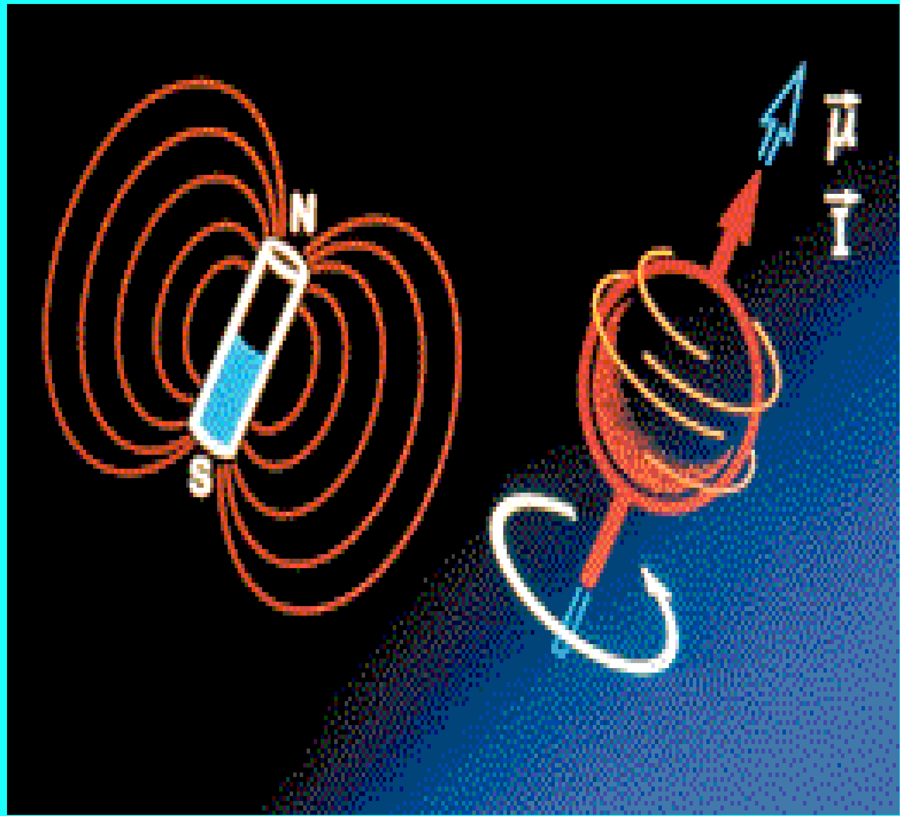
Dynamics of Hyperpolarized ^{129}Xe Production

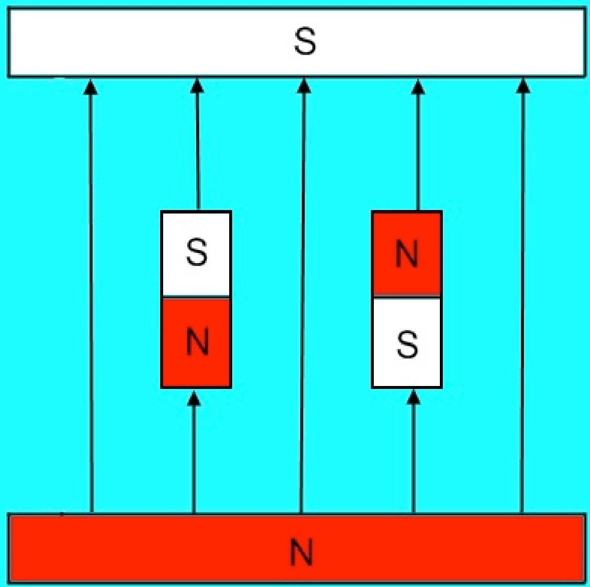


Geoffry Schrank
Department of Physics
University of Utah

Outline

- Define Hyperpolarized
- Uses of Hyperpolarized Noble Gases
- Physics of How to Prepare Hyperpolarize Gases
- How to build a ^{129}Xe Polarizer
- Dynamics of a ^{129}Xe Polarizer

Spin Polarization

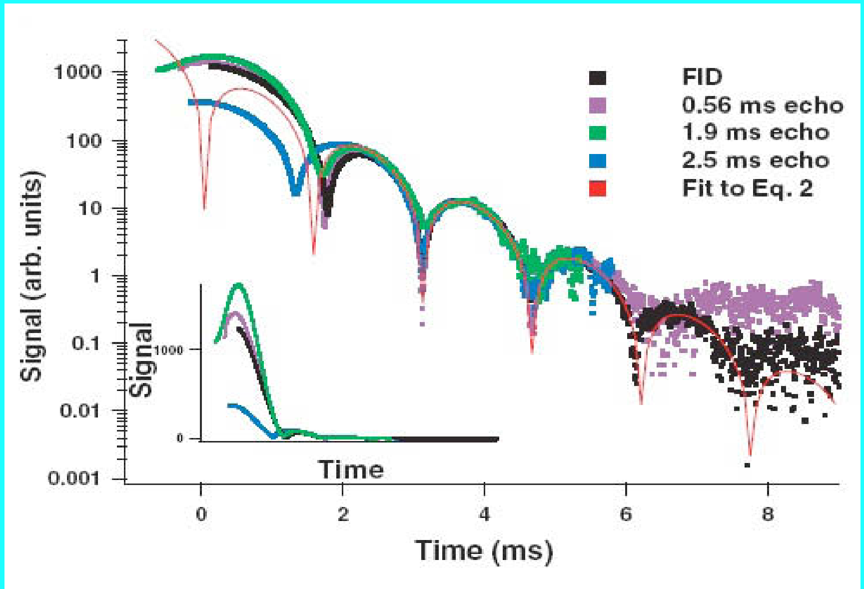


$$P = \frac{N\uparrow - N\downarrow}{N\uparrow + N\downarrow}$$

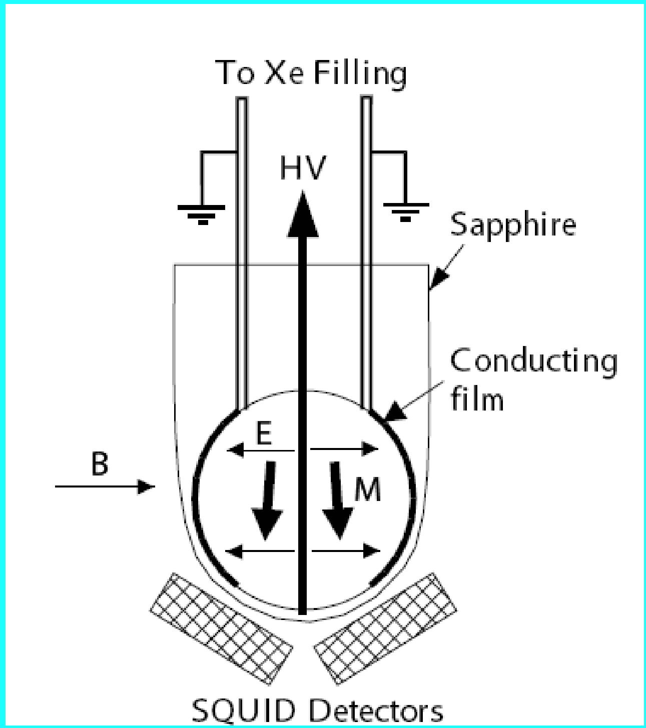
- Thermal Polarization: $10^{-6} – 10^{-5}$
- Hyperpolarization: 10^{-1}

Enhanced Sensitivity for Nuclear Spin Dependent Experiments

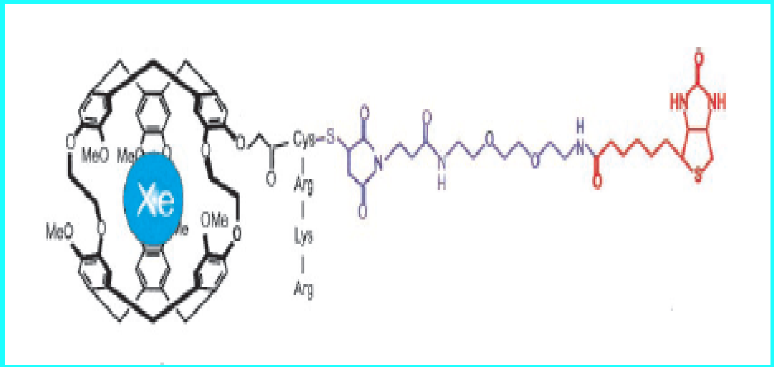
Uses of Hyperpolarized Gas



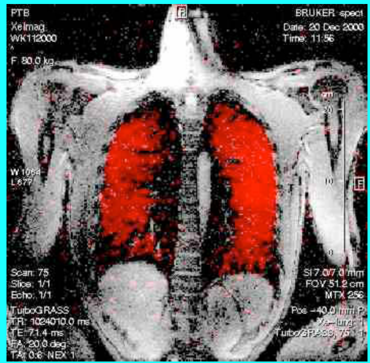
Morgan et al. 2008



Ledbetter 2005

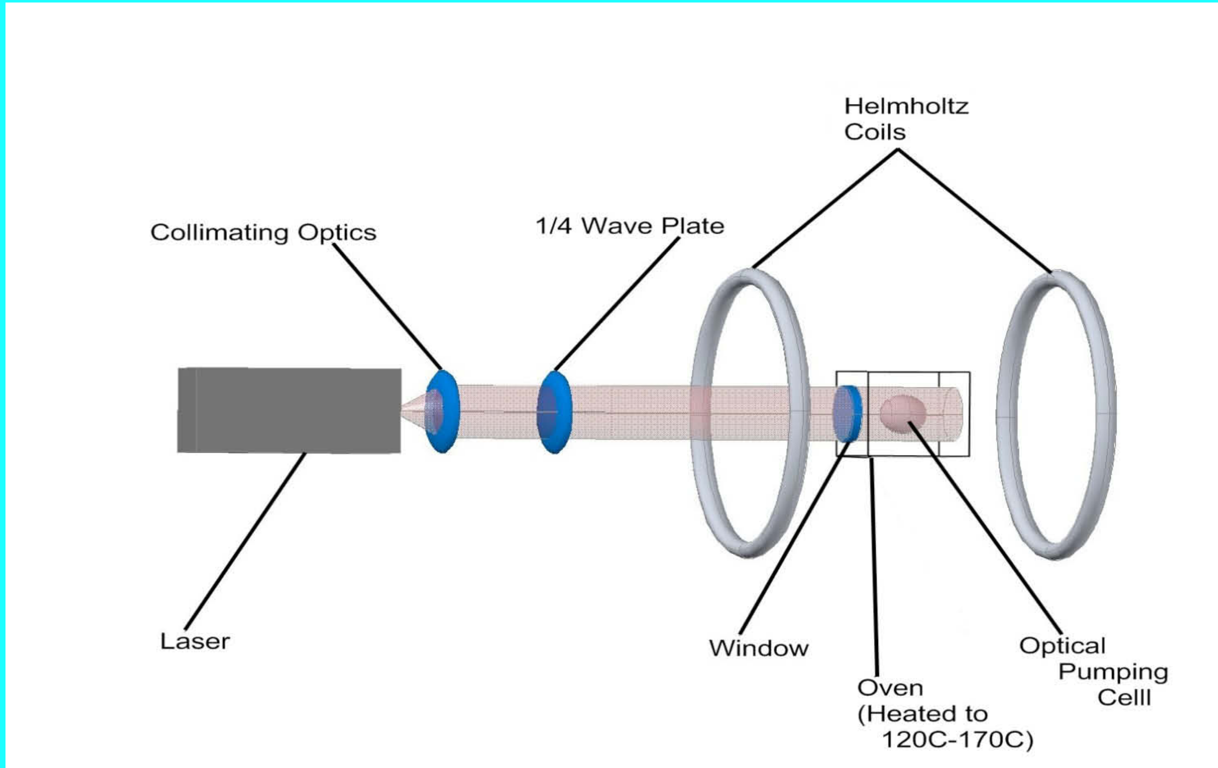


Spence et al. 2001



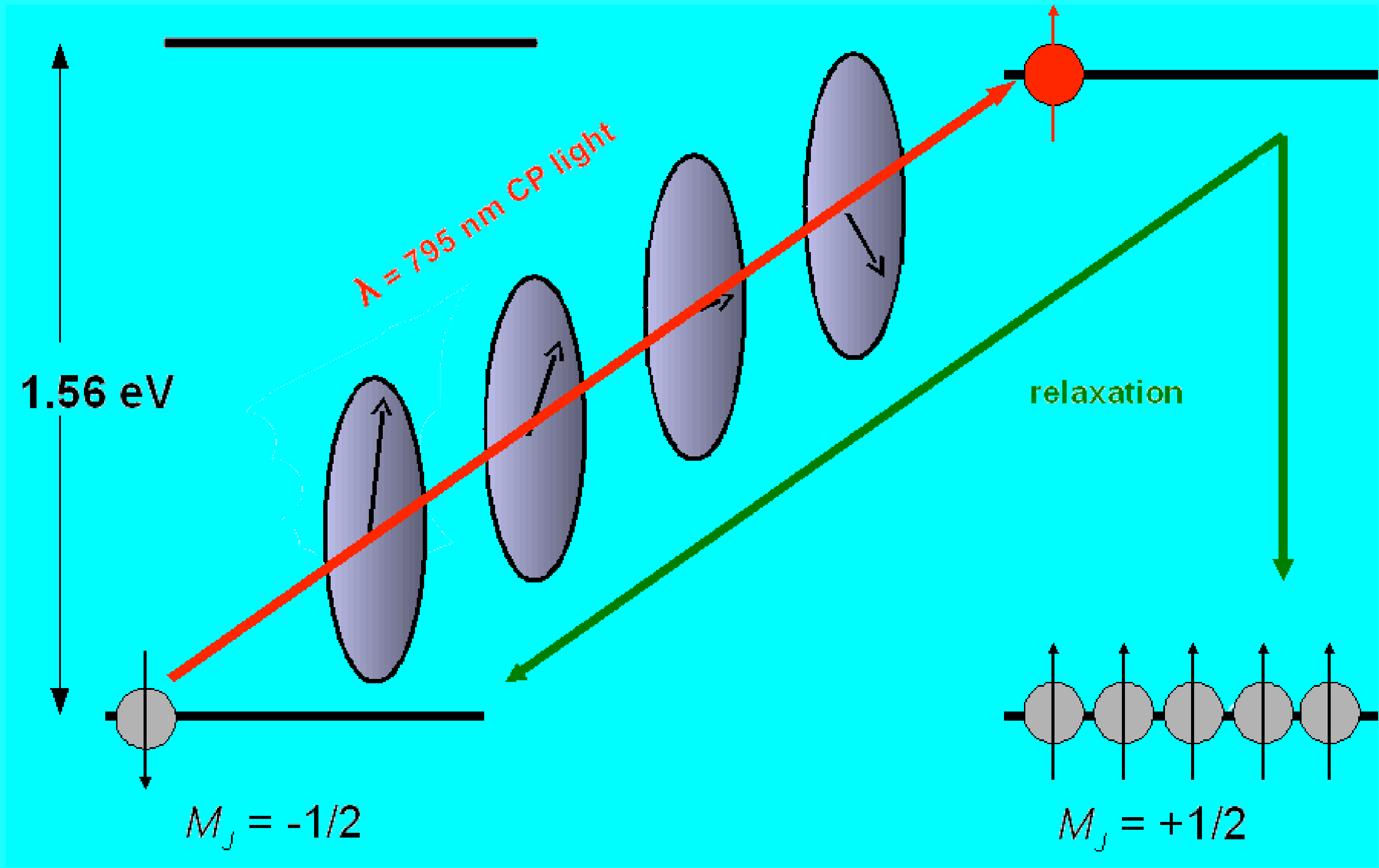
W. Killian 2001

Spin-Exchange Optical Pumping

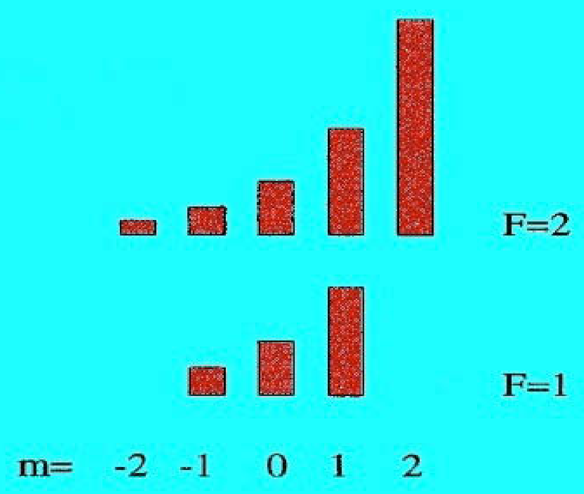


- Optical Pumping: Circularly Polarized Light Spin Polarizes Rb
- Spin Exchange: Rb Electron Interacts with Xe nucleus

