- Low total pressure increases Rb-Xe spin-exchange rates through vdWaals molecules allowing continuous flow of gas mix

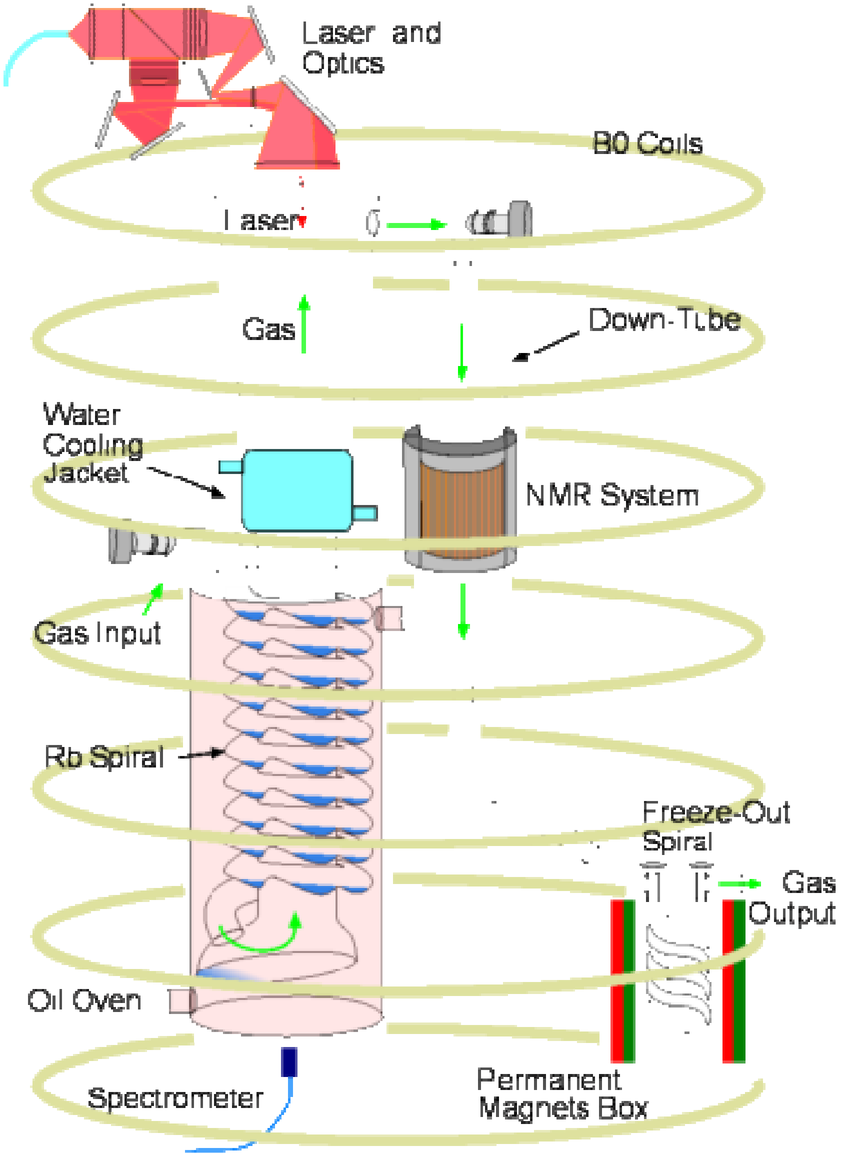


[1] I.C. Ruset et al., *Phys Rev Lett*, **96**:053002 (2006).

Continuous Counter-Flow Polarizer – Prototype

- Long glass column (1.8m) separated in hot and cold sections.
- Capable of producing 64% at 0.3slh Xe and 50% at 1slh.
- Relocated at BWH as of 2005





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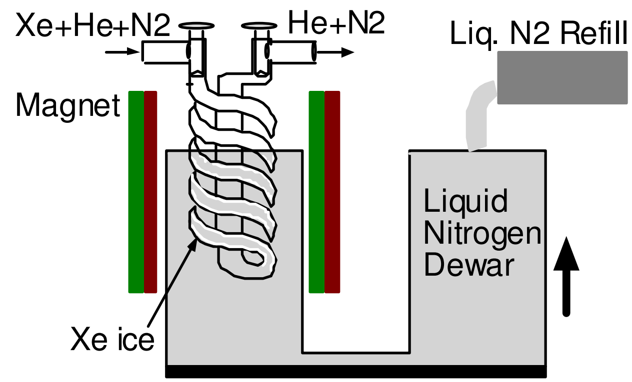
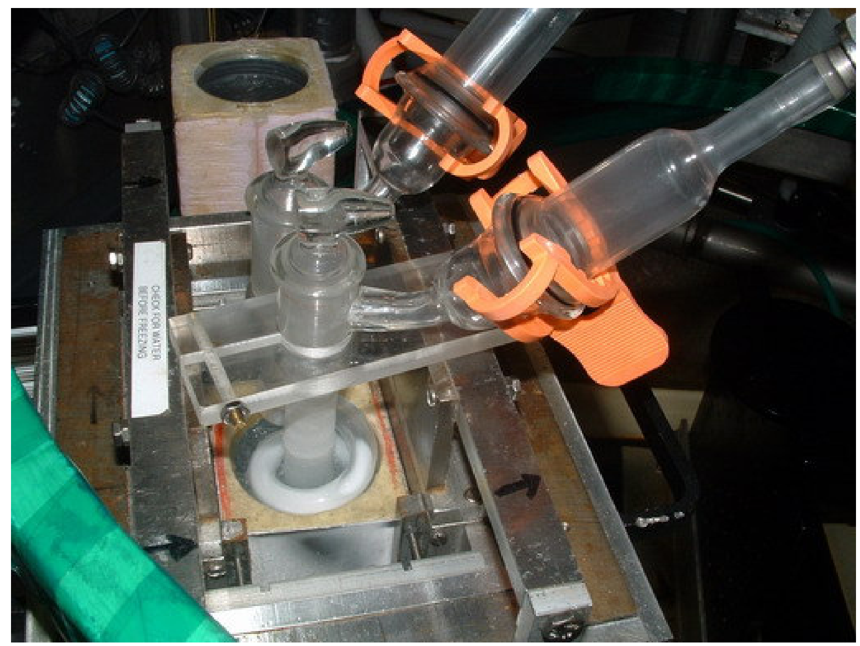
Freeze–Thaw and Polarization Recovery

- Existing technologies recovered ~60-80% polarization
- New freeze-out design with a helix tube provides for larger cold surface
- Moving cryostat can uniformly coat frozen xenon over entire surface



Xe Flow (L/h)	P_{gas} (%)	P_{thawed} (%)	Ratio (%)	Frozen Volume (mL)
0.6	49.1	49.0	100	100
3.0	25.3	25.2	100	507
4.5	19.8	18.2	92	746
6.0	16.9	15.0	89	1000



