Polarized helium-3 target with two hundred-fold improvement

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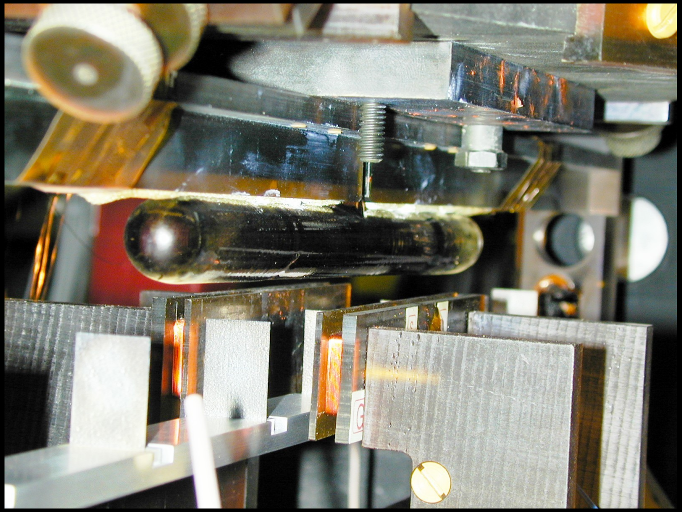
Talk outline

- Hall A polarized ^3He target: capabilities and limitations of *in situ* pumping
- Xemed's large volume helium polarizer and associated technologies
- Data
- Optimization of an *ex situ* JLab polarized ^3He target
- Predicted performance
- Outlook

Hall A polarized ^{3}He target

- *In situ* spin exchange optical pumping (SEOP)
- Pumping cell and target cell are combined
- Helium diffusively coupled from pumping to target cell

- Best in world performance!



Best in world performance

- Luminosity L assumes 15 μA beam, 40 cm target at 10 amagat
  - Target thickness ~1.07E+22
  - Electrons in beam ~0.94E+14
  - Luminosity ~1.0E36
- Polarization calculations assume cell “Eva”
  - bench polarization 53%
  - beam-on polarization 47% (hybrid pumped)
- Figure of merit p^2L=0.22E+36

Recent improvements

- Performance improvements

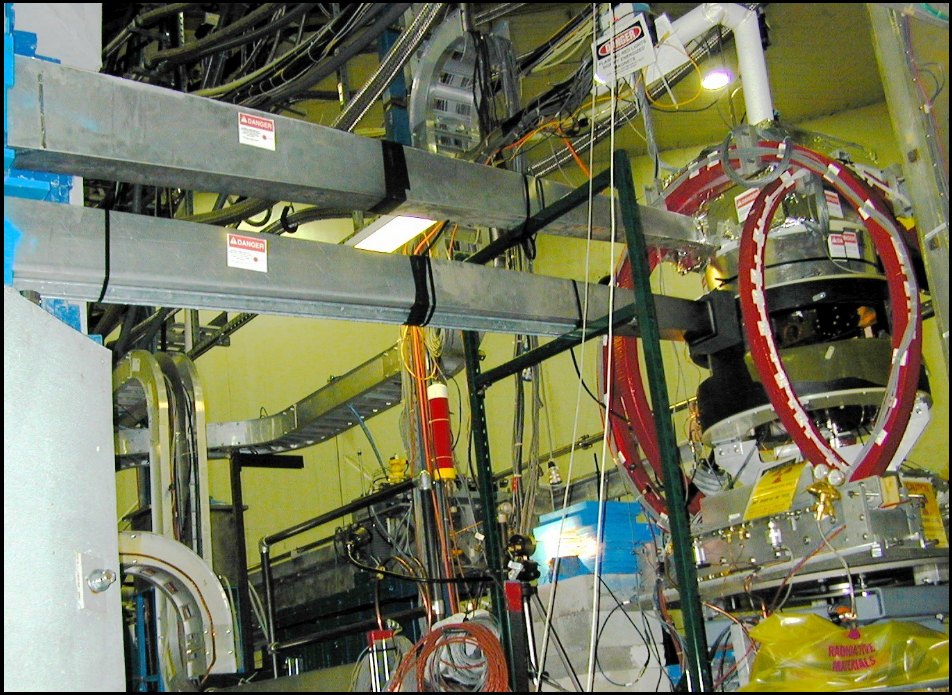
  Hybrid pumping

  Pol.from ~40% to ~50% gives 60% improvement!

- Operational improvements

  transverse coils, laser path

- ^{3}He target is a dynamic system, its infrastructure is continually upgraded, high level of user involvement



Intrinsic limitations

- Pumping cell pressure (optimal)
- Target cell pressure (not optimal, limits luminosity)
- Pumping cell material (optimal)
- Target cell material (not optimal, limits luminosity)
- Target cell geometry (optimal)
- Pumping cell geometry (not optimal, must fit in beam line, uniform field)

Linkage between pumping cell and target cell limits performance

Spin-up vs spin-down

- At 225℃ and K:Rb vapor ratio 17, spin-up time = 7.1 hours
  (^{3}He pump cell density 7.6 amagat and pump cell volume ~ 124 cm^3 yields 6 millimoles/hour)

$$P_{^3He} = \bar{P}_{Alkali} \frac{\gamma_{se}}{\gamma_{se}(1+X) + \Gamma_{wall} + \Gamma_{dipole} + \Gamma_{beam}}$$

- Loss of polarization depends on four factors:
  - Dipole-dipole = 1/770 hours * pressure
  - Cold cell wall relaxation rate ~ 1/33 hours
  - Warm cell relaxation rate correction: *X* ~ 0.3
  - Beam induced depolarization ~ beam current /622 hours

Beam depolarization (closer look)

- Loss rate of $(622\text{ hours})^{-1}$ per microamp = $(41\text{ hours})^{-1}$ for 15 microamps
- Scales linearly with target cell length, inversely with affected volume
- Causes ~ 6% drop in polarization
- Limits figure of merit p^2L at high luminosity
- In practice beam current is presently limited by target cell material

A high luminosity target will have losses dominated by beam depolarization, requiring very high production of polarized 3He

How to increase ^3He polarization rate?