Depopulation Optical Pumping



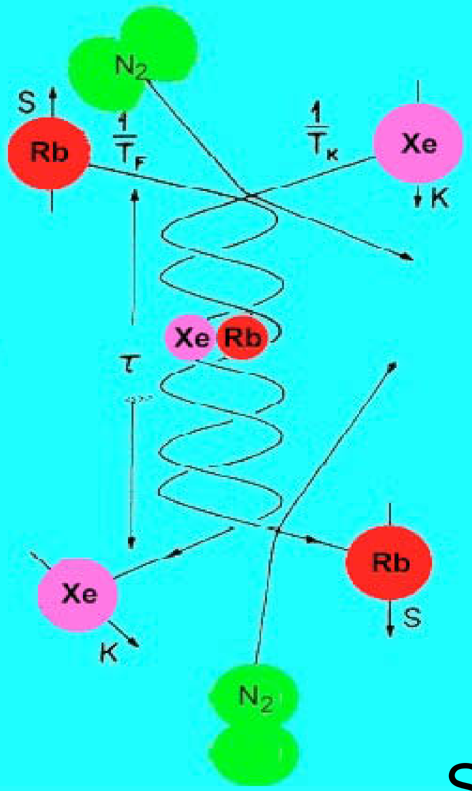
Establish Spin Temperature



$$\rho = \frac{e^{\beta F_z}}{Z}$$

- Require that sudden processes dominate
  - Sudden processes fast with respect to hyperfine precession frequency
  - Allow ΔF=±1, 0 transitions
- Slow processes only allow ΔF=0 transitions

Rb-Xe Spin Exchange



Fermi Contact Interaction

$$\alpha\, S \cdot K$$

Spin-Exchange Rate

$$\gamma_{SE} = \left(\frac{1}{\frac{[Xe]}{\beta_{Xe}} + \frac{[N2]}{\beta_{N2}} + \frac{[He]}{\beta_{He}}} + \kappa_{Se}^{Rb-Xe} \right) [Rb]$$

$$\frac{m_{87}}{\left(\frac{[G]_1(T)}{[G]}\right)^2} \Bigg\} + \langle \sigma_{SE} v \rangle \Bigg) [Rb]$$

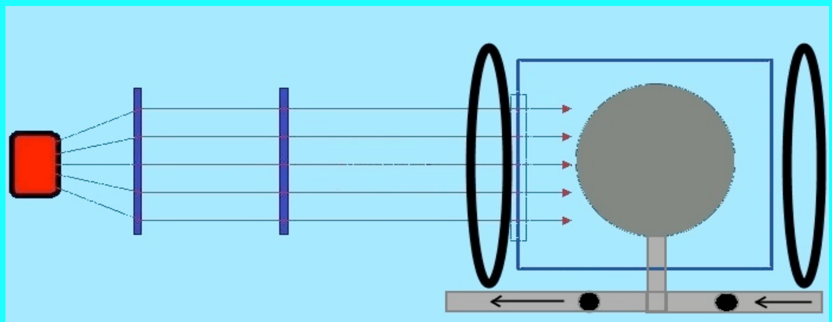
-Ruset 2005

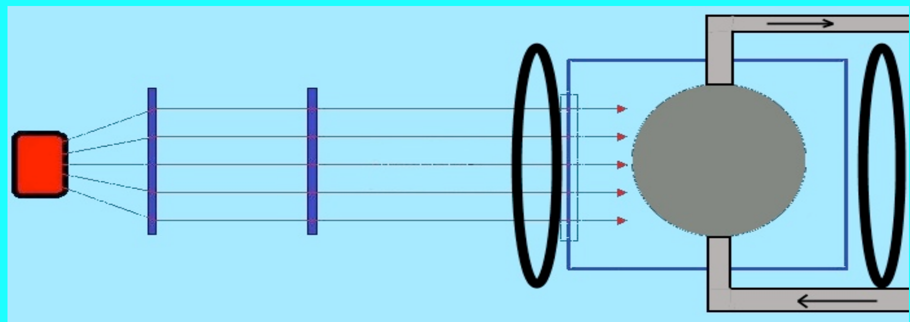
-Nelson, 2001

Batch Mode vs. Flow-Through

- Xe Gas Mixture Stationary
- Requires Low Xe Partial Pressure
- Production Discontinuous

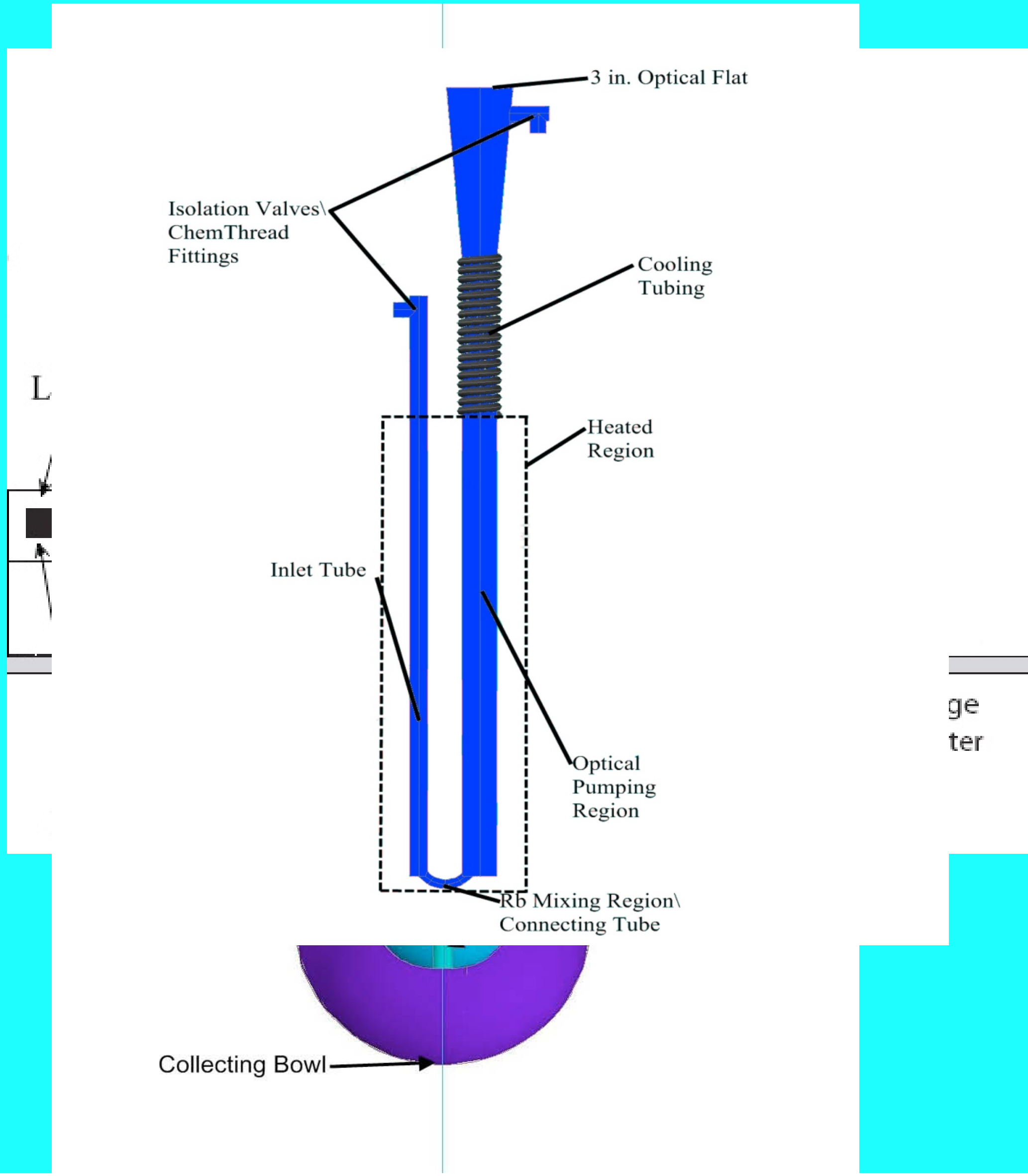
- Xe Gas Mixture Flowing
- Still Use Low Xe Partial Pressure
- Production Continuous