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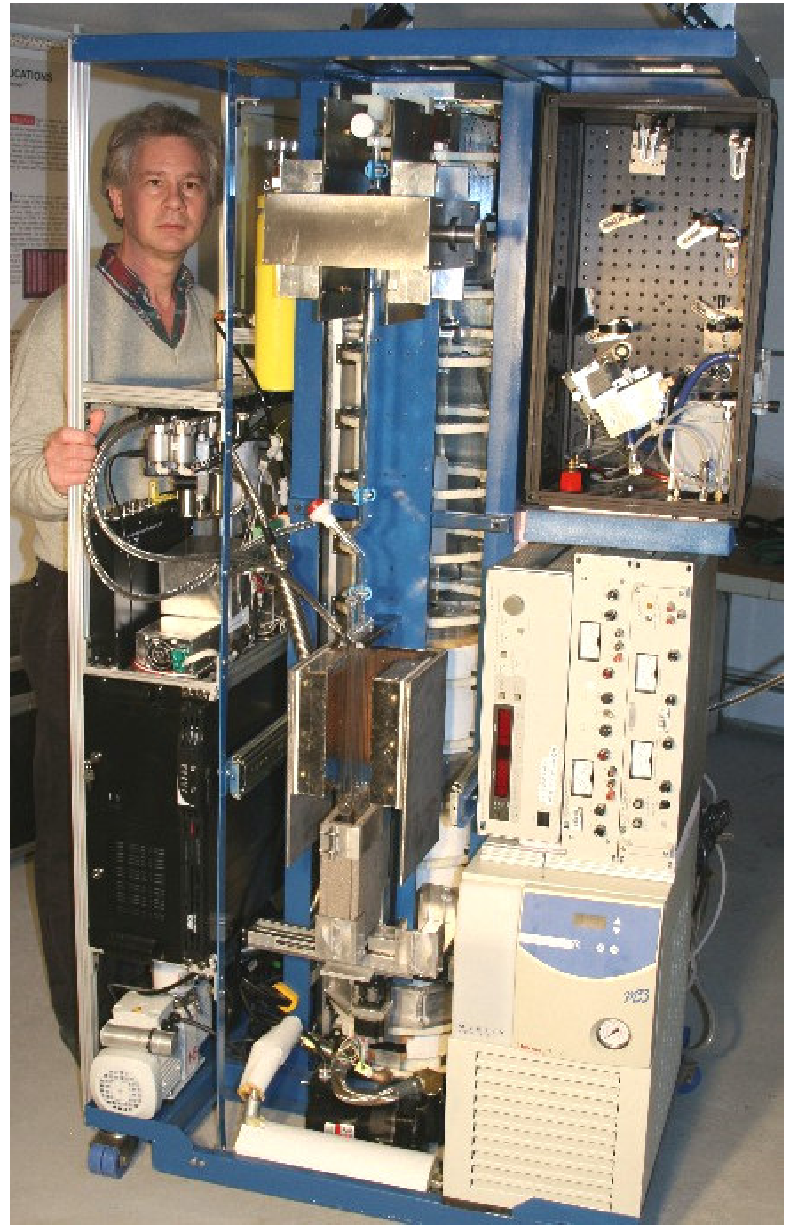
Xenon Polarizer – "Bell" Commercial Prototype

- Compact system (26"x38"x74")
- Portable modular frame
- Automated freeze-thaw system
- Computer controlled, light supervision
- Low easy maintenance (off-site)
- Easy to relocate



"Bell" system. Column replacement position (left). Operational system (right) including motorized freeze-out.

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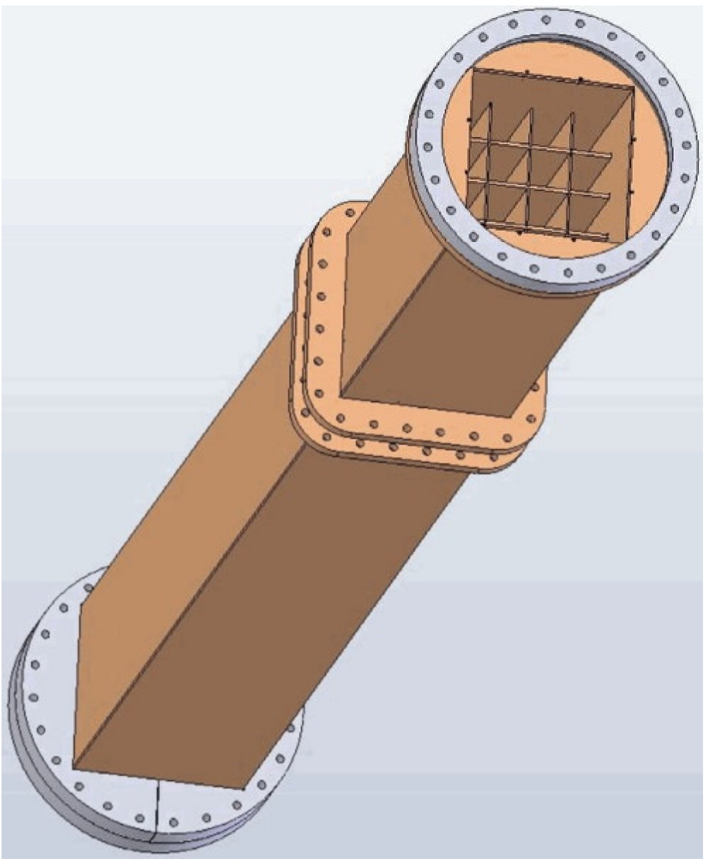
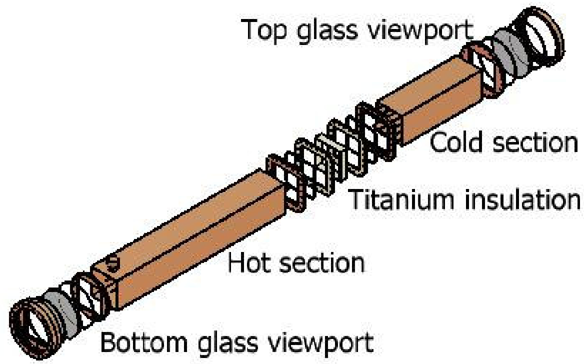
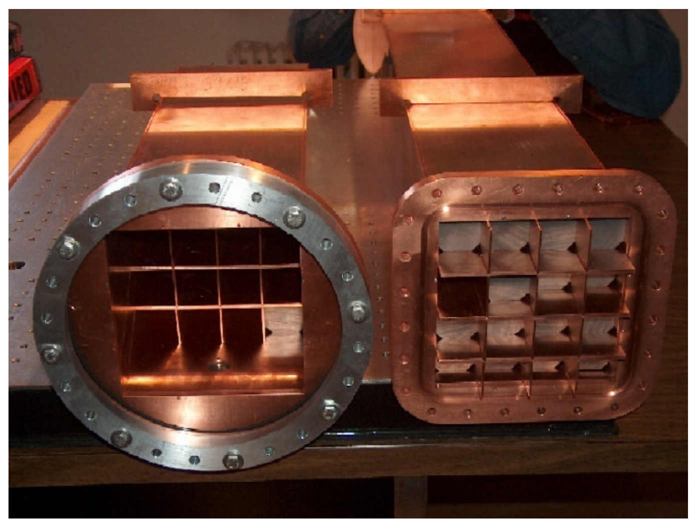
Xenon Polarizer – "Einstein" Research Prototype

- Designed to scale production rate by a factor of more than 10
- Copper body for the column for efficient heat transfer
- Over kilowatt narrow-band laser power (2.2 kW nominal power)







"Einstein" polarizer schematics with 16 channels copper column and 160 cm^2 cross section area.