- Increase pump cell pressure (increase number of atoms, factor x2)
- Increase pump cell temperature (increase spin-up rate, factor x2)
- Increase pump cell volume (big opportunity here, factor ~70)

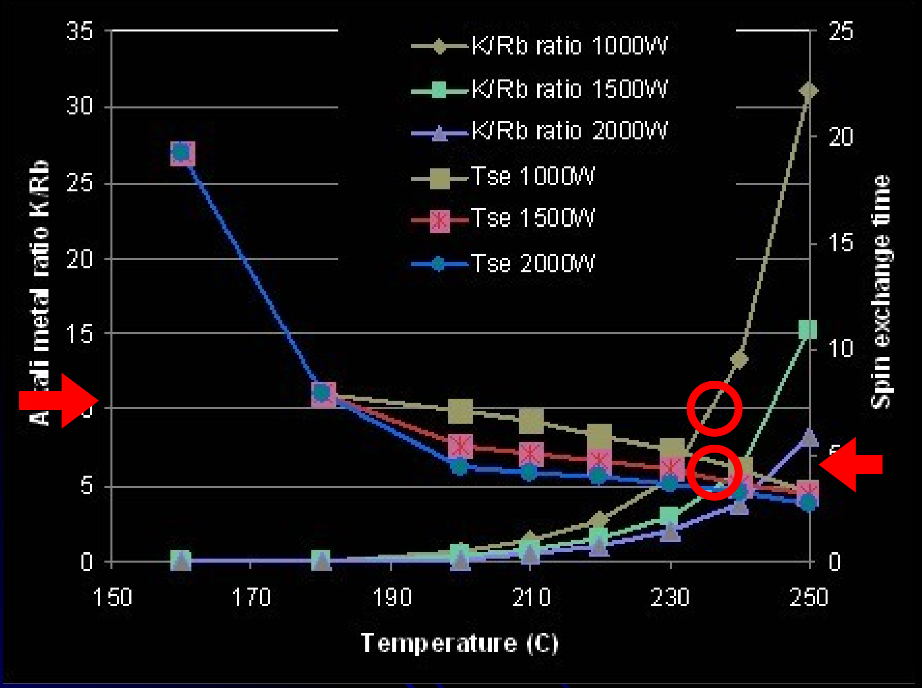
End of introduction

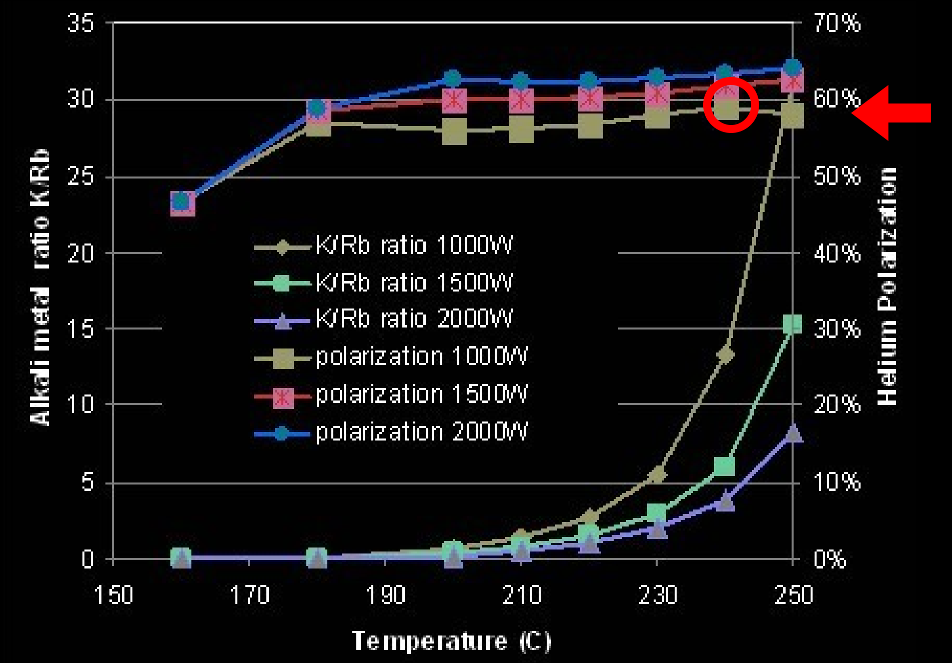
Xemed's large volume ^{3}He polarization

- Cell dimension (4" dia x 48" length) = 8.3 Liters
- Theoretical simulation
  - Optimal temperature
  - Optimal alkali mix
  - Required laser power
  - Optimal pressure
- Implementation
  - Pressure vessel
  - Aluminosilicate cell
  - Heat exchanger
  - Laser
  - Magnetic subsystems
- Data

Theoretical simulation-temperature

K/Rb ratio, polarization, and spin-up rate as a function of laser power for a broad 4nm laser into a 4”x48” diameter cell with X-factor of 0.3, temperature dependent wall relaxation (assume 37 hr to 18 hr) and cell temperature