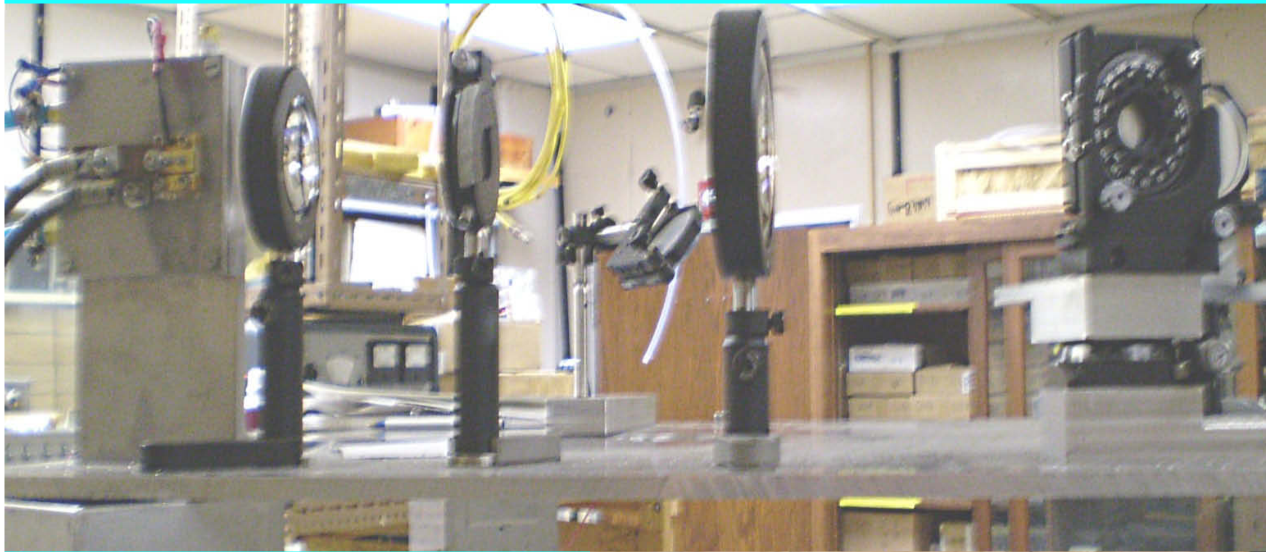


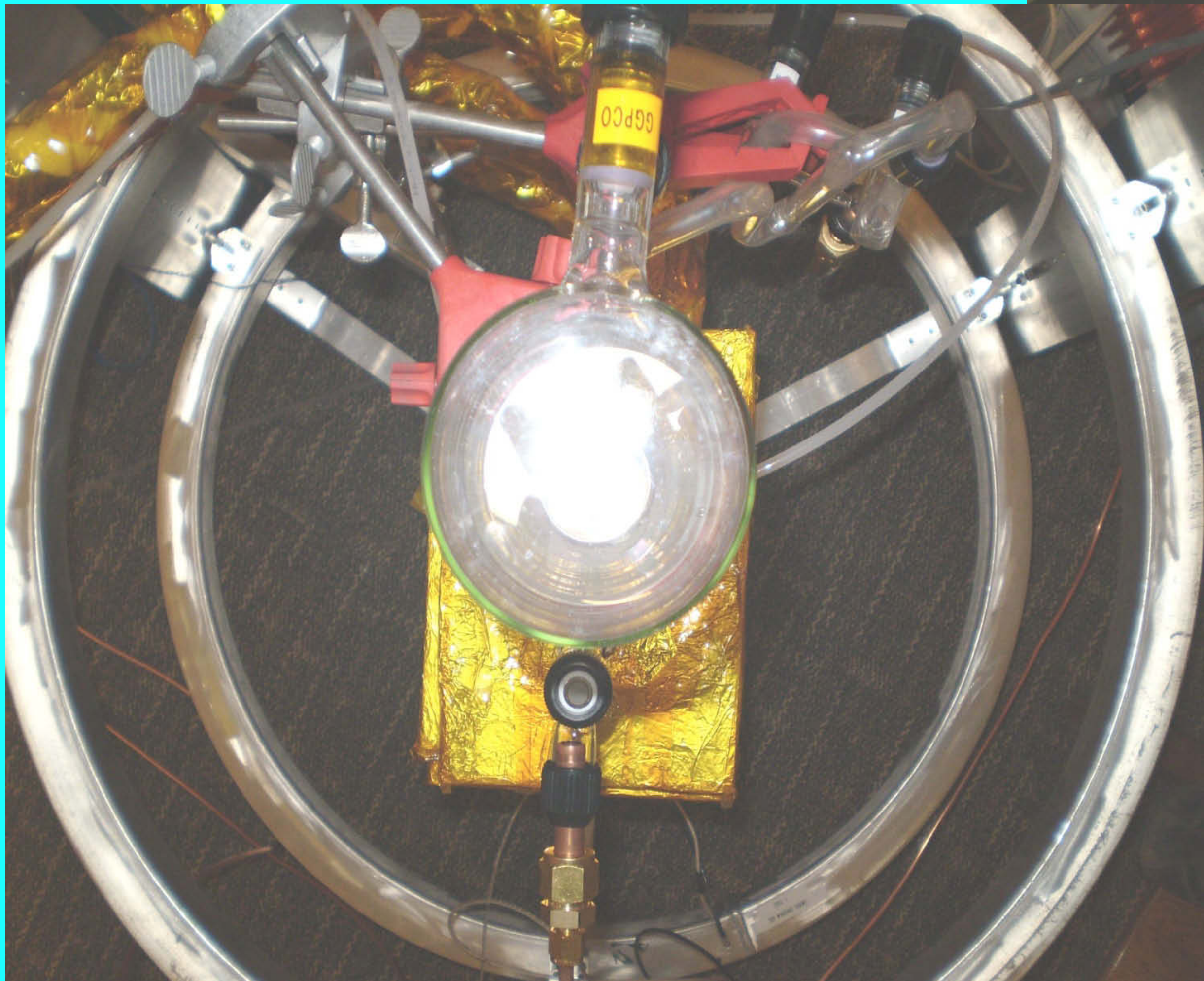


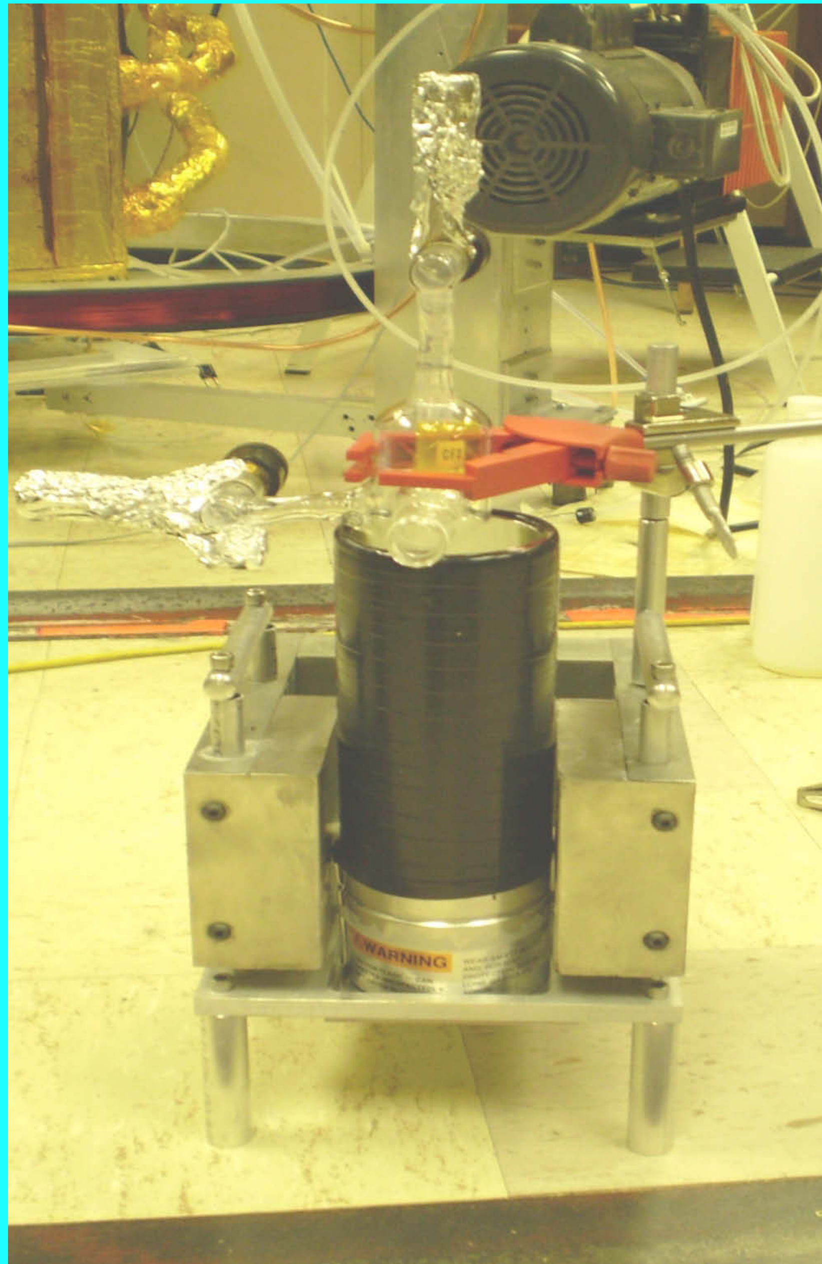
Building a Flow-Through Polarizer

- Laser
- Polarizing Cell
  - Long Cell
  - Low-Pressure
  - Counter-Flow Light Propagation
    - Ruset et. al (2006)
- Separation and Storage





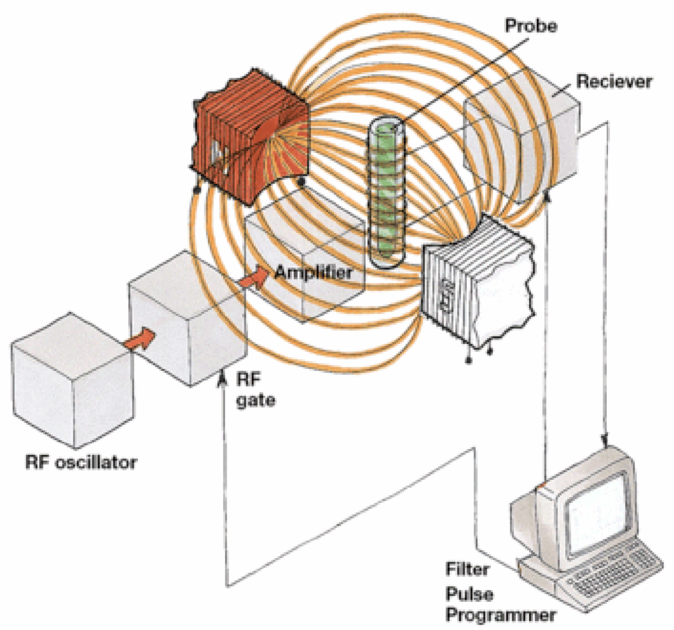



WARNING

Characterization of Polarizer

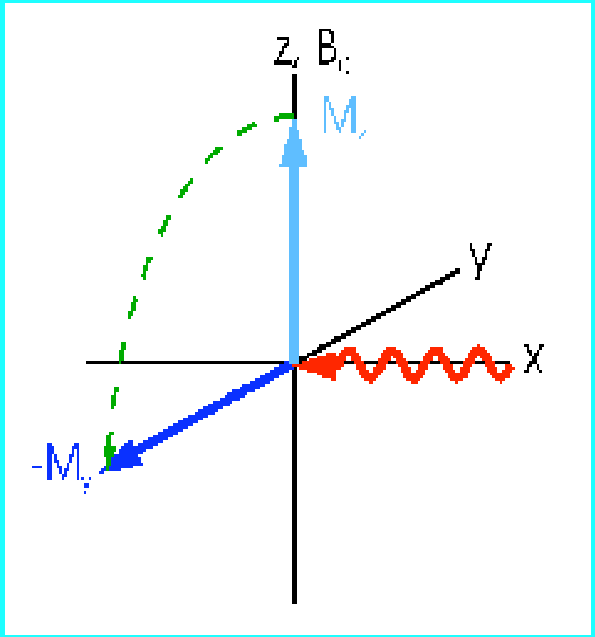
- Characterize Output ^{129}Xe Polarization as Function of Variable Parameters
  - Oven Temperature
  - Xe Concentration
  - Total Flow Rate
  - Optical Pumping Cell Total Pressure
- Characterize Rb Polarization as Function of Variable Parameters
- Compare Measurements to Model of Polarizer

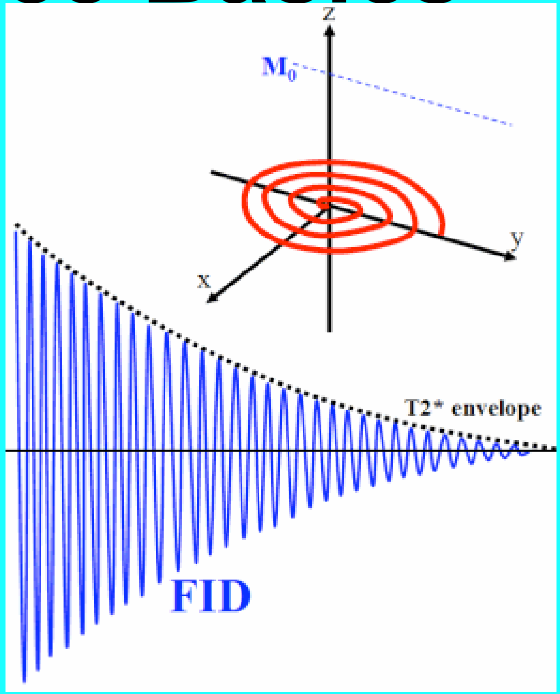
Nuclear Magnetic Resonance Basics



Place sample magnetic field

Apply RF pulse to tip magnetization into plane





Record induced EMF from precessing magnetization

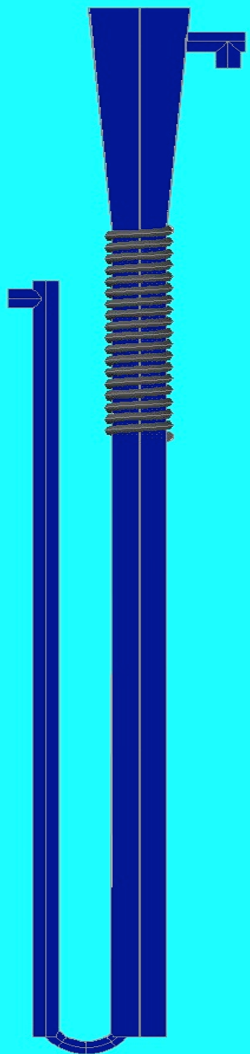
Nuclear Magnetic Resonance

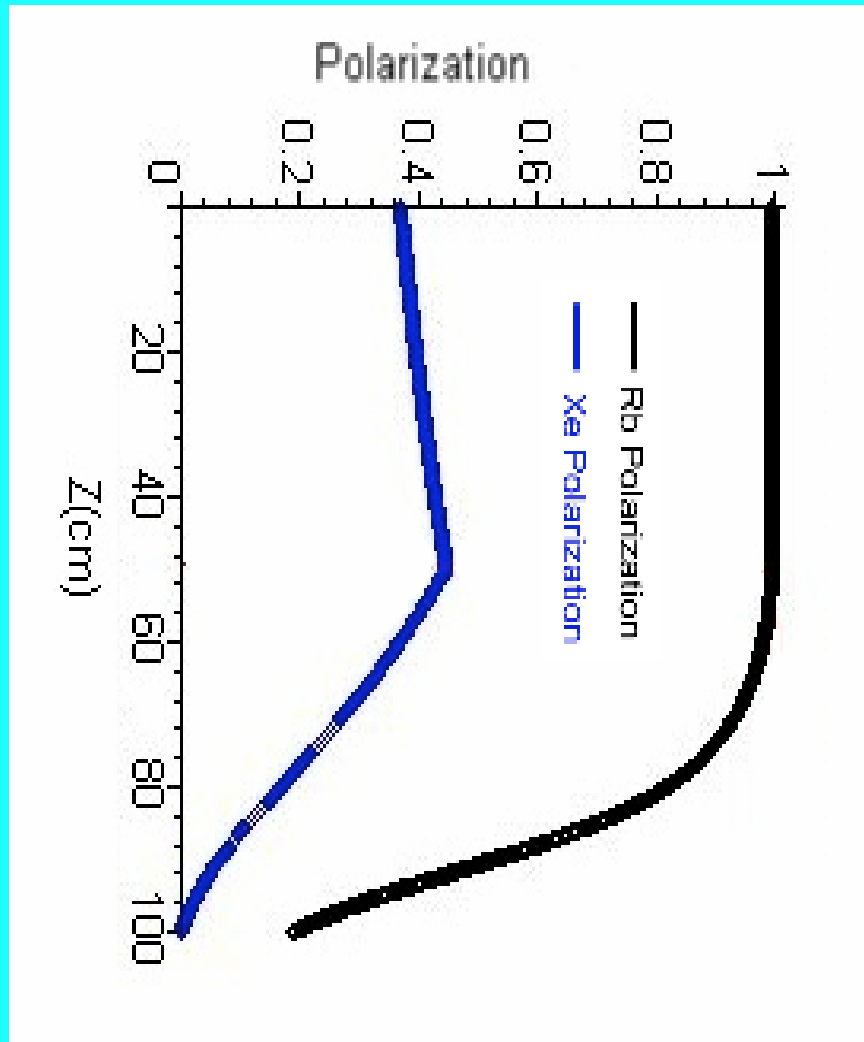
Basics

- Compare Water NMR to Xe NMR

$$\frac{S_{Xe}}{S_p} = \frac{\mathcal{P}_{Xe}}{hf} \frac{\mathcal{M} P_{^{129}Xe}}{\rho_{H_2O} N_A} \frac{\gamma_{Xe}}{\gamma_p}$$