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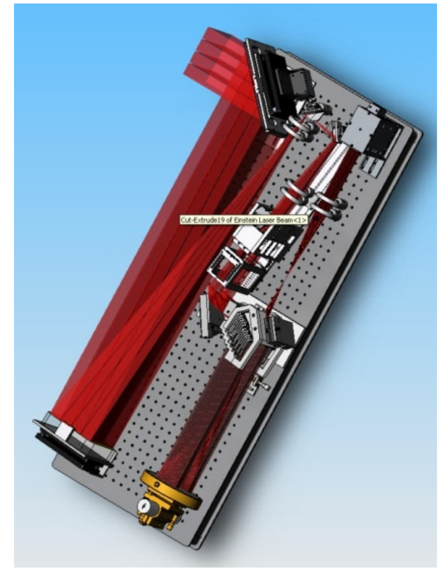
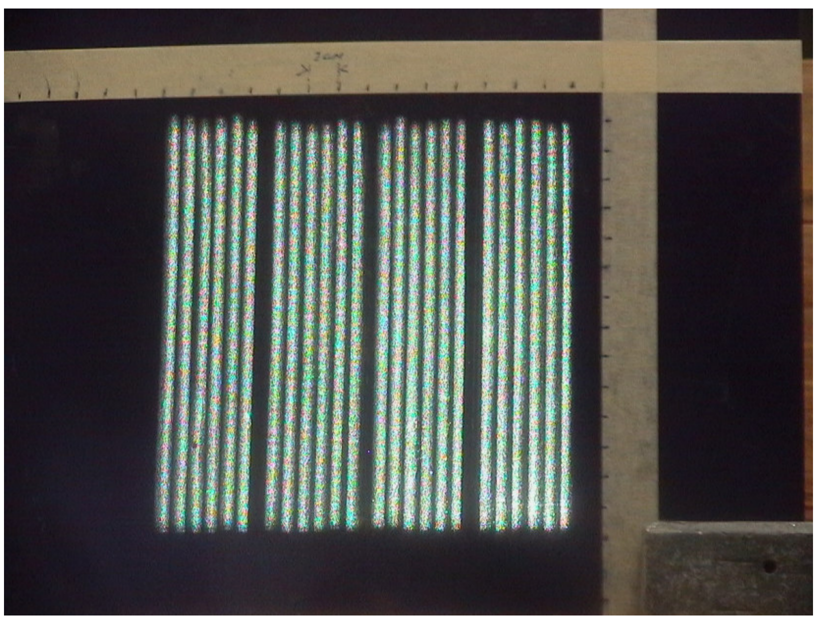
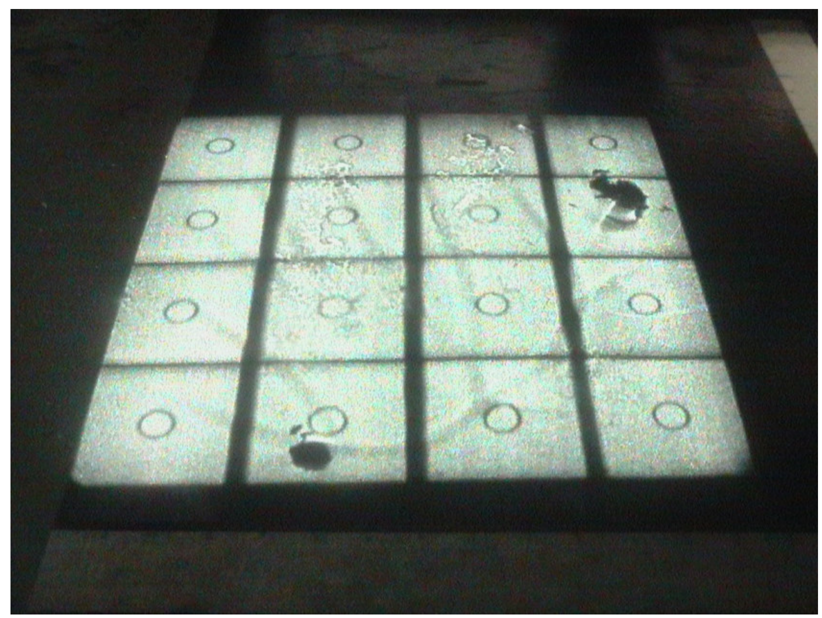
High-Power Spectrally Narrowed Lasers

- High power diode bar laser stacks (presently 2 arrays of 12 bars each)
- Precision optics for low divergence square beam (< 2mrad)
- Over 1.4kW CW capable, wavelength narrowed
- 0.5 nm spectral resolution





14x14 cm beam pattern, with spaces for channel separators (no diffuser used)



Laser beam at column exit with diffuser.