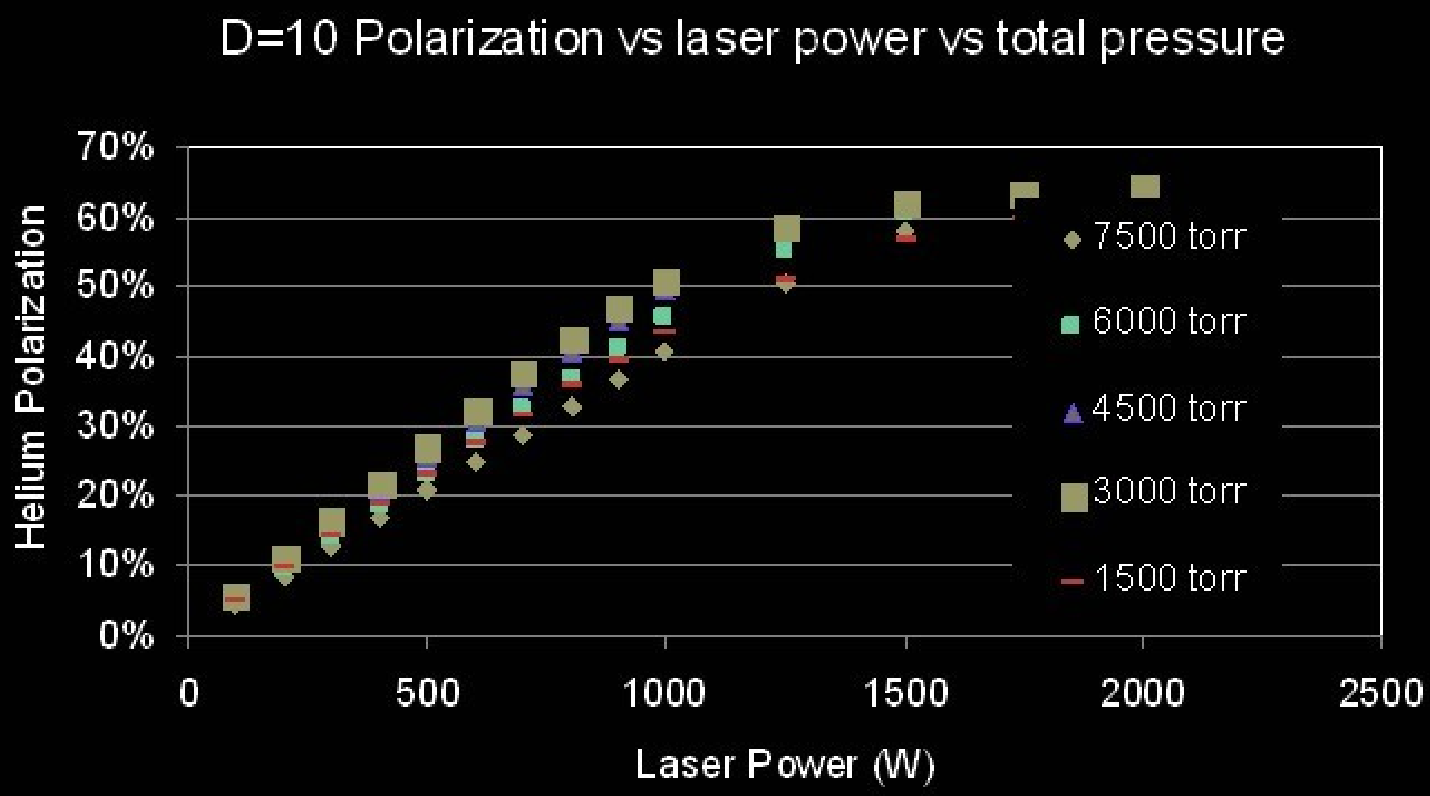




Selected K:Rb metal ratio of 10, 220°-250 ℃, laser power 1.5 kW, for the first prototype, anticipating 4 hour spin-up towards 60% polarization.

Theoretical simulation-pressure

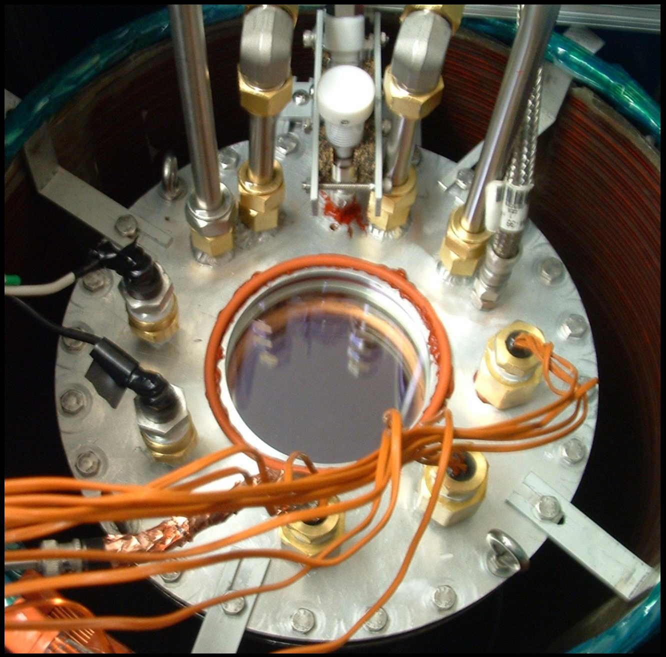
- Polarization vs laser power for different cell pressure show optimum at 4 bar, but pressure independence at high laser power.



- We suggest 15 amaget for nuclear physics e- beam target applications

Design of a large-scale polarizer of ^3He

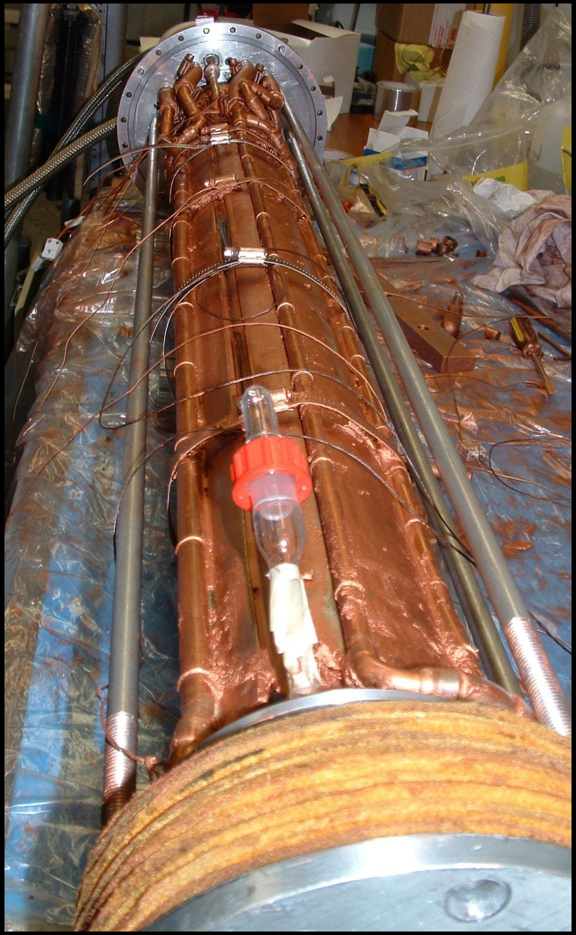
- Equalize pressure inside and outside glass optical pumping cell by surrounding the cell inside with a pressure vessel
- Cell temperature is stabilized by a flowing silicone oil heat exchanger
- Heat is delivered to cell initially to establish alkali vapor density; removed from cell after 1.5kW laser is turned on