Check Rb Polarization Profile

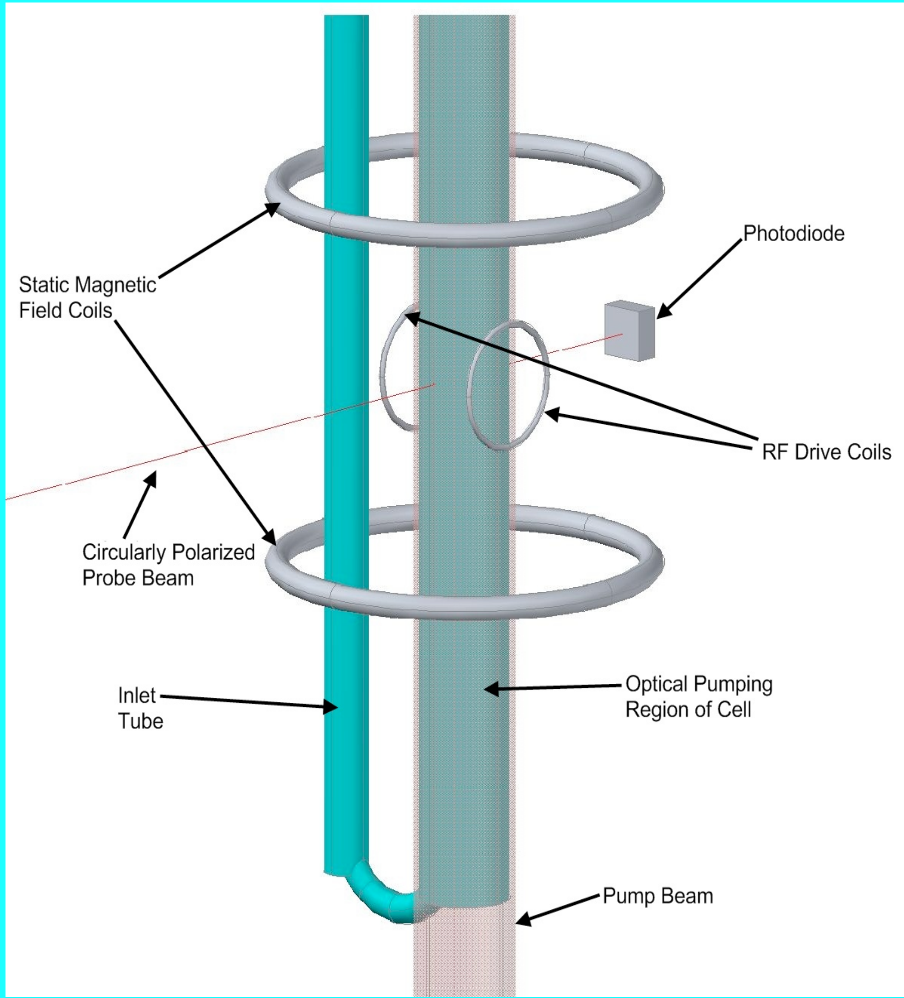




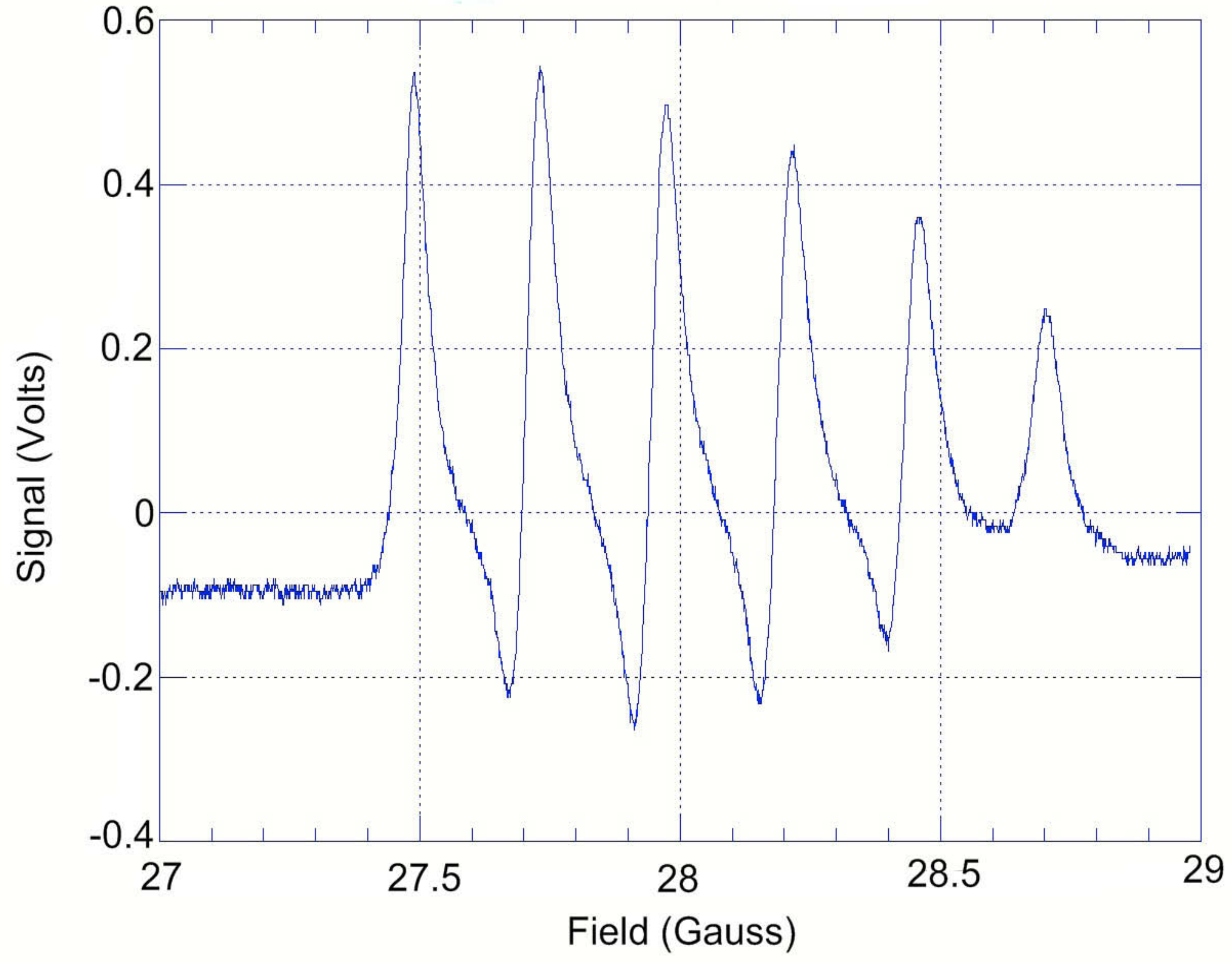
Rb Polarimetry

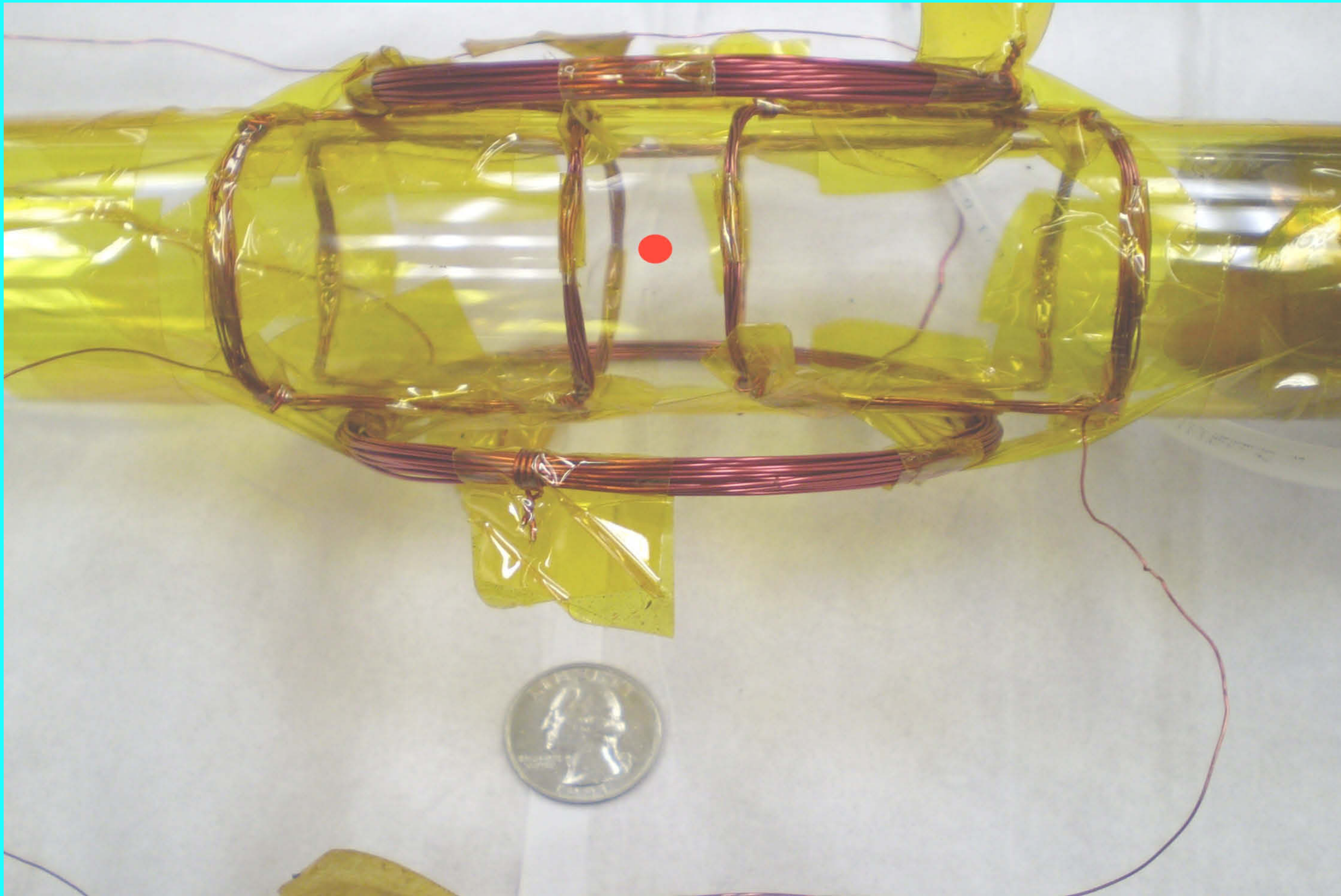
- RF Creates Steady-State Magnetization
- Probe Light Modulated by Magnetization
- Sweep Field and Detect Resonance
- Resonance Area Ratio Proportional to Polarization

$$P_{Rb} = \frac{5r - 3}{5r + 3}$$



Rb ODEPR Spectra





Modeling a Flow-Through System

Step 1: Model Laser Absorption

$$\frac{\partial}{\partial z}\psi = -\frac{\psi}{L_r}$$

Photon Flux Density

Absorption Length

Step 2: Model Rb Polarization

$$P_{Rb} = \frac{\gamma_{opt}}{\gamma_{opt} + \Gamma_{SD}}$$

Rb Polarization

Optical Pumping Rate

Rb Spin Destruction Rate

Step 3: Model Xenon Polarization

$$\frac{\partial}{\partial z}P_{Xe} = \frac{\gamma_{SE}(P_{Rb} - P_{Xe}) - \Gamma P_{Xe}}{v}$$