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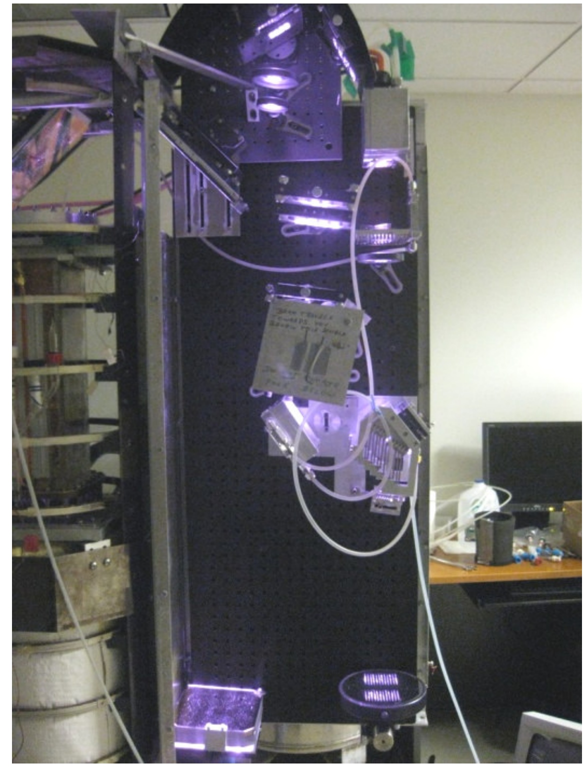
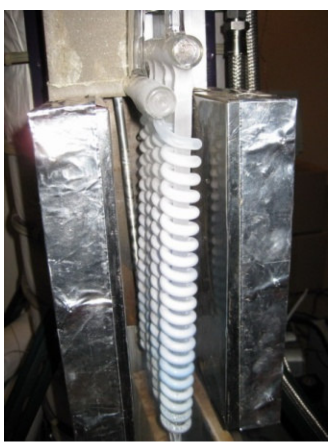
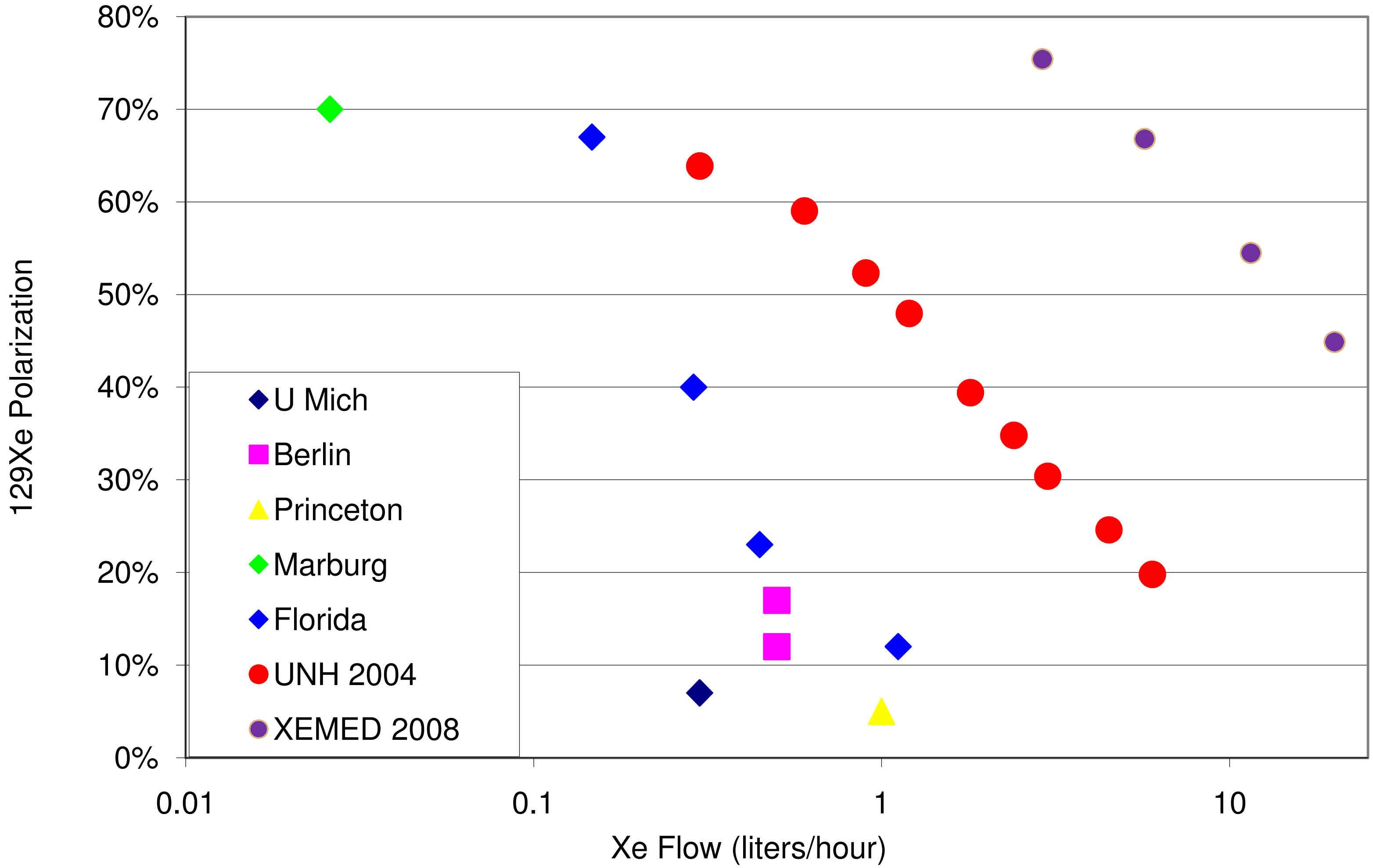
Xenon Polarizer – Implementation





Xenon Polarizer – Results 2008

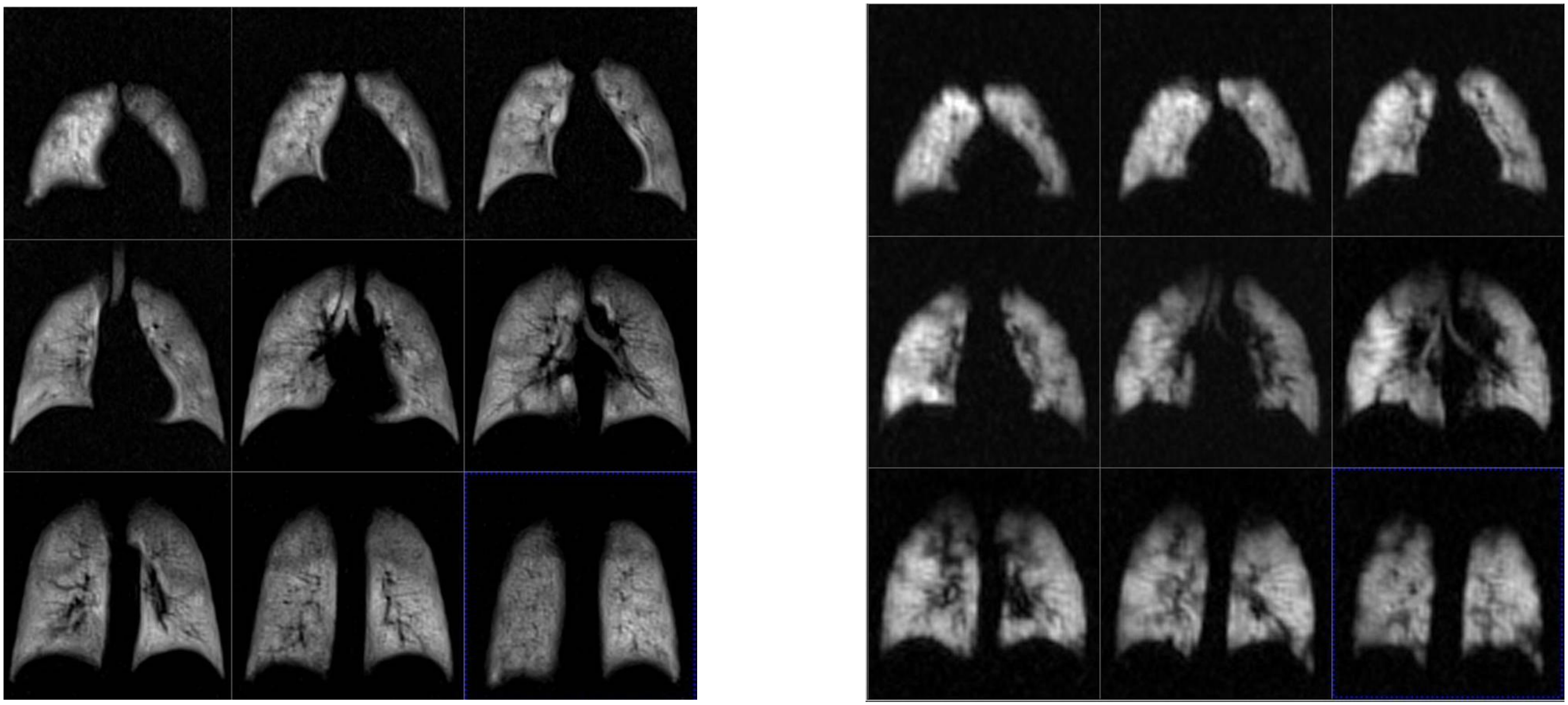
- Polarization higher than 75% at 3 liters/hour
- Production rate of 12 liters/hr with > 50% polarization (XeBox-E10)



Copper column parameters: 4.5 liter/min He, 7.5 liter/min N2, pressure 200 torr, narrowed laser (1000W).
Glass column parameters: 1.0 liter/min He, 0.35 liter/min N2, pressure 500 torr, broad band laser (90W).