Aluminosilicate cell and heat exchanger

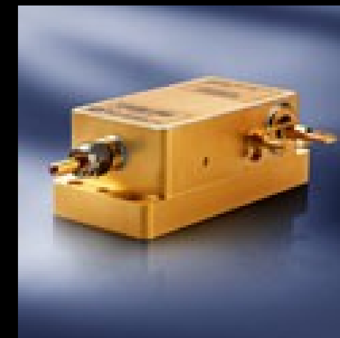
- Cell volume 8300cc (compare with “Eva” 125cc)
- Cell body of 4” Corning 1720 with 1723 windows

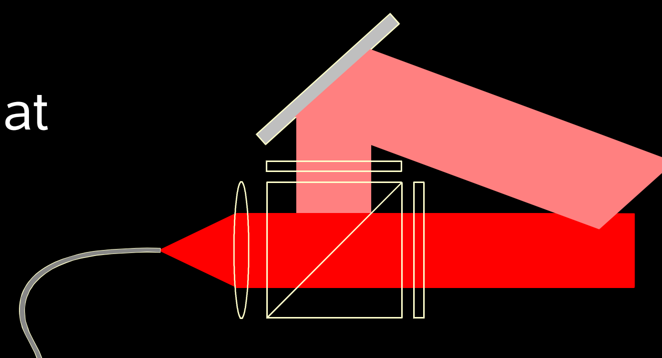
- Two-zone copper jacket with two aluminum end-heaters
- Closed-loop silicone oil thermal fluid capable of ~300℃



Diode laser arrays

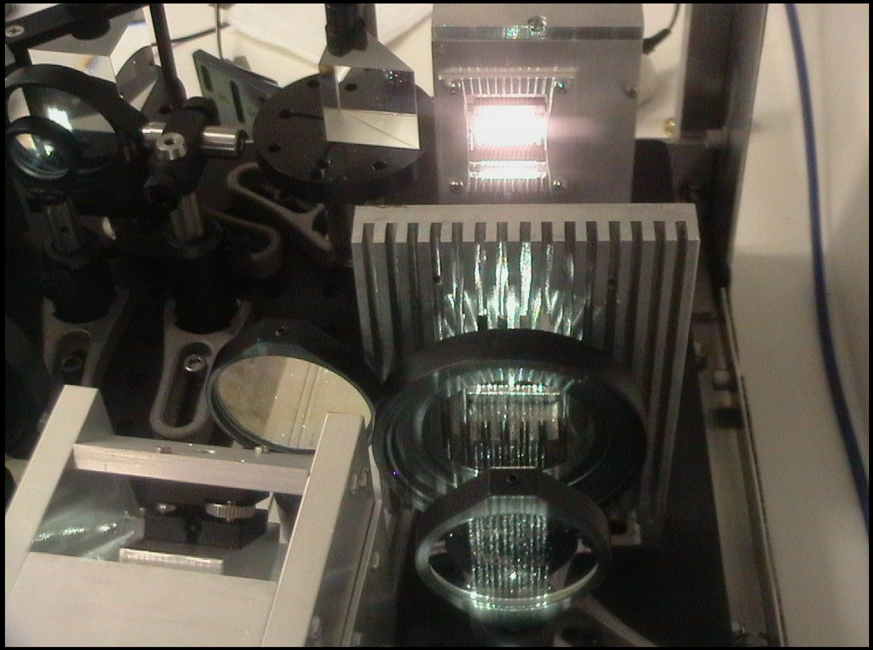
- During early 1988-1992 infrared 795 nm optical pumping required solid state titanium sapphire lasers pumped by argon-ion lasers (approximately 6W for $120k = $20,000/W)
- Inexpensive diode arrays became available around 1995, now achieving high-power at low cost (40W for $40k = $1000/W)
- Broad spectral line ~4 nm exceeds absorption width, not all light falls within useful range
- Although convenient, fiber coupling mixes polarization states and spreads beam
- Repolarizing results in two wide beams at different angles





Scalable laser power

- Xemed uses laser bar output directly; incremental cost $16/W
- Simple low-cost methods for laser transport
- Beam spread (etendue) reduced to 6 milliradians along both angles
- We plan for three 12 bar stacks, 3.6kW (square) 2.8kW (circle)