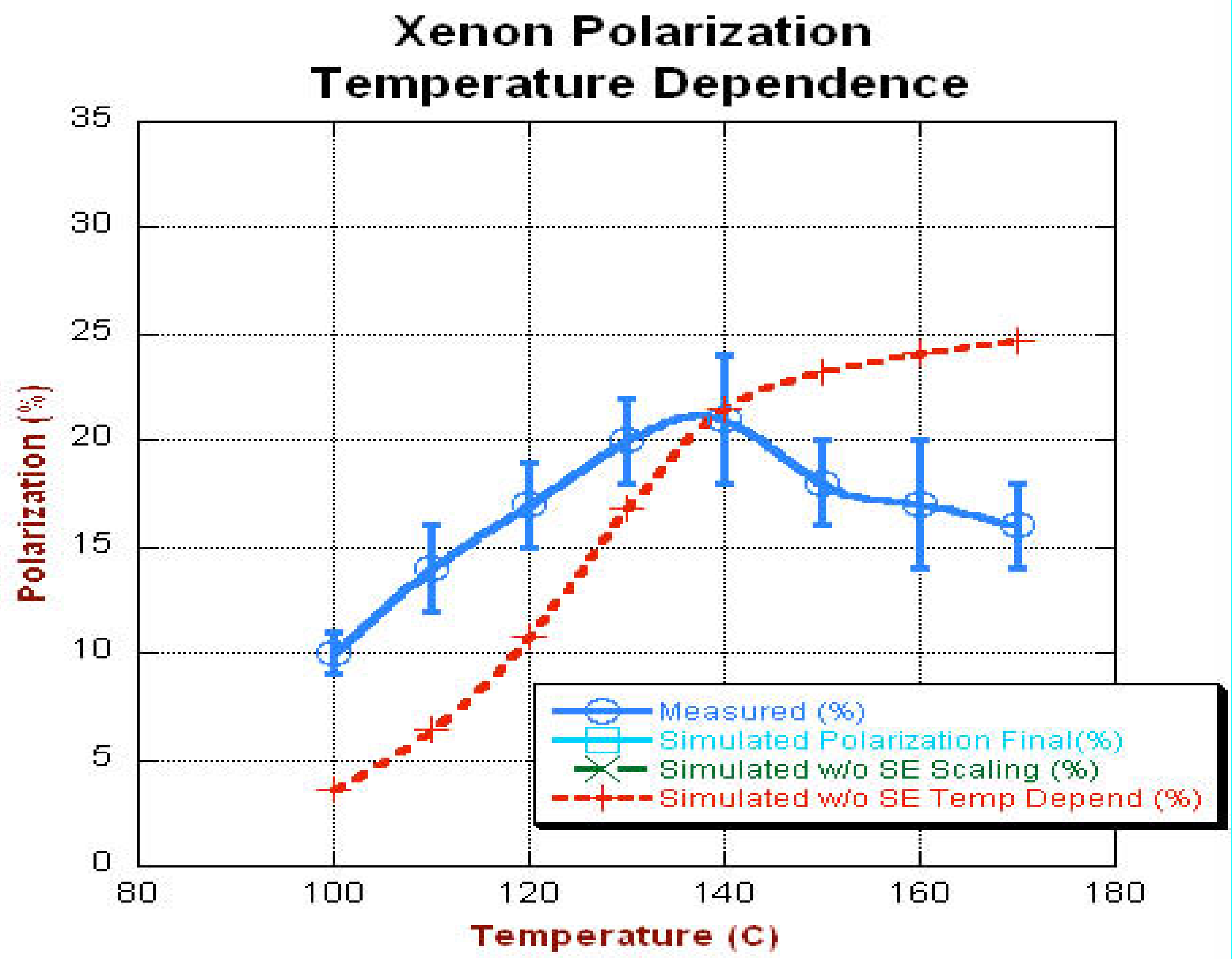
Spin Exchange Rate

Xenon Spin Destruction Rate

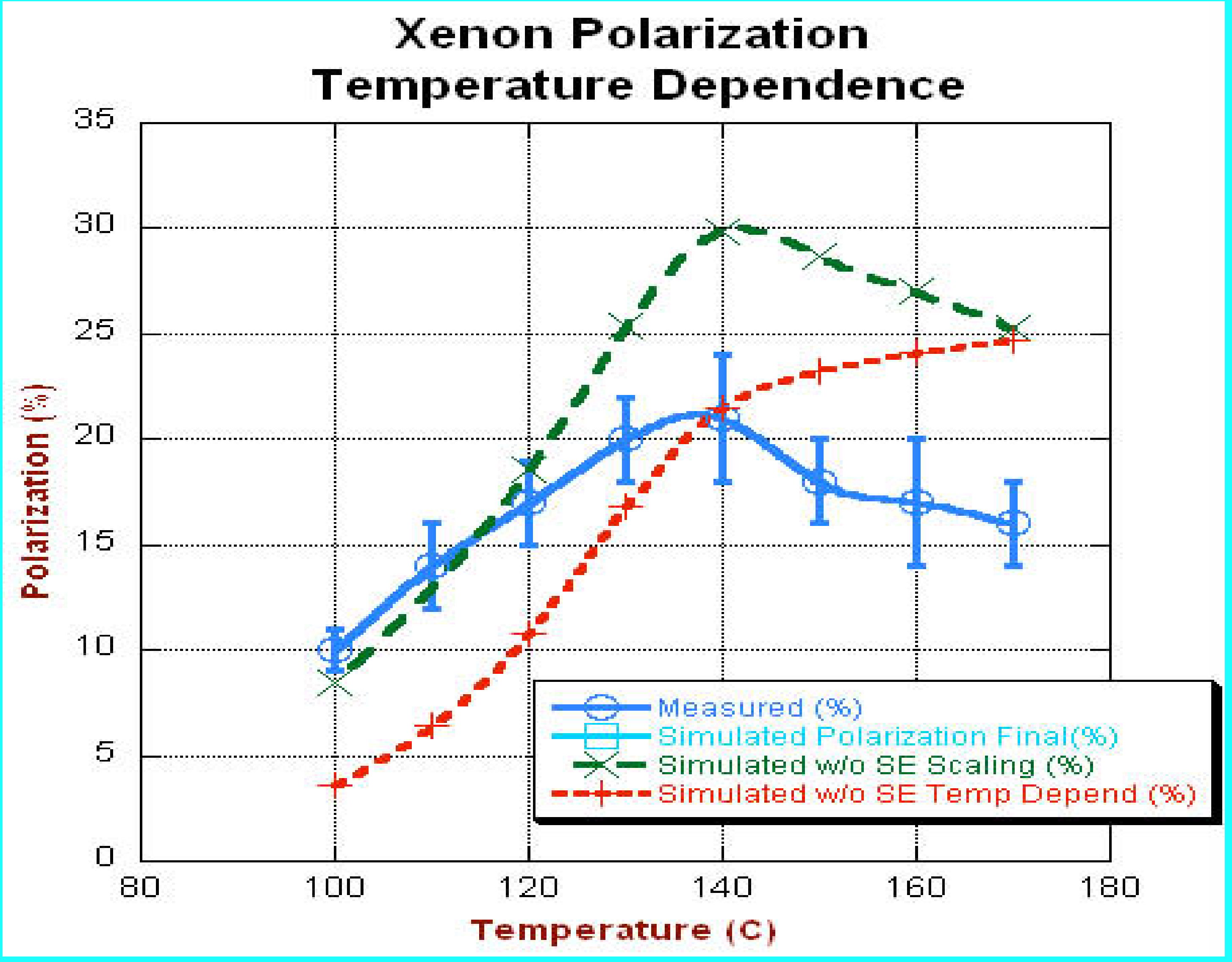
Xenon Polarization

Linear Velocity

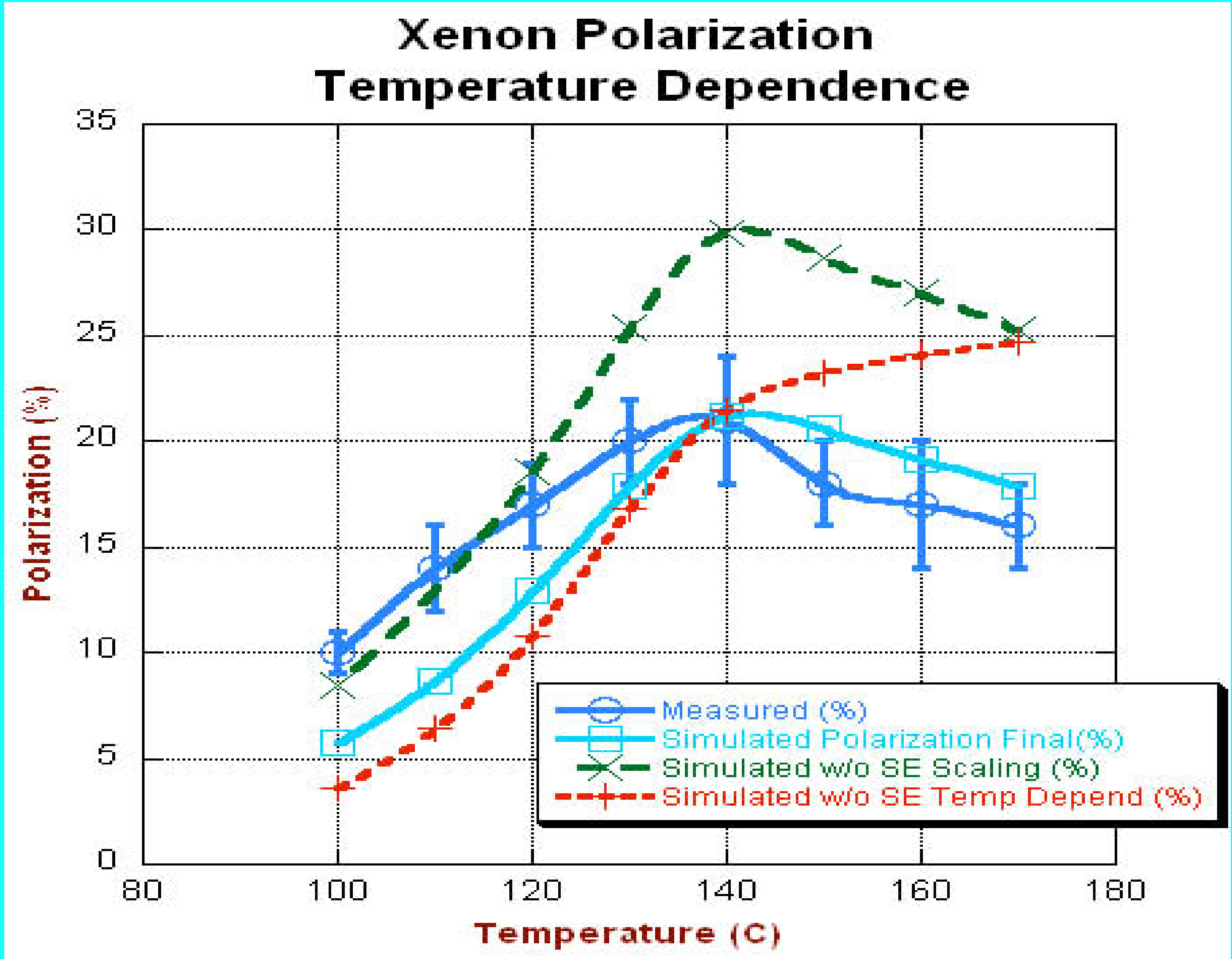
Fitting the Model



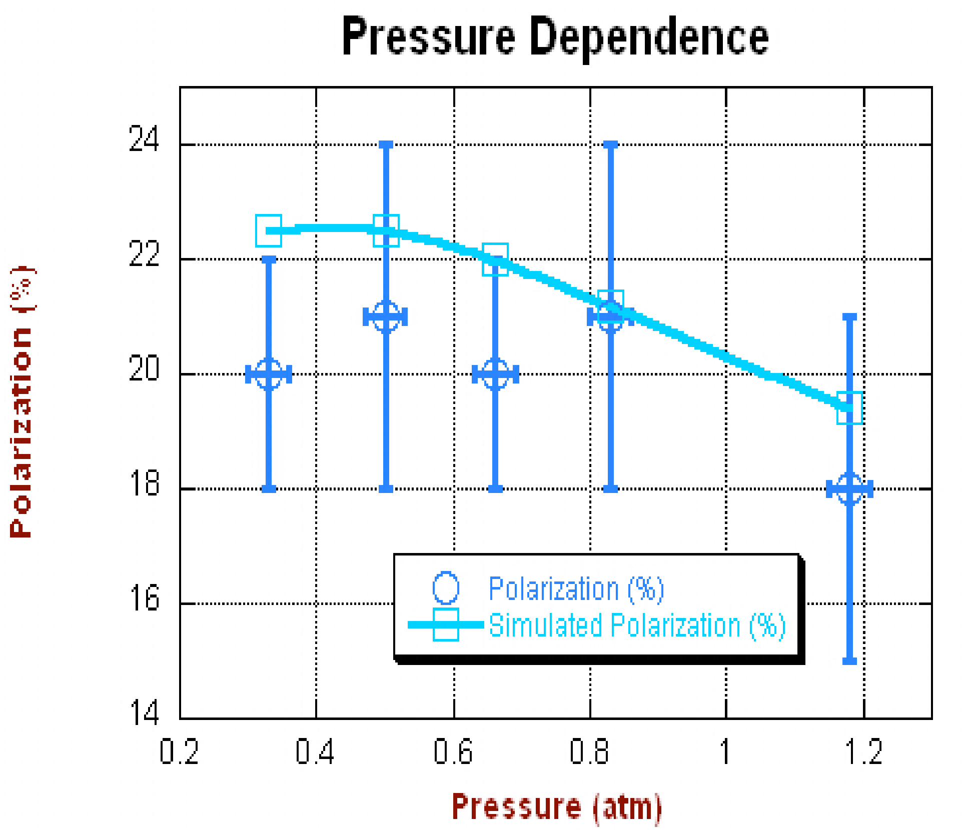
Fitting the Model



Fitting the Model



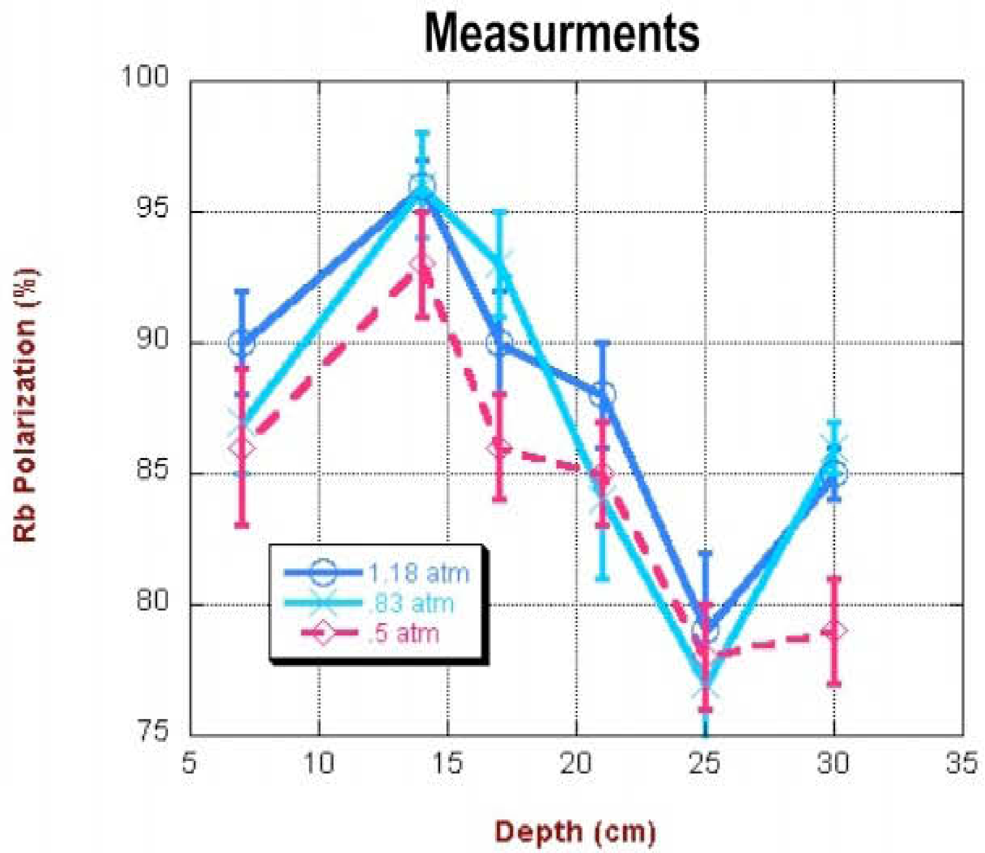
Xe Polarization

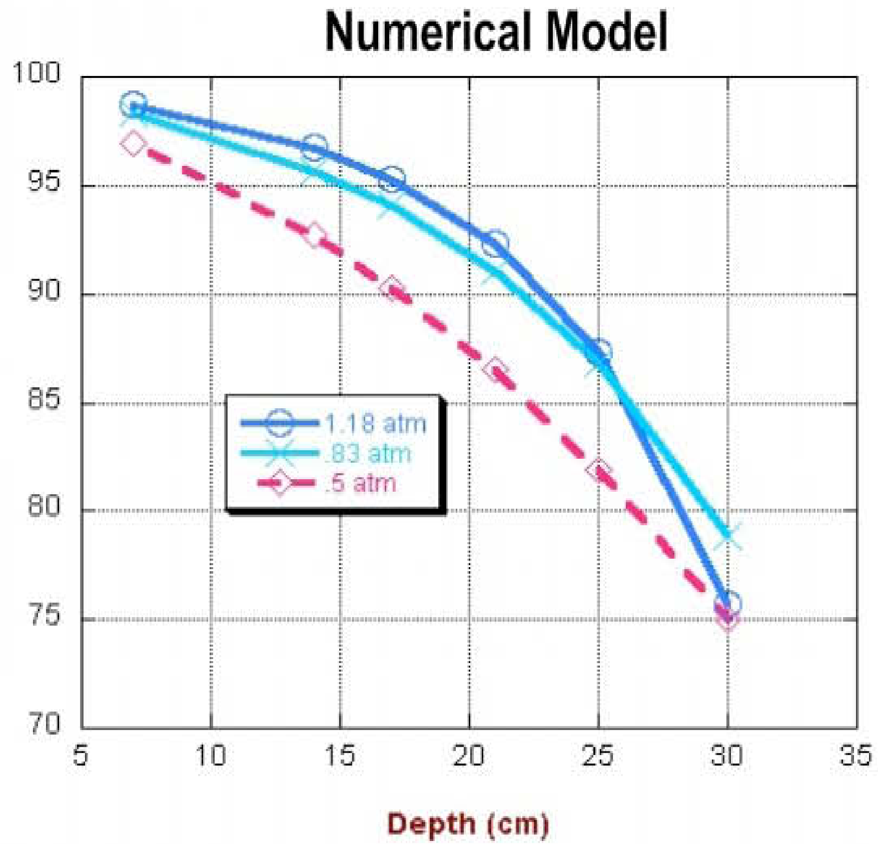


Polarization Decrease at Higher Pressures

Rb Polarization

Pressure Dependence

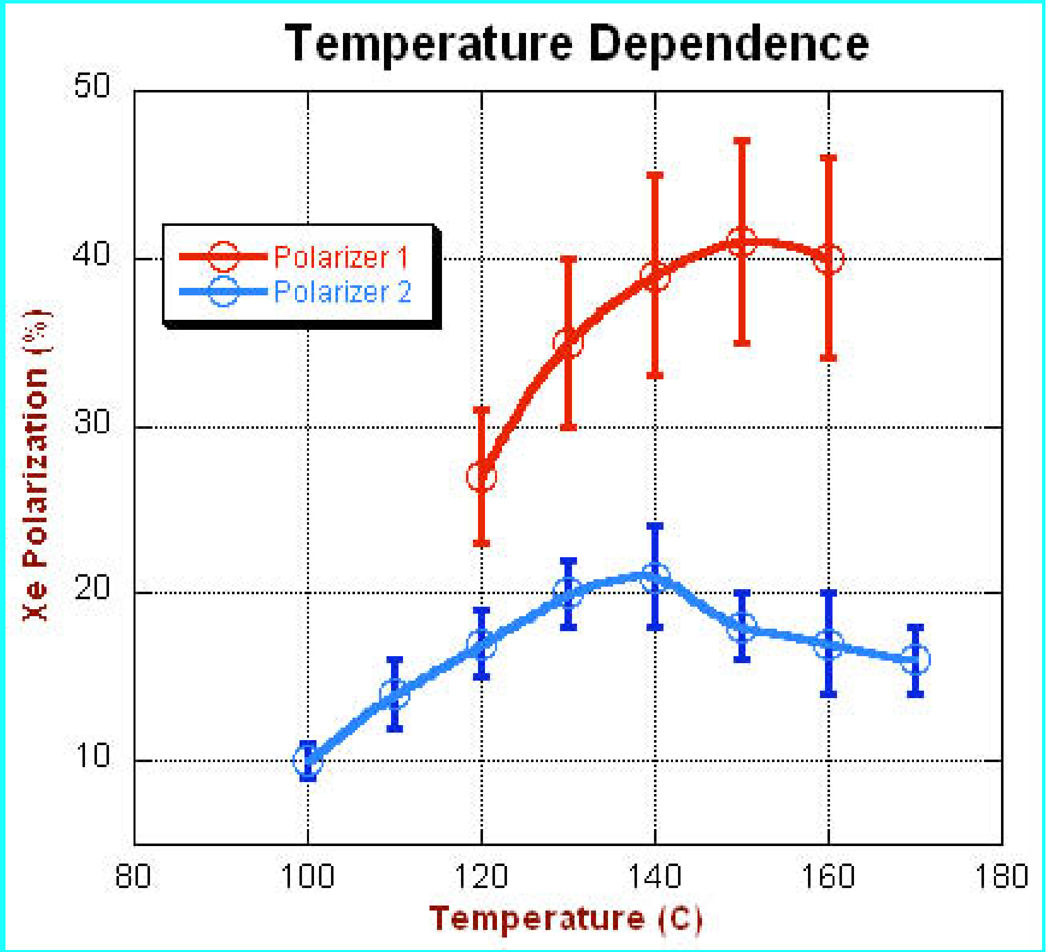




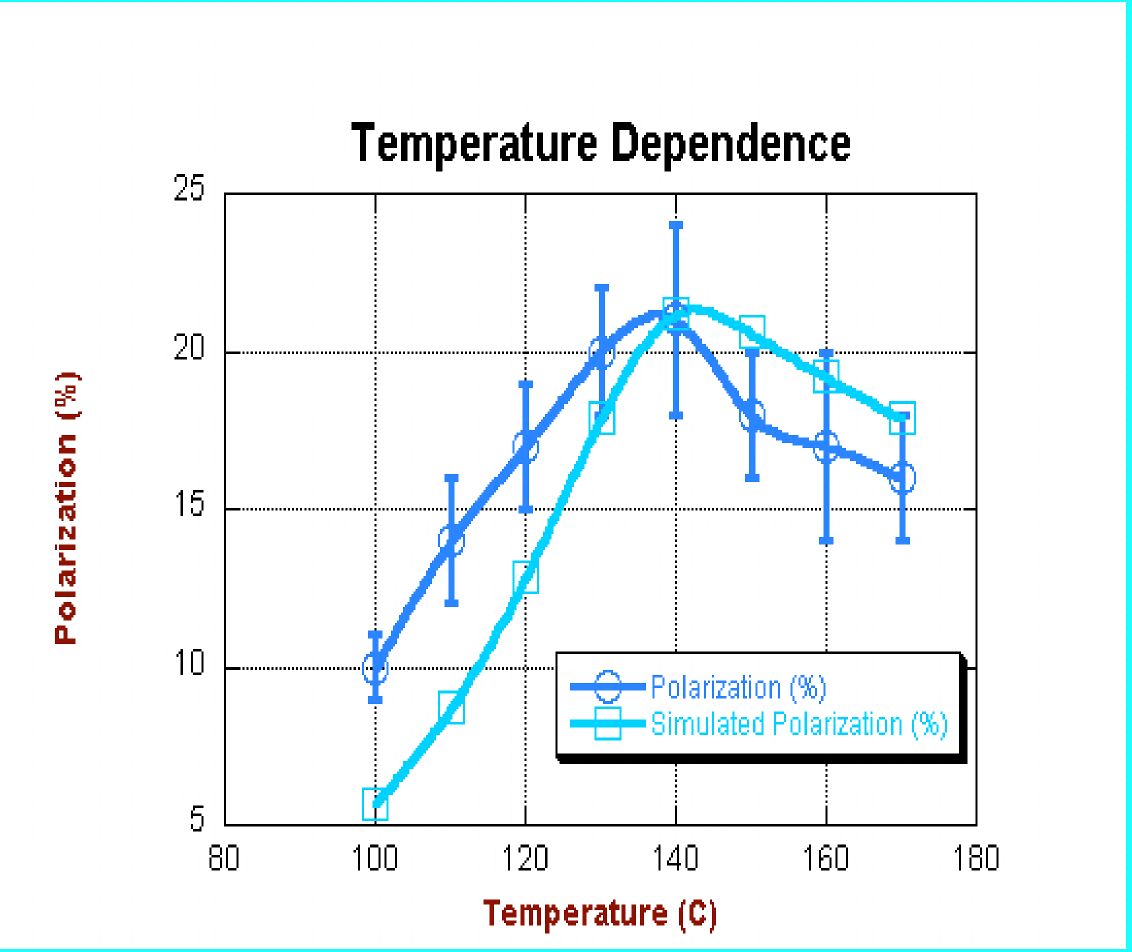
Xe Polarization

Higher Laser Power Generates Higher Polarizations

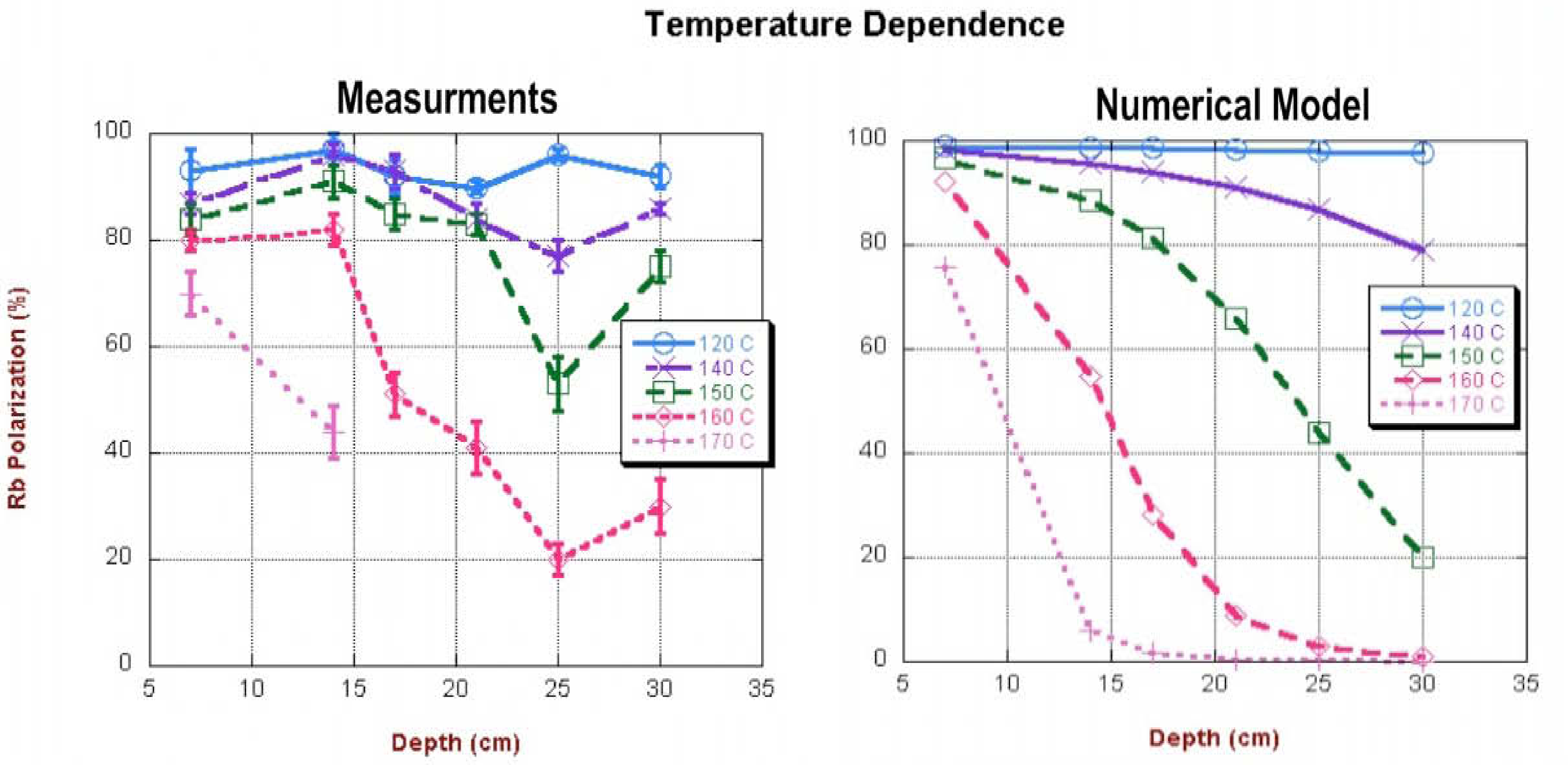
Higher Laser Power Moves Maximum



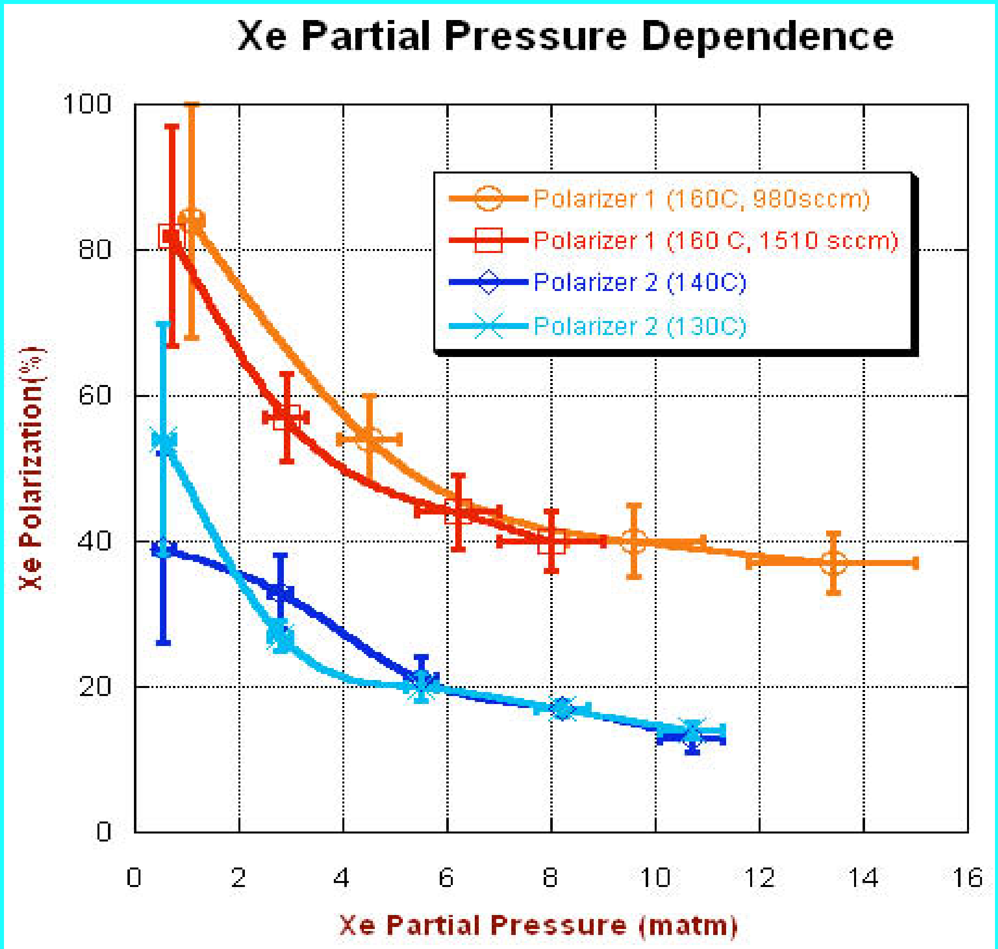