Xenon Polarizer – MRI Applications

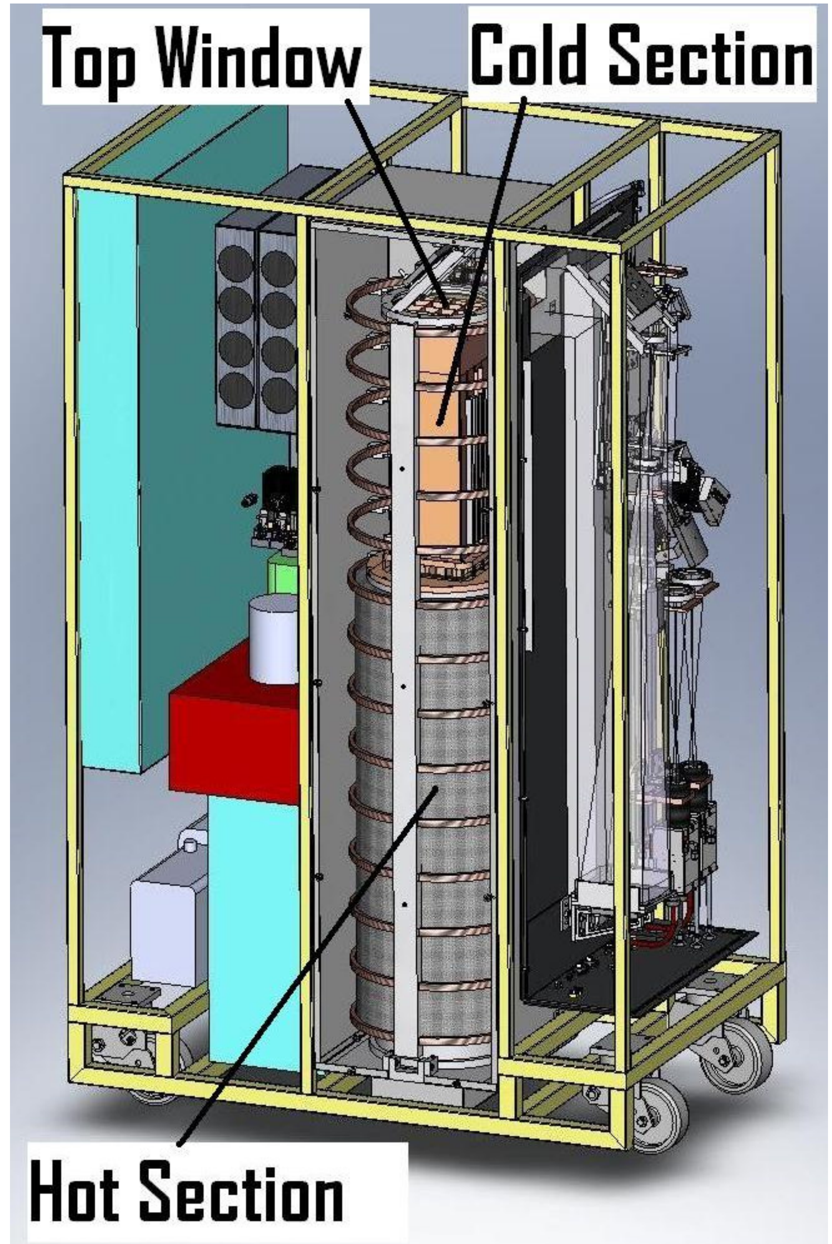
- Polarizers successfully relocated to MGH and UVa for imaging studies
- Expected to deliver one ~2liter batch every half-hour
- Polarization limited by output system (up to 40%)
- Field-gradients and freeze-thaw losses (partially corrected)
- 32-channel chest coil for xenon imaging with Siemens Tim Trio



2D GRE slice of normal subject (left) and cystic fibrosis (right). Acknowledgements to University of Virginia.

Xenon Polarizer - Future Outlook

- Polarizer design under final engineering reviews
- Freeze-out system to be scaled-up and tested
- Software under development
- System self-operating, minimum user interface
- Several proposals to build systems for collaborative research
- Arrangements for a first polarizer order in final stages



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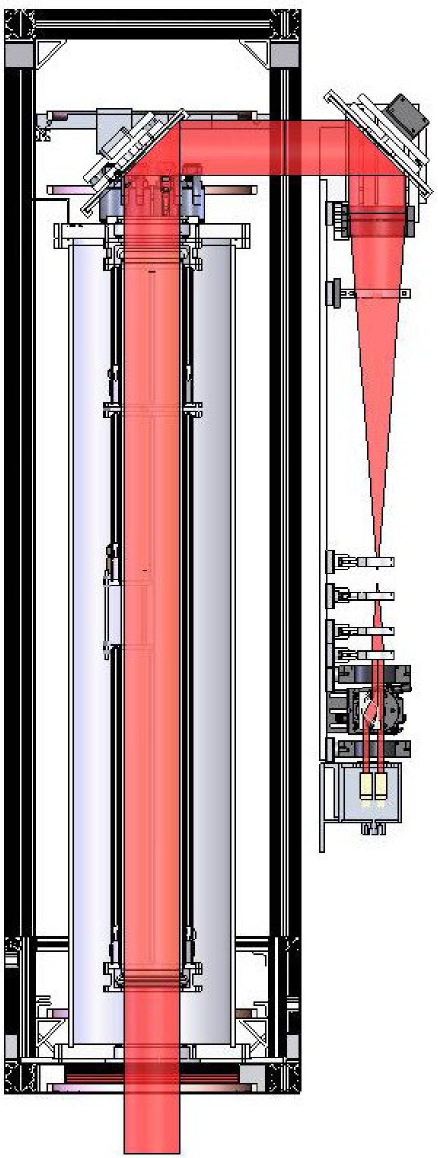
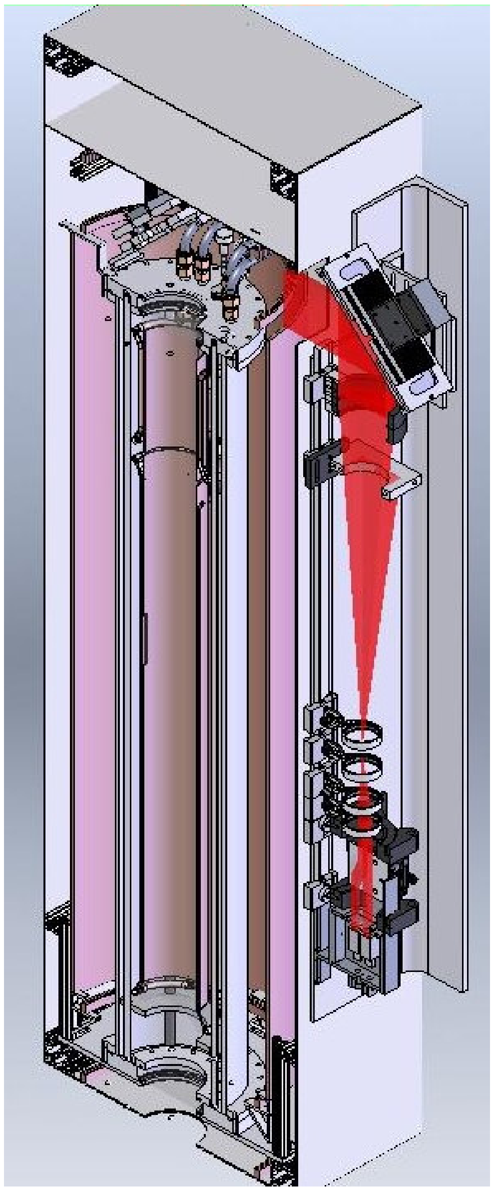
Large Scale 3He Polarizer