Magnetic environment and NMR

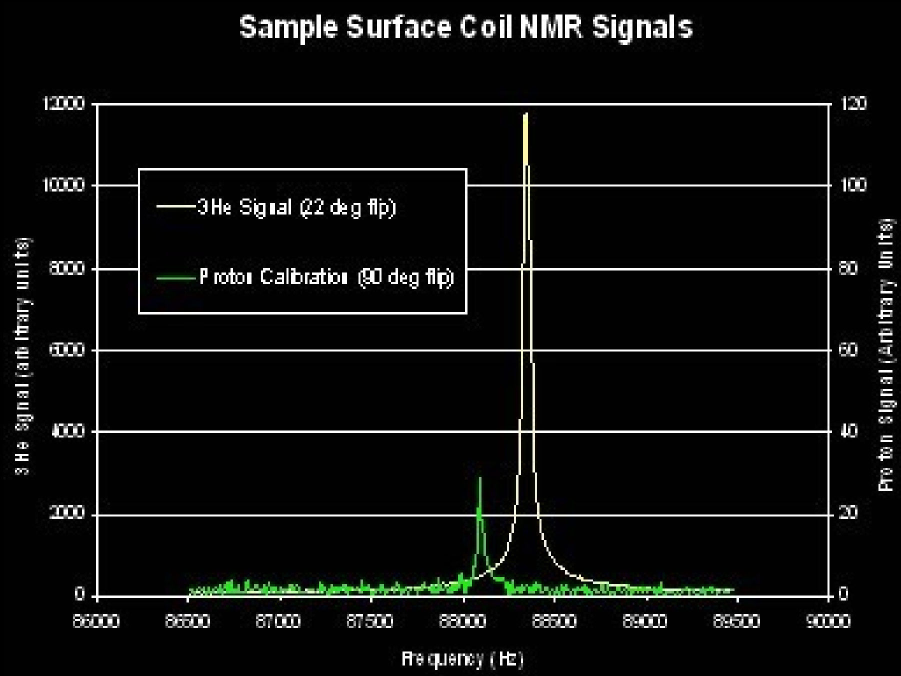
- Solenoid 38 cm diameter x 133 cm with two rings each end surrounded by soft iron and capped with mu-metal
- Flush mounted spiral NMR coil calibrated with identical water-filled system mock-up.
- Field uniformity 2×10^{-4} within NMR coil

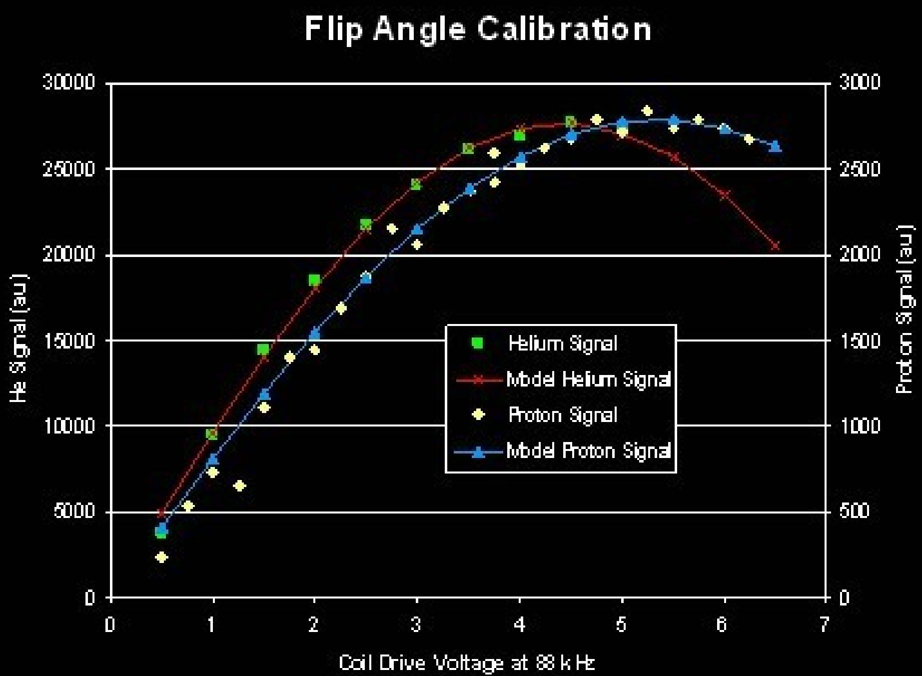
NMR polarization measurement

- Signal strength computed using Lorentzian fit.
- Water signals with 64 averages
- ^{3}He polarization computed from ratio of signal strengths.

$$\frac{V_{90,{}^3He}}{V_{90,H}} = .82 \quad \text{vs.} \quad \frac{\gamma_{{}^3He}}{\gamma_H} = .76$$

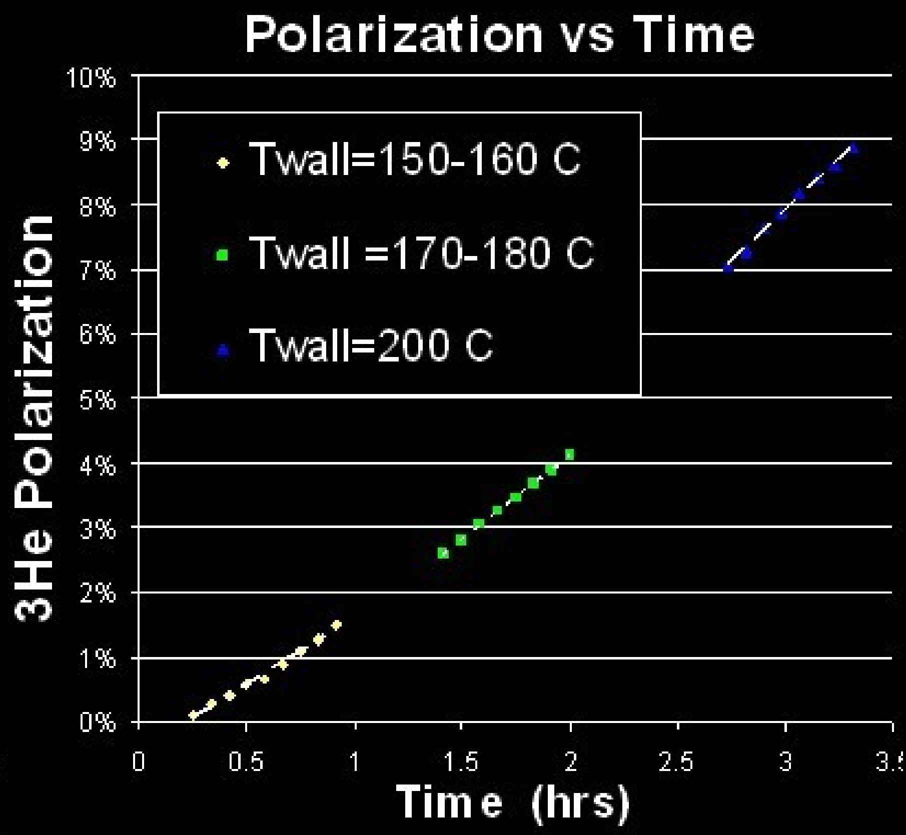
- Corrections for helium number density, flip angle, and changes in coil Q.
- Remaining uncertainty ~8%