Xe Polarization Compared to Simulation



Rb Polarization



Xe Polarization

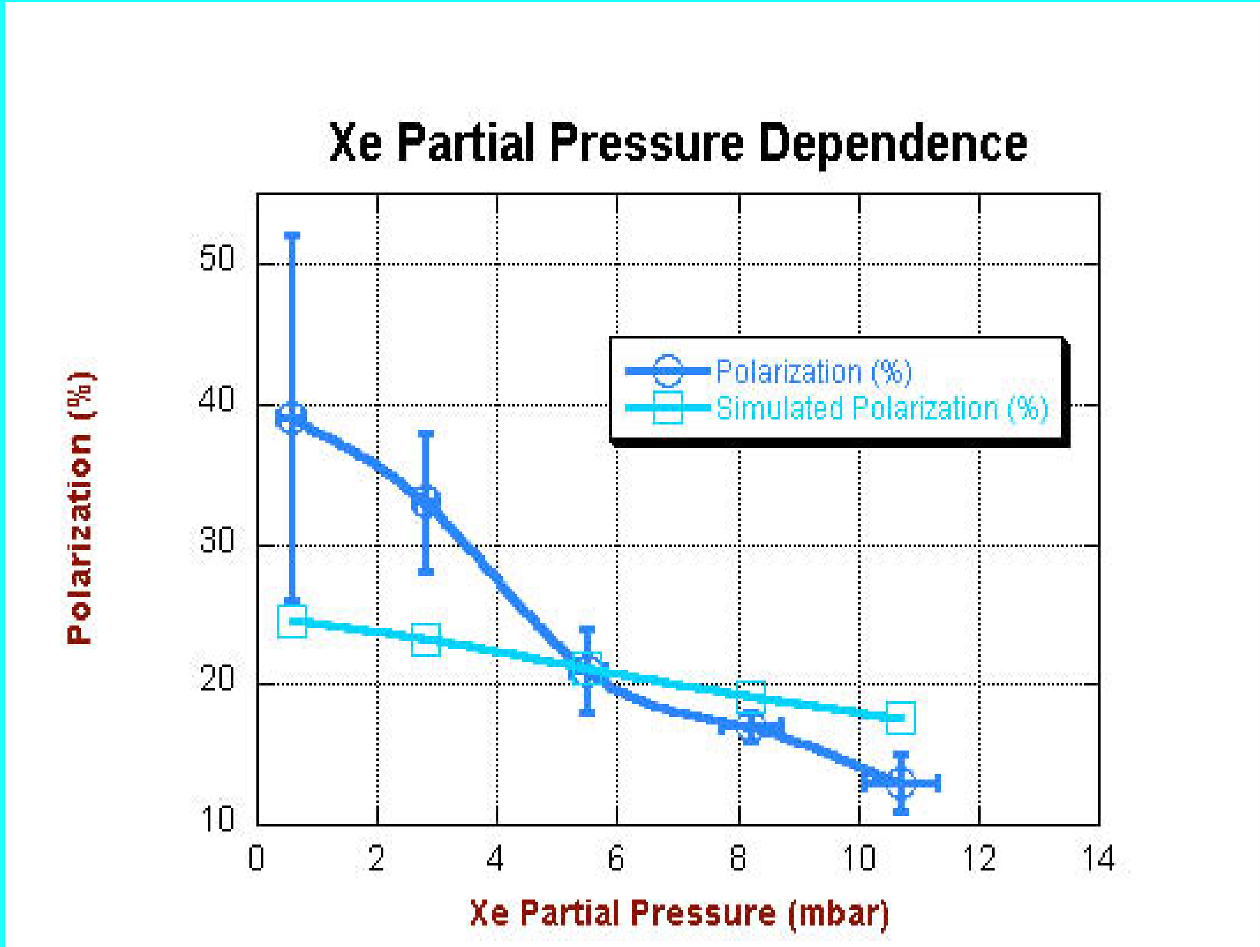


Higher Laser Power Generates Higher Polarization

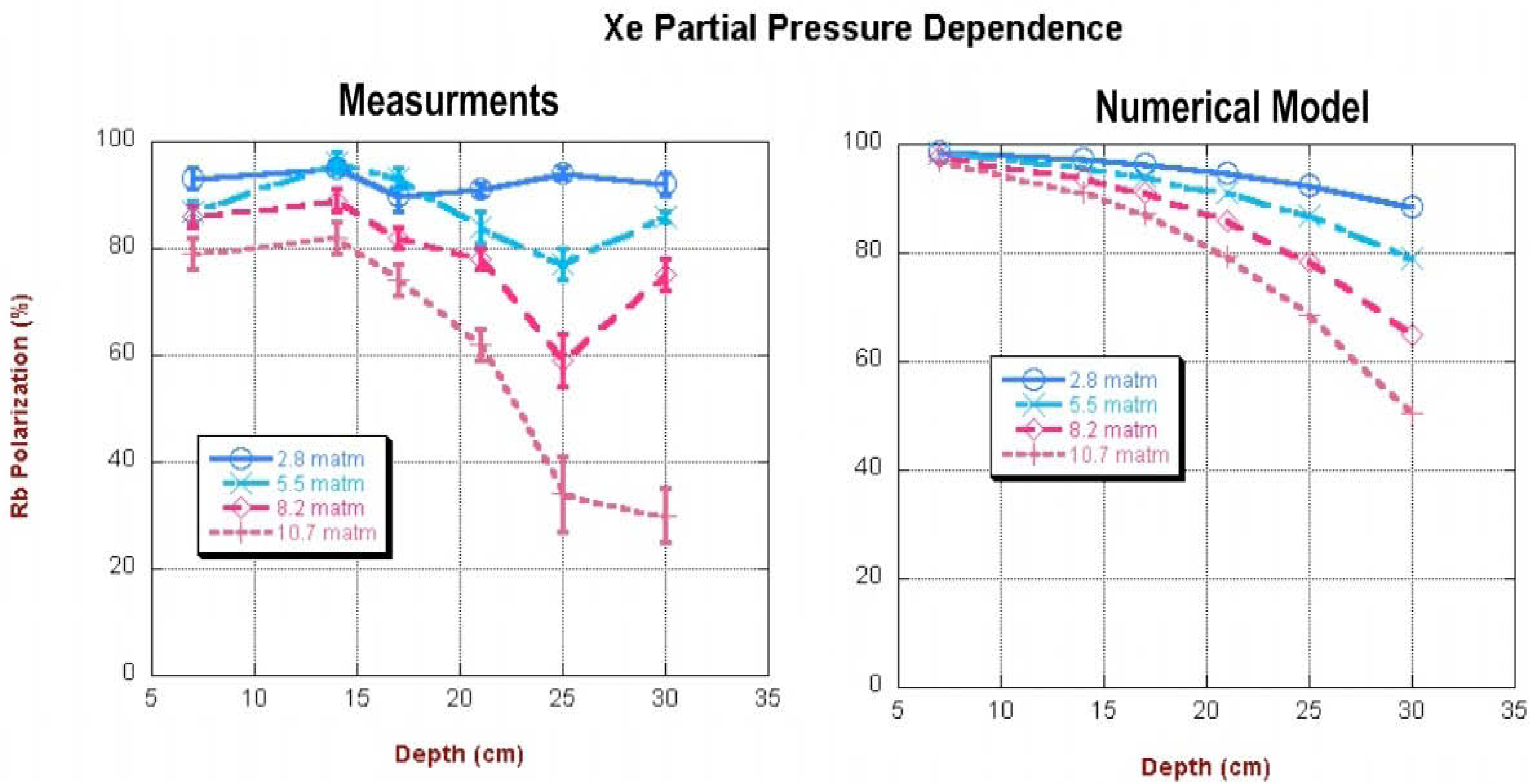
Lower Xe Concentration Gives Rise to Larger Polarizations

Xe Polarization Compared to Simulation

Model Qualitatively Predicts Dependence

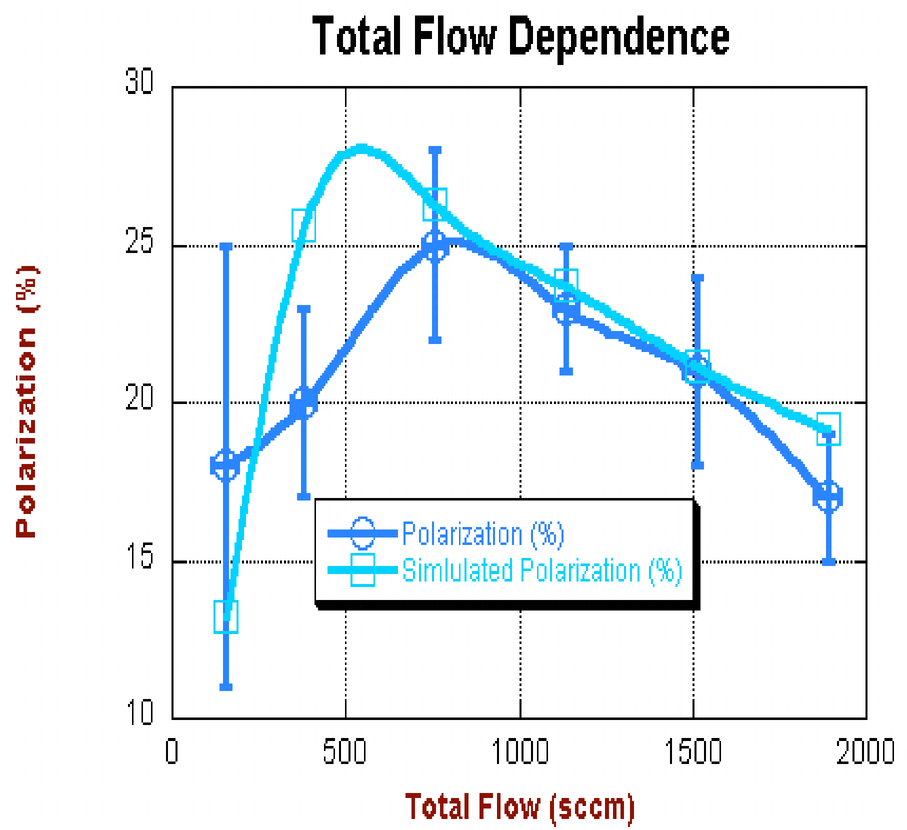


Rb Polarization

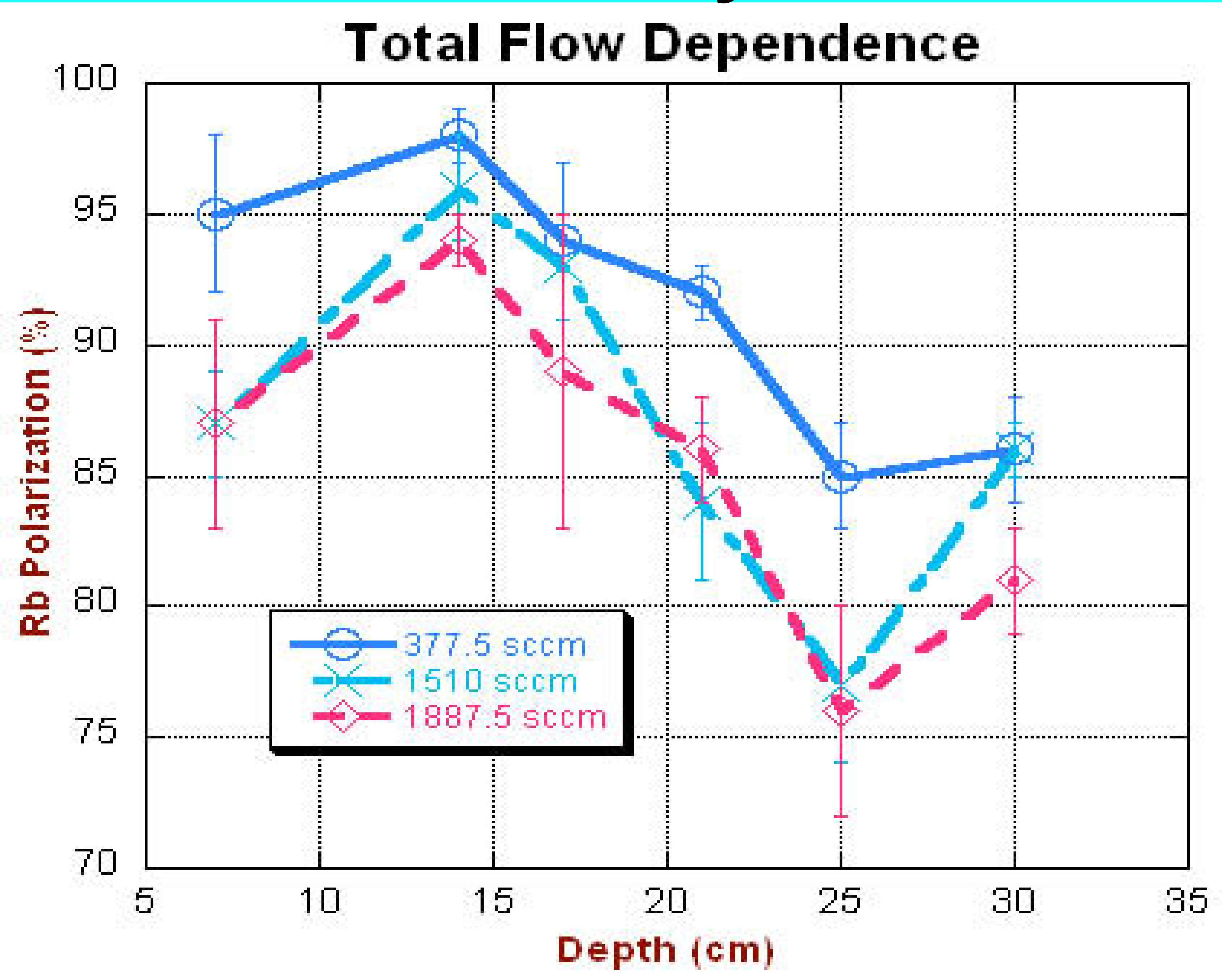


Xe Polarization

Total Flow Maximum Due to competition between resident time in cell and wall relaxation



Rb Polarimetry Results



Comparing Numerical Model with Data Reveals Inadequacies in Our Understanding

- Temperature Data Indicates Different [Rb] than Calculated
  - Requires Direct [Rb] Measurement