- Motivation
  - ^{3}He wider spread and longer history into the MRI community and imaging applications
  - Nuclear physics applications (polarized targets, neutron filters and analyzers)
  - Large scale laser technology already developed
- Challenges
  - Rb-3He long spin-exchange time constants (hours)
  - Extremely long lifetimes for polarizing cell required
  - Consistent cell manufacturing process still magic
  - High pressure allows efficient broad laser absorption, limits size of the cell
  - Cells are made of glass only: fragile and hard to get
  - MEOP system reported to produce 60 liters/day with 50% polarization

Large Scale 3He Polarizer - Concept

- XEMED's system is based on SEOP using hybrid alkali mix (K-Rb) [1].
- Large cylindrical cell (10 cm dia, 125 cm length, ~8.5L volume, S/V=0.45) pressurized up to 6 atm cold (initial target 50L polarized 3He per batch).
- Equalize pressure inside and outside glass optical pumping cell by surrounding the cell inside with a pressure vessel
- Cell temperature is stabilized by a clam-shell heat exchanger with silicone oil as thermal agent
- Cold top (30cm), hot bottom (85cm)
- High power laser diodes (2.4kW nominal, 1.5kW pumping) allow for short pump-up times (4h).
- Final asymptotic polarization depends greatly on the cell lifetime and the X-factor.



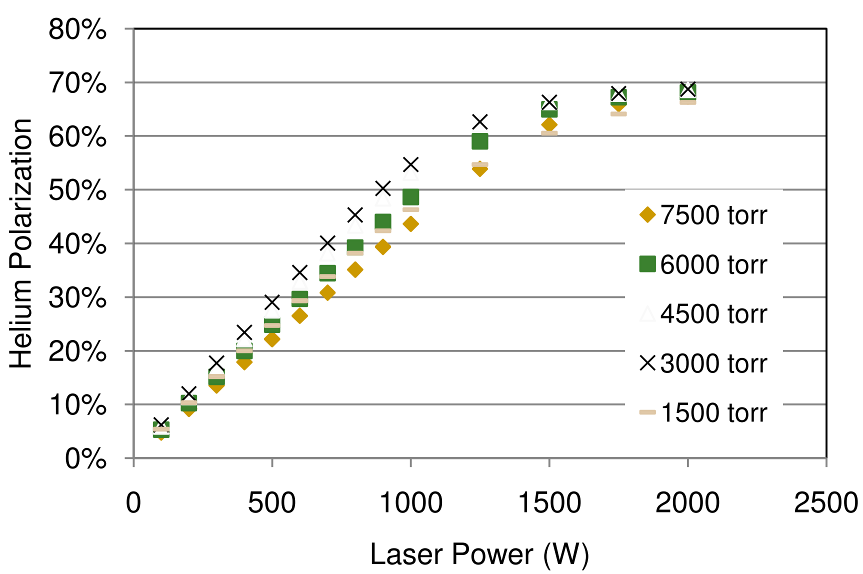


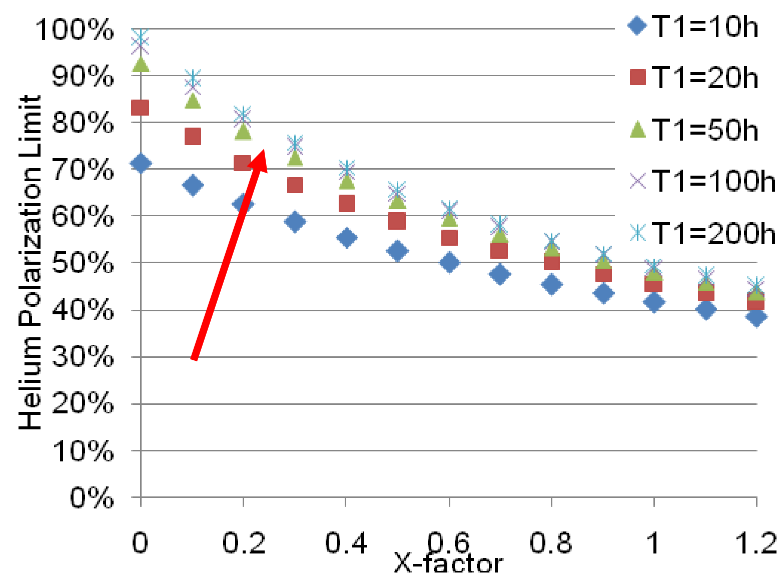
Cross sections of the polarizer.

[1] E. Babcock et al. *Phys Rev Lett*, **91**:123003 (2003).
[2] E. Babcock et al. *Phys Rev Lett*, **96**:083003 (2006).

Numerical Calculations - SEOP

- Theoretical framework includes spectral dependence of laser absorption, variable alkali ratio, temperature, pressure variables
- Program calculates alkali polarization as function of alkali thickness, obtains 3He spin-up rate and polarization (1D).
- Can optimize a defined figure-of-merit function of specified operating parameters (laser power, temperature, alkali ratio). Program determines optimal operating temperature and minimum laser power required.
- K/Rb vapor density ratio chosen below 5 to maintain high alkali polarization.
- K/Rb liquid ratio of 10 chosen for Xemed's polarizer to be operated at ~250°C (4.4 vapor ratio, ~3.5h pump-up time).
- High pressure preferred to maximize ^{3}He volume and to use broad spectrum lasers.