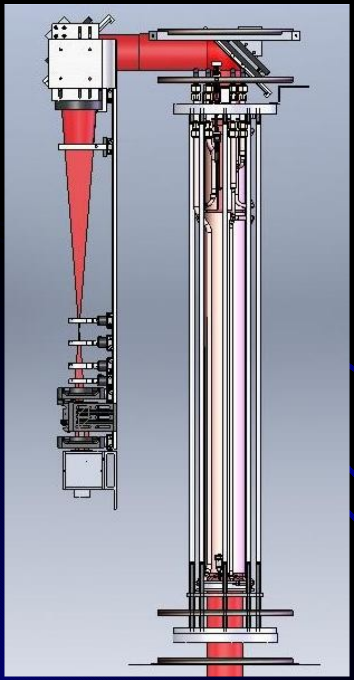
Test data

- High-pressure tests
  - Confirmed that vessel pressure consistently tracks cell pressure
- Low-pressure tests
  - Confirmed polarization increases as predicted with half laser power
- 3.1% per hour spin-up at 200°C
- next tests: higher temperature, higher pressure, higher laser power



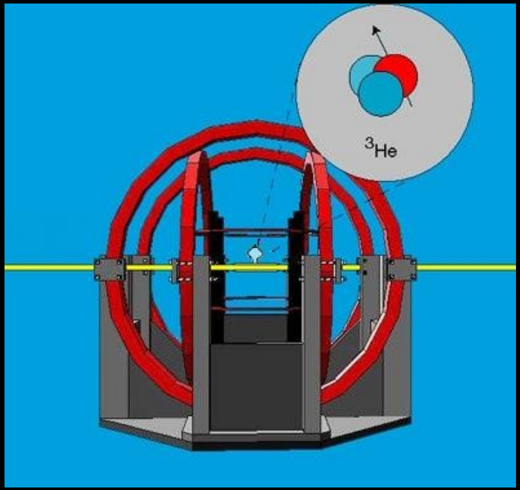
Target loop

- Compress polarized ^{3}He and deliver to 40cm long titanium target cell
- Commercial compressors achieve >3500 psi (238 bar)
- Requires compression ratio ~16, immersion in magnetic field, rubidium-free gas leaving polarizer, entrance and exit, <3% polarization loss



15 Bar

238 Bar



Requires two ports, entrance and exit

1 cm x 40 cm titanium target cell

Recirculating at 1.0 scfm

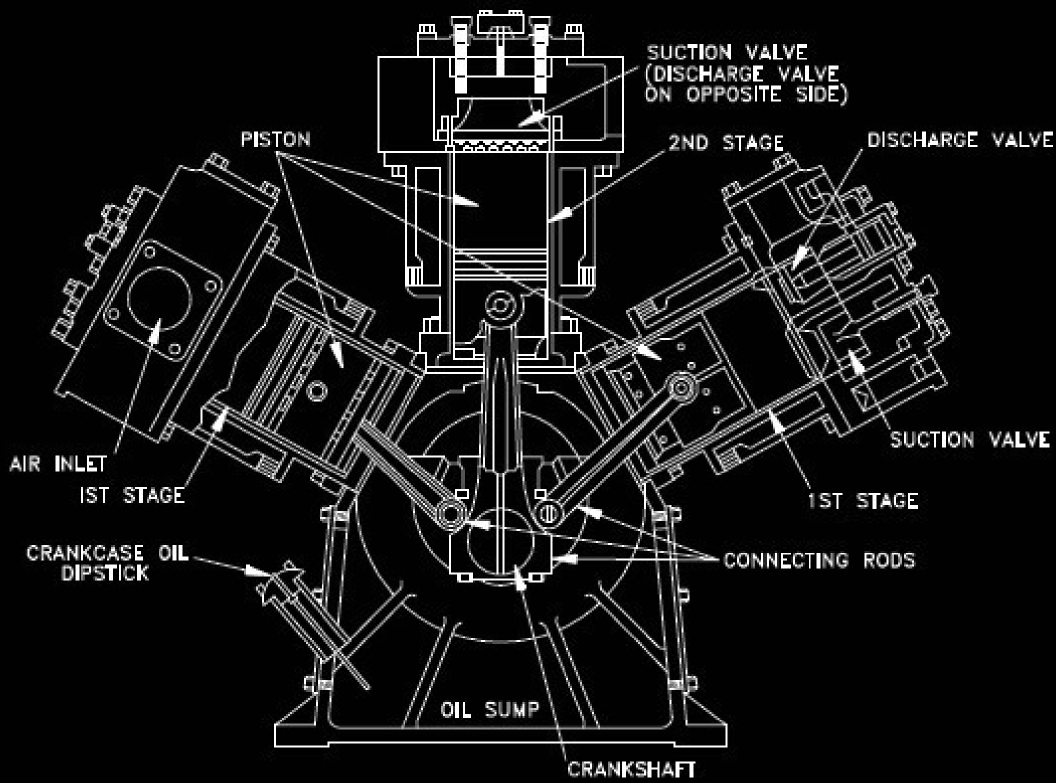
Getter purifier? RGA?