- [Xe] Data Xe-Rb Spin Destruction Term Indicates Complicated Dependence
- Total Flow Data Suggested Complex Fluid Dynamics

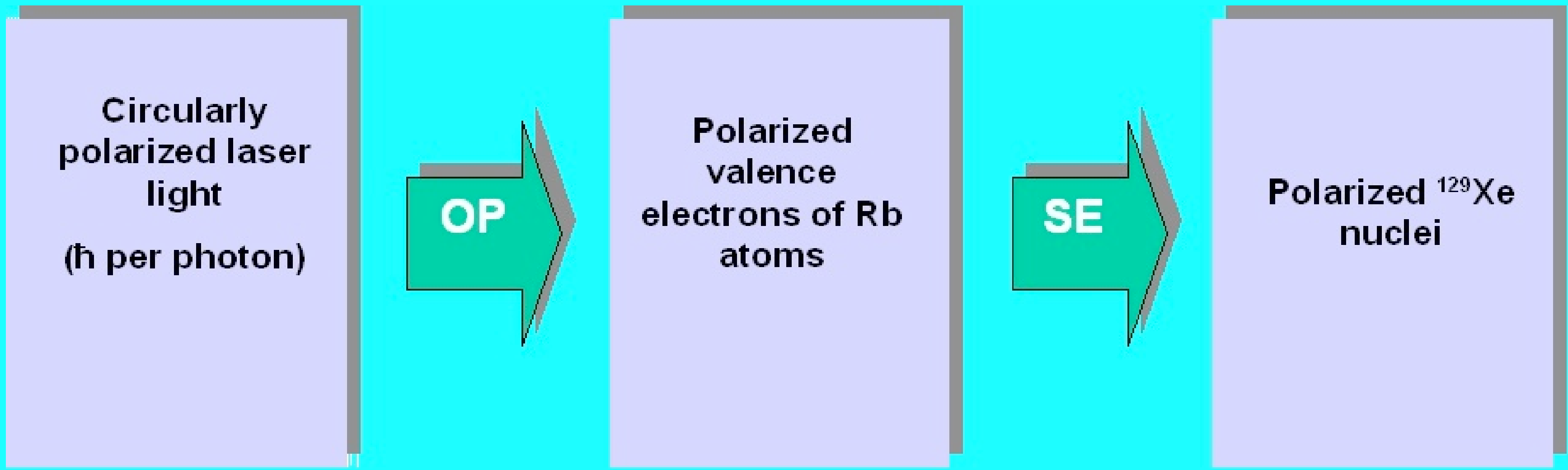
Summary and the Future

- Presented State-of-the-Art ^{129}Xe Flow-Through Polarizer
- Basic Theoretical Understanding
  - Can Explain Most Phenomenon in terms of simple ideas
  - Temperature Dependence of Spin-Exchange Rate is Important
- Measurements to Better Understand Inadequacies
  - Determine Rb Number Density
  - 2D Image Rb Polarization
  - In situ Xe Polarization Profile
- Improve Model
  - Extend Dimensionality
  - Write Fitting Routine

Thanks to:

- Brian Saam
- Zayd Ma
- Allison Schoeck
- Eric Sorte & Gernot Laicher
- Kimberly Butler & Liz Dupont
- Li-Qiong Wang