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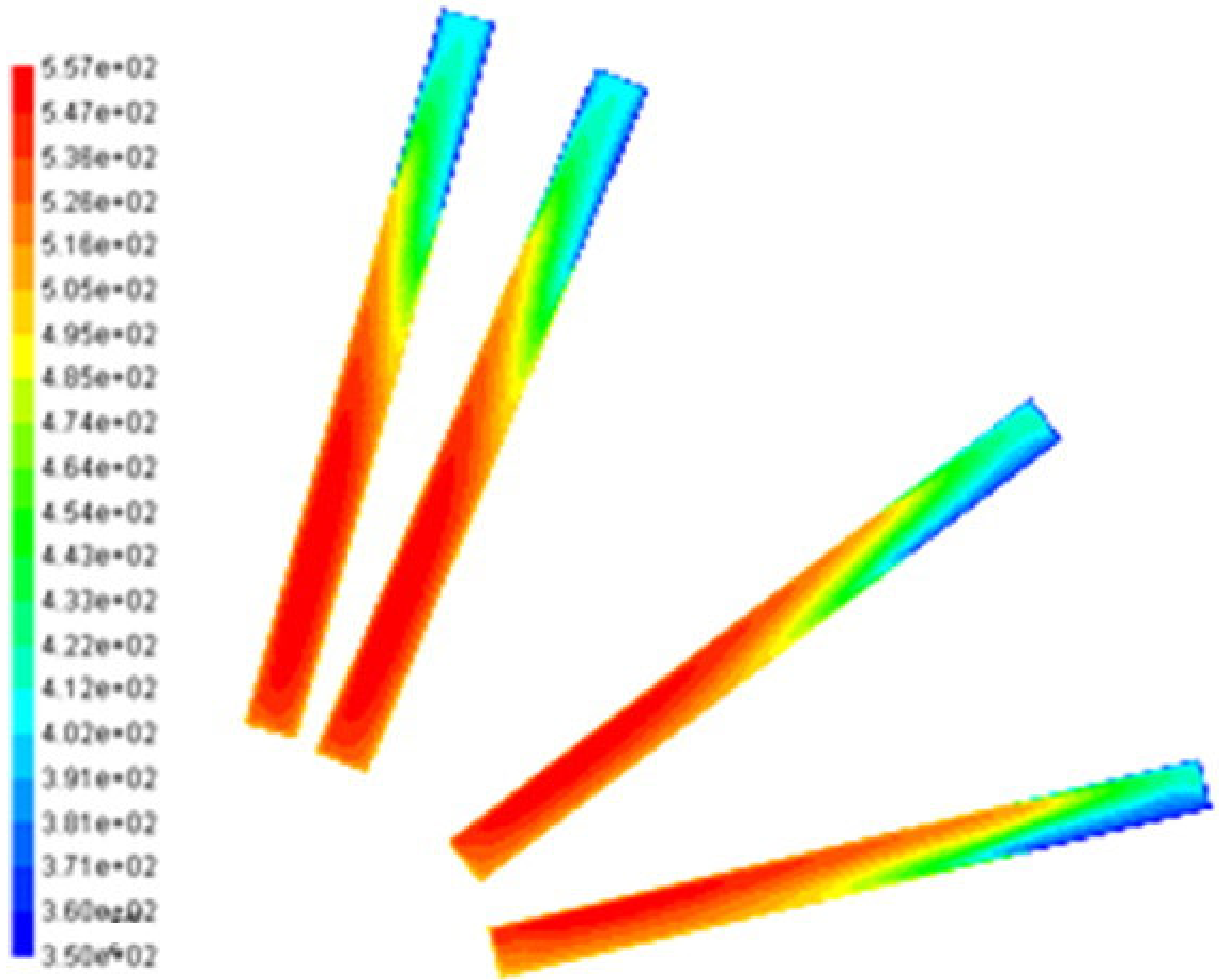
Numerical Calculations – Fluid Dynamics

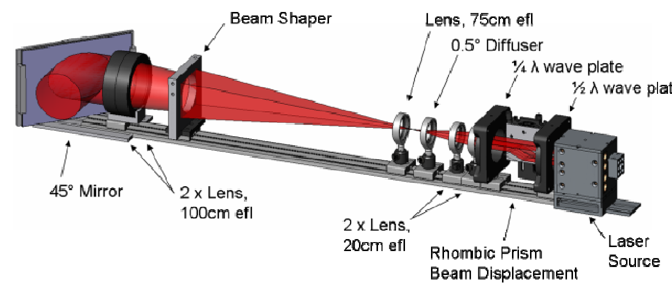
- Fluent^{TM} simulation for temperature, flow, alkali density distribution inside cell
- Vertical operation was temperature unstable. Model did not converge as well.



Temperature (Kelvin) along the central plane of the polarizer at tilt angles of 20º, 30º, 60º, and 80º

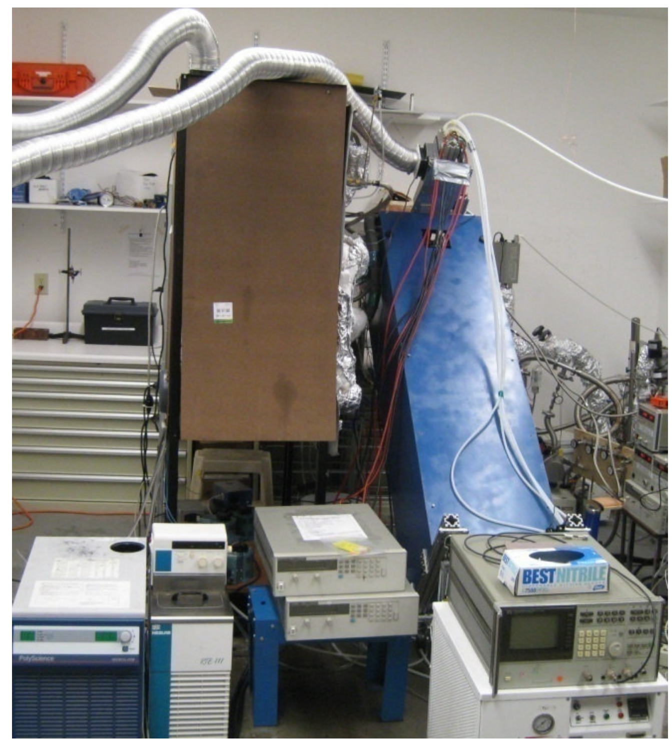
Concept Implementation of 3He Polarizer

- Vertical tower (2 meters height) to minimize foot print.
- Large 40cm dia and 120cm long solenoid assures mg field uniformity
- Pressure vessel encases pumping cell. Vessel and feed-throughs tested at 160psi
- Multiple zone thermal bath regulated by flowing silicone oil, electrical heaters, and copper heat spreaders.



Broad spectrum laser with 1.5kW power.