Compressor considerations

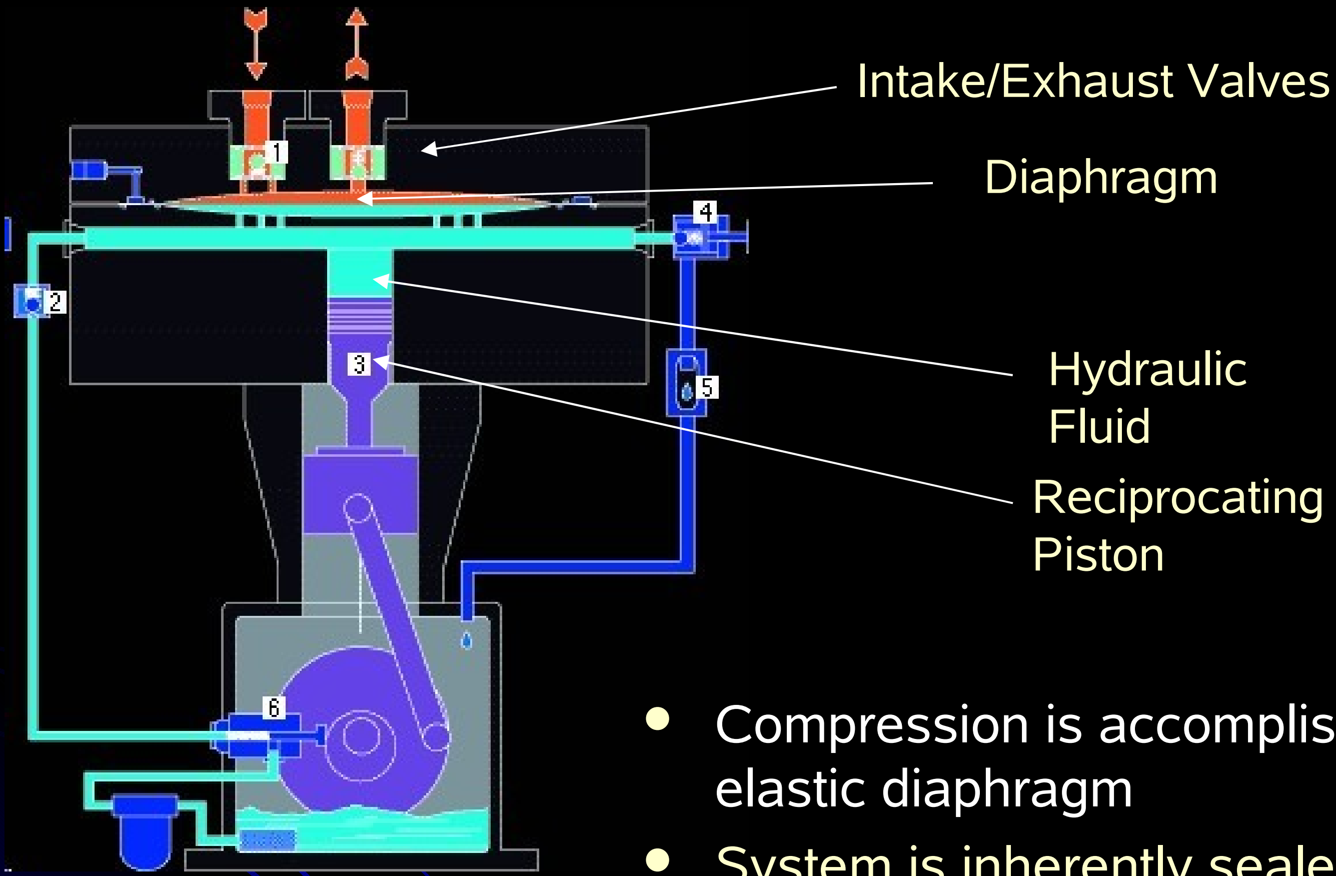
- Multistage compressor with intercooler reduces temperature rise
- Motor must generate no spurious magnetic field or EMI
- Compressor materials must have little or no residual magnetism
- Gas contact surfaces must have low relaxation rates
- ^3He flow path requires immersion in magnetic field

Piston compressor

- Reciprocating pistons driven by an eccentric crankshaft
- Inherently compact design
- Modern designs use oil free piston rings
- Minimal blow-by and contamination
- RIX Industries (Benicia CA) is experienced in fabricating pumps with suitable non-magnetic materials

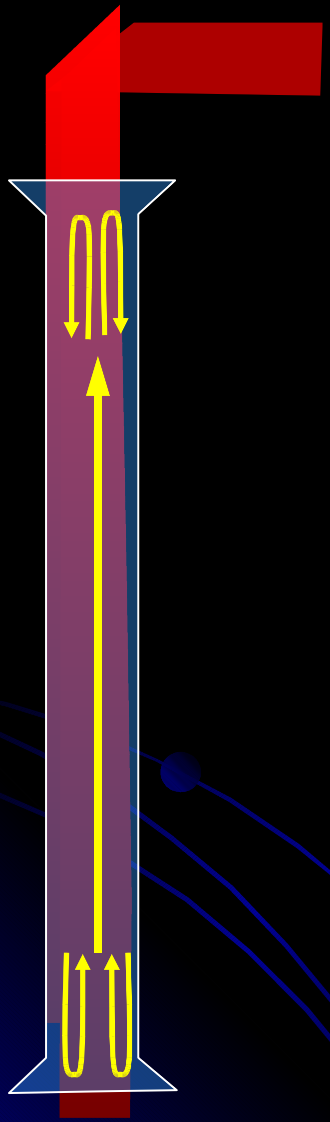


Diaphragm pump



- Compression is accomplished by displacing an elastic diaphragm
- System is inherently sealed
- Hydraulic plumbing allows remote drive motor
- Pressure Products Industries (Warminster,PA) is a potential partner

Alkali-vapor-free delivery



- Deposition of laser energy induces radial buoyancy gradients that induce circulation.
- In Vertical Configuration, flow rises in the center and falls along the walls.
- Dimensional arguments (and modeling) show that flow is turbulent.
- Modeling with FLUENT™ solves momentum, energy, and transport of alkali.
- Some Important Results