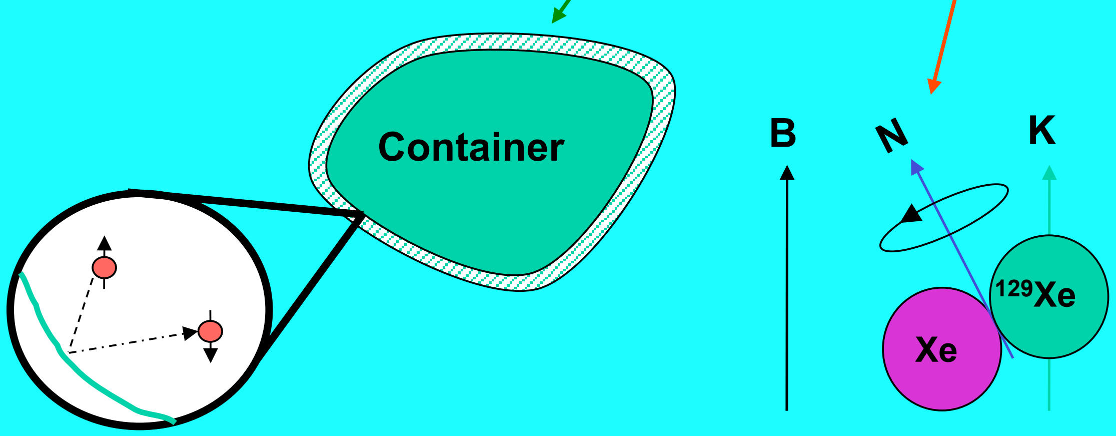
The SEOP Process



Relaxation Processes Limit Polarization

Xe Relaxation

$$\frac{1}{T_1} = \Gamma_{wall} + \Gamma_{bulk}$$

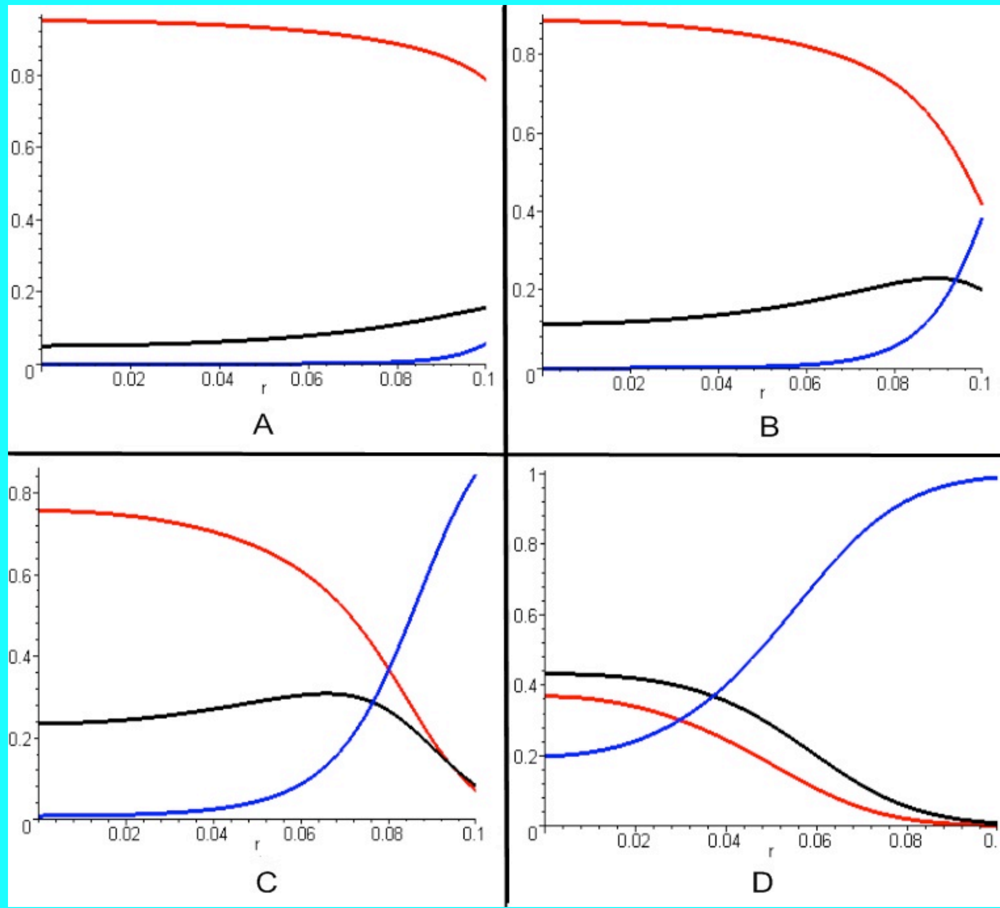


Intrinsic Relaxation:
Binary and Molecular Interactions

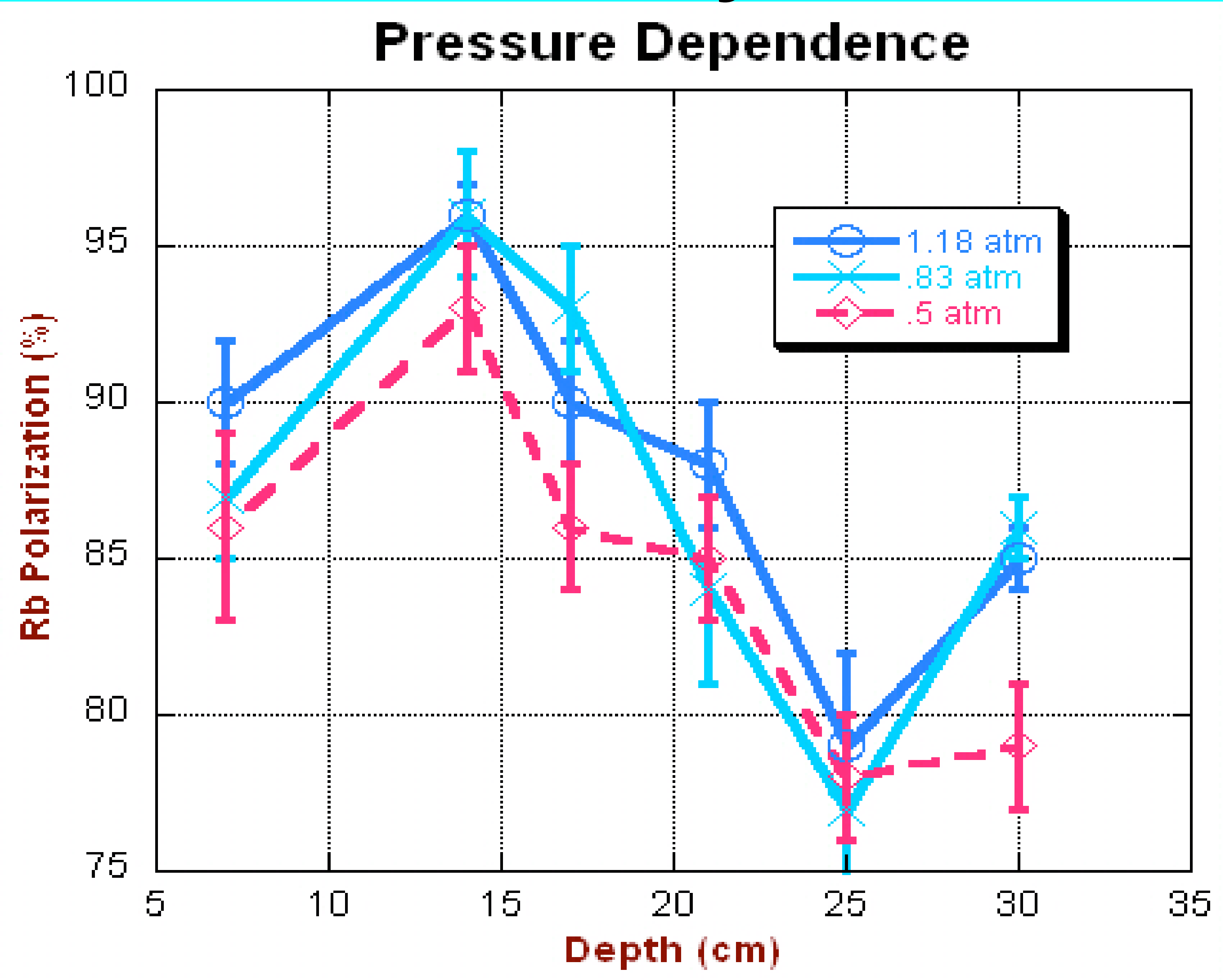
Extrinsic Relaxation:
Walls and Magnetic Field Gradients

Gas Phase Storage and Separation?

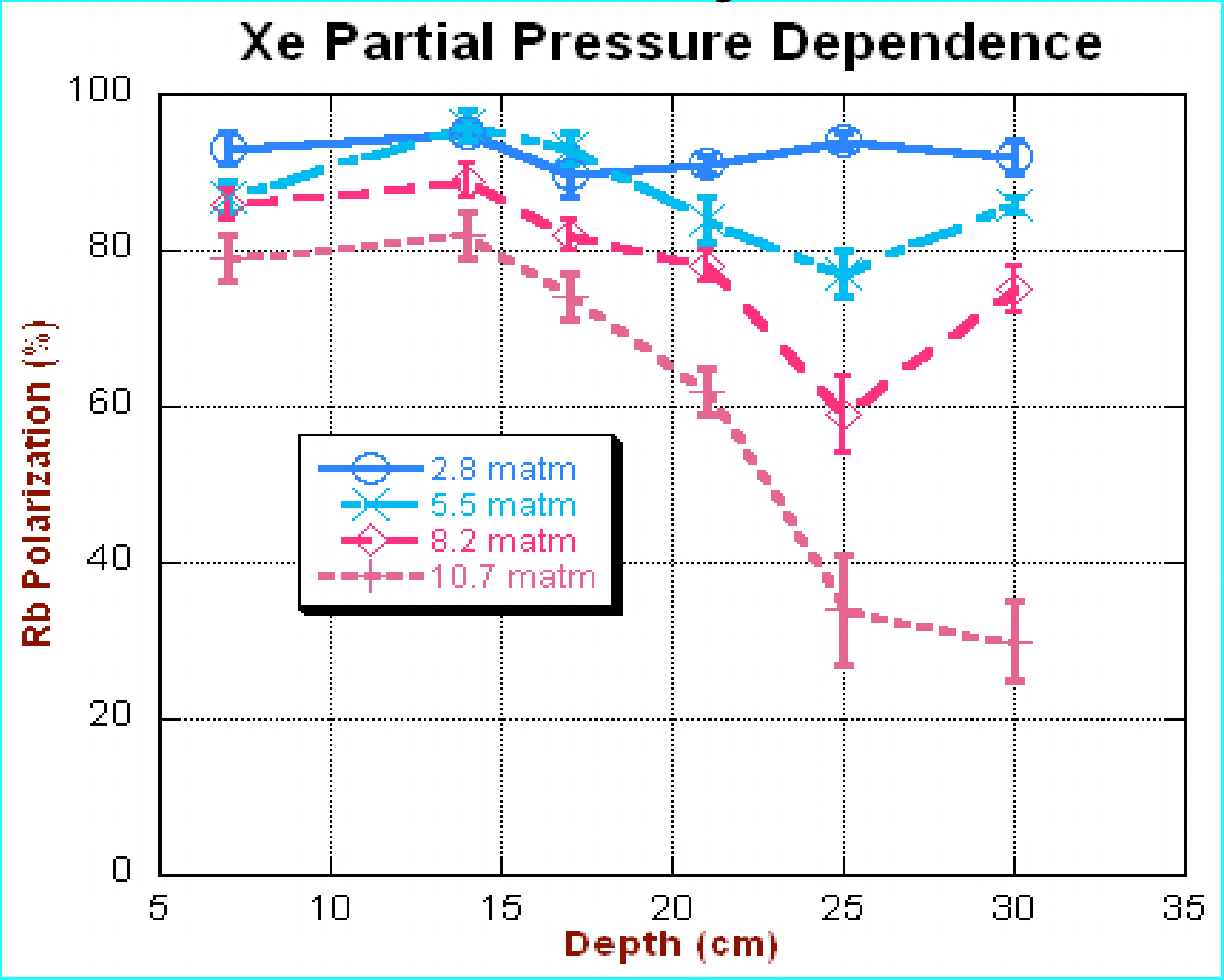
- Cryogenic Storage and Separation
  - 2.5 hr Relaxation Time @ 77 K & 2000 G
- Gas Phase Storage
  - 5 hr Relaxation Time @ 30 G & Rm Temp.
- Gas Phase Separation
  - Gas Centrifuge



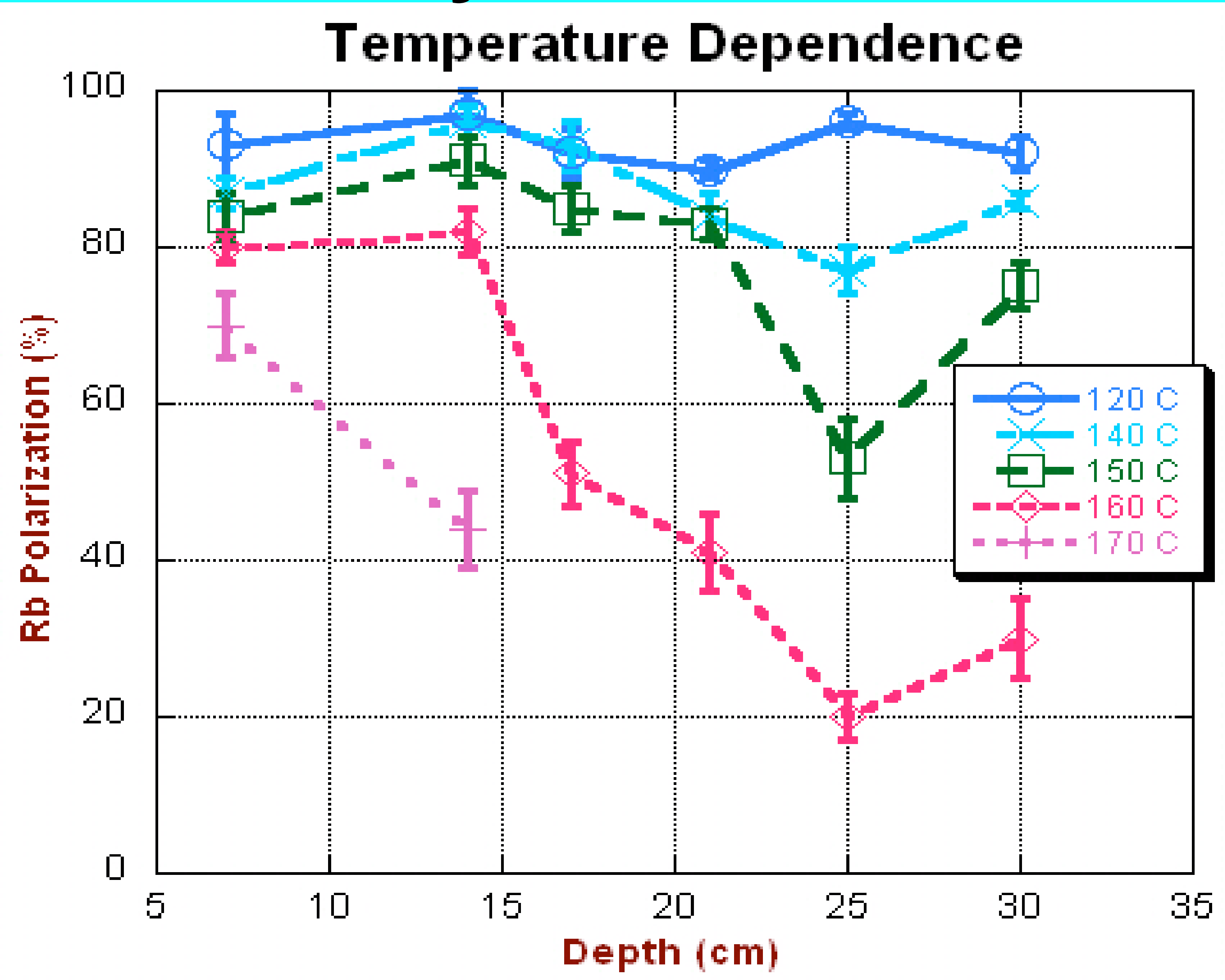
Rb Polarimetry Results