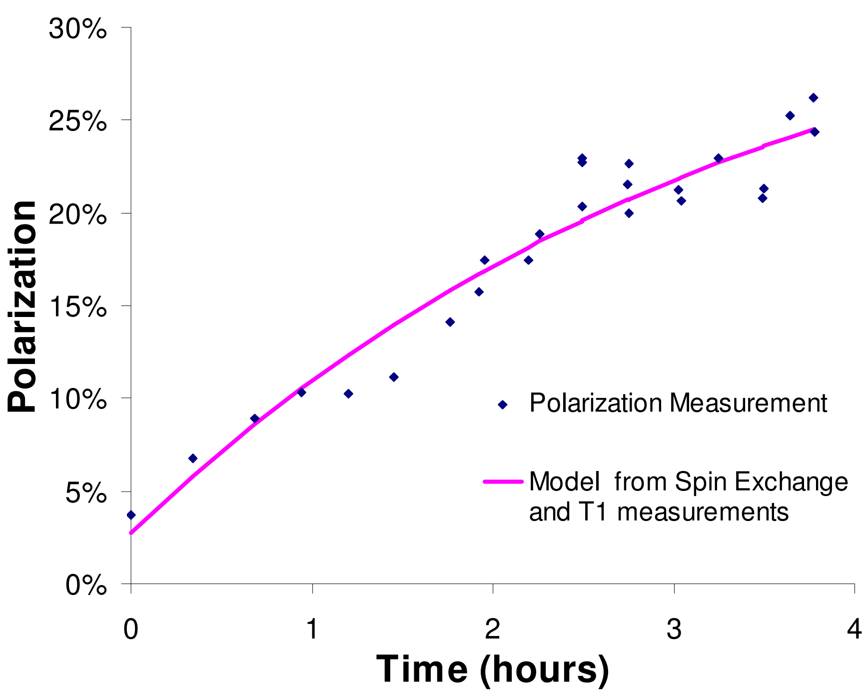
Cartridge with cell and oven, to be loaded in pressure vessel.

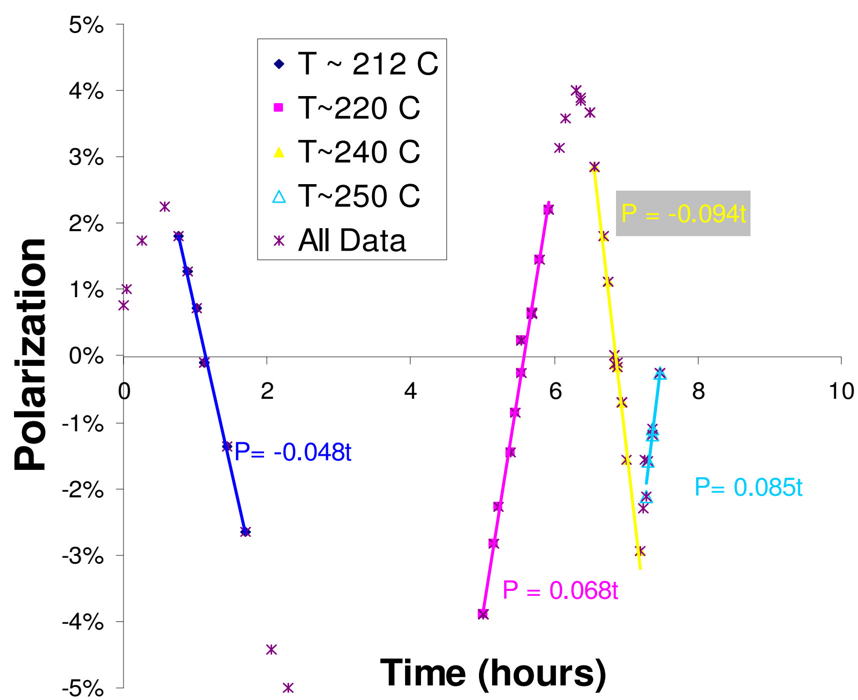


Prototype polarizer in operating state.

First Results Helium

- Several Pyrex cells and one aluminosilicate cell have been successfully mounted into the system
- Low relaxation times of up to 7 hours limiting achieved polarization
- Demonstrated feasibility of the idea by operating polarizer at high pressure
- Polarization build-up curve fitted and extrapolated polarization 35%
- Numerical model in agreement with measured parameters





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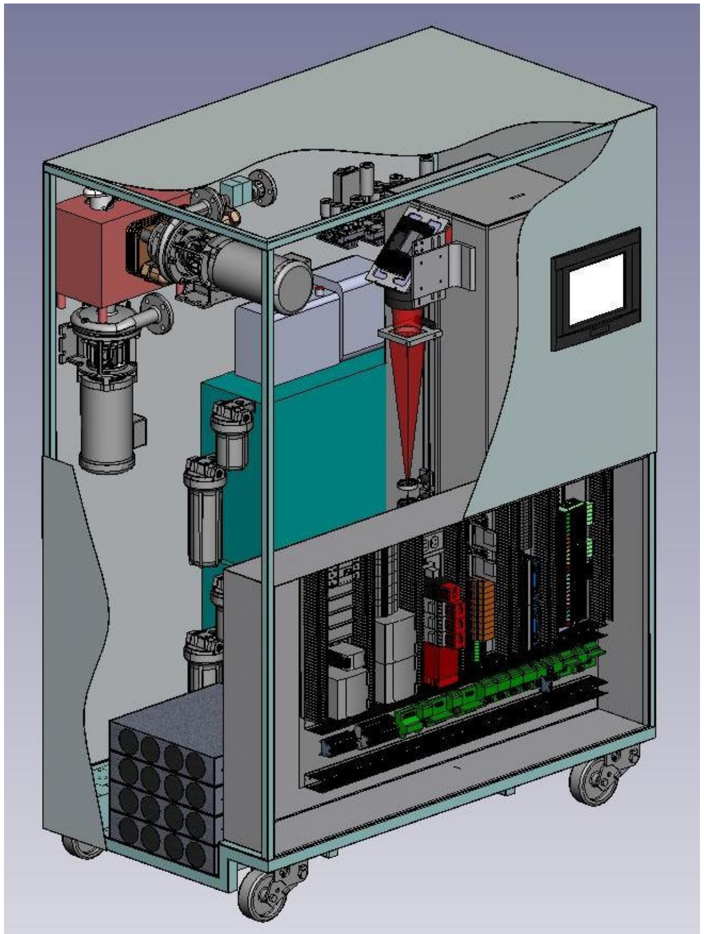
Helium Polarizer - Future Outlook

- Obtain first long-life cell and achieve 60% polarization in prototype system
- Establish optimum operating regime
- Implement developed technology of spectrally narrowed lasers (four 12 bar with expected useful power of 2.2kW)
- Redesign assembly into a compact, portable, commercial, clinical system
- Develop software and fully automate system for clinical gas delivery (minimum user interface)
- Methods for filling neutron spin filters and analyzers by recirculating the gas without polarization loss
- Titanium electron target and high pressure compressor (200 atm)
- Methodologies for producing 3He?



Compact redesigned 3He polarizer system.

Summary

- Xemed LLC – small spin-off company started to commercialize polarizing technology
- ^{129}Xe polarizer – highly advanced, going final design revisions and software development, first customer expected
- ^{3}He polarizer – in prototype phase, feasibility of concept demonstrated, looking to maximize polarization
- Xemed seeks ISO-9001 certification
- MagniXene^{TM} approval by FDA (finished phase I, moving to phase II clinical trials)
- MagniHelium^{TM} to be initiated as IND with FDA
- Xemed searches for new collaboration opportunities

Acknowledgments

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- Group of Sam Patz and Hiroto Hatabu at Brigham and Women's Hospital
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- DOE: DE85387T08 , DE85274T08