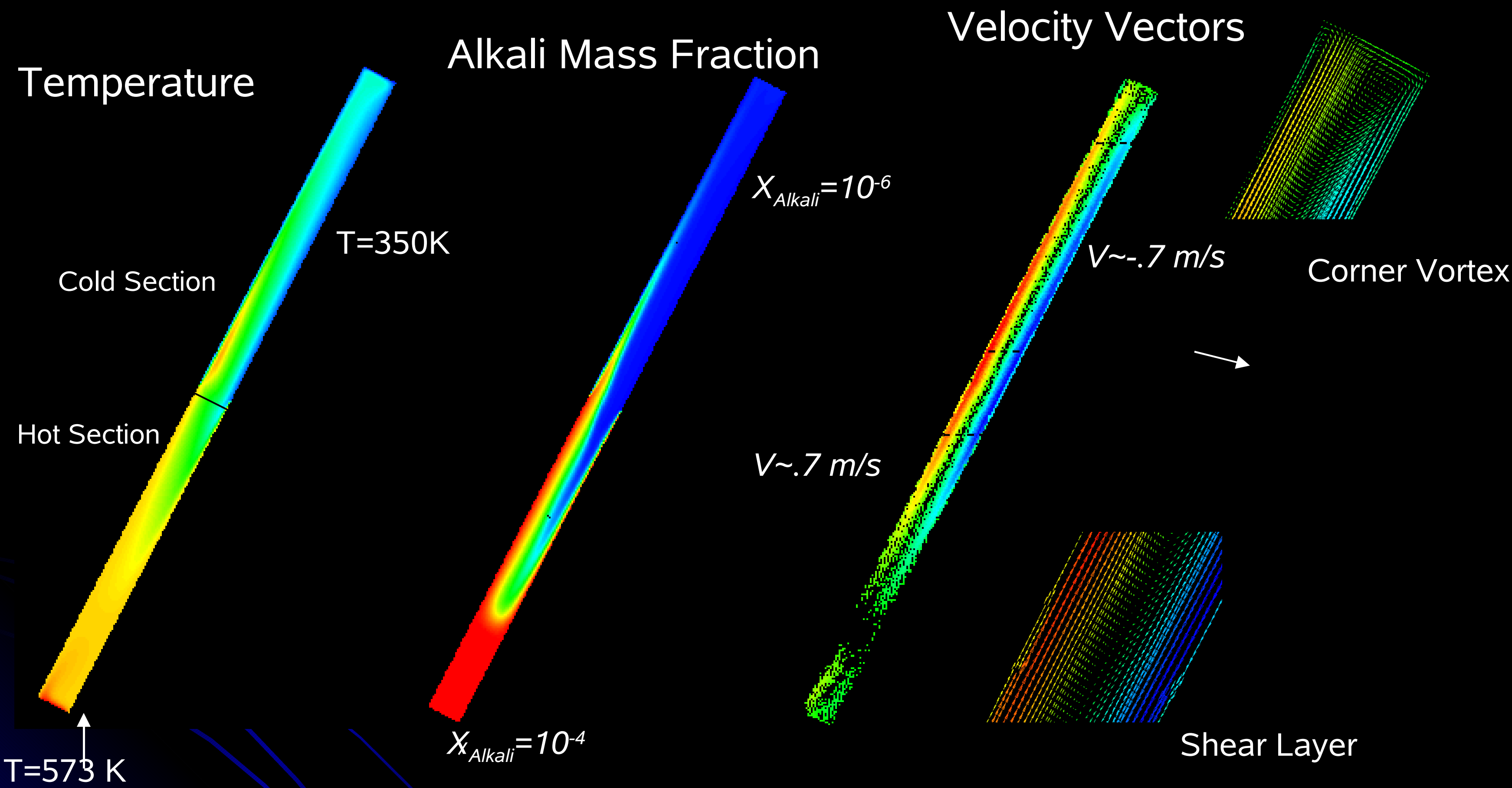
  Vertical velocities are very high (+/- ~.5 m/s)

  Vertical two-zone flow is unstable.

  Tilting polarizer by 10° or more creates a stable asymmetric flow that rises along the upper side and falls along the lower side.

  Tilted configuration produces an alkali-depleted zone in cold region that will allow continuous operation.

Result for 2 meter Polarizer, 600 W absorption, tilted 30° from vertical



- Tilted Buoyant flow induces asymmetric temperature, velocity and alkali distributions.
- Shear layer promotes heat and mass transfer between up- and downward streams.
- Circulating flow creates alkali-depleted cold region.

Predicted performance

- Depolarization rate 30% higher: Current100 μA (x7) through 40cm scaled up by density (x24), reduced by increased total ^{3}He content (÷ 130)
- Spin-up rate 75% higher: Polarizer operation at higher temperature

AND…

- Beam depolarization time constant in target cell only is 6 minutes
- Compressor flow 1.0 SCFM yields ^{3}He target residence time of 23 sec
- ^{3}He polarization difference at gas entrance and gas exit is 6% (rel.)

- Expected in-beam ^{3}He polarization at gas entrance is 59% exit 55%
- Luminosity is 1.6e+38 with 100μA on 40cm at 3500psi
- Figure of merit p^2L=0.55e+38 improvement over existing target x200

Outlook

- Development is currently shared between DOE and Xemed reserves
- NIH announced last week a commitment of $750k Phase 2 SBIR, first allotment expected in May 2008
- An SBIR Phase 1 proposal to DOE for $100k, if approved, would allow polarization tests of two aluminosilicate vessels and engineering. If Phase 2 is awarded in January 2010 we will procure and test compressors, completion of R&D in January 2012

BUT…we could complete the project sooner with earlier funding

- We would welcome Jefferson Lab involvement in specifying and procuring a suitable compressor sooner than January 2010
- We would also welcome a purchase order for a helium polarizer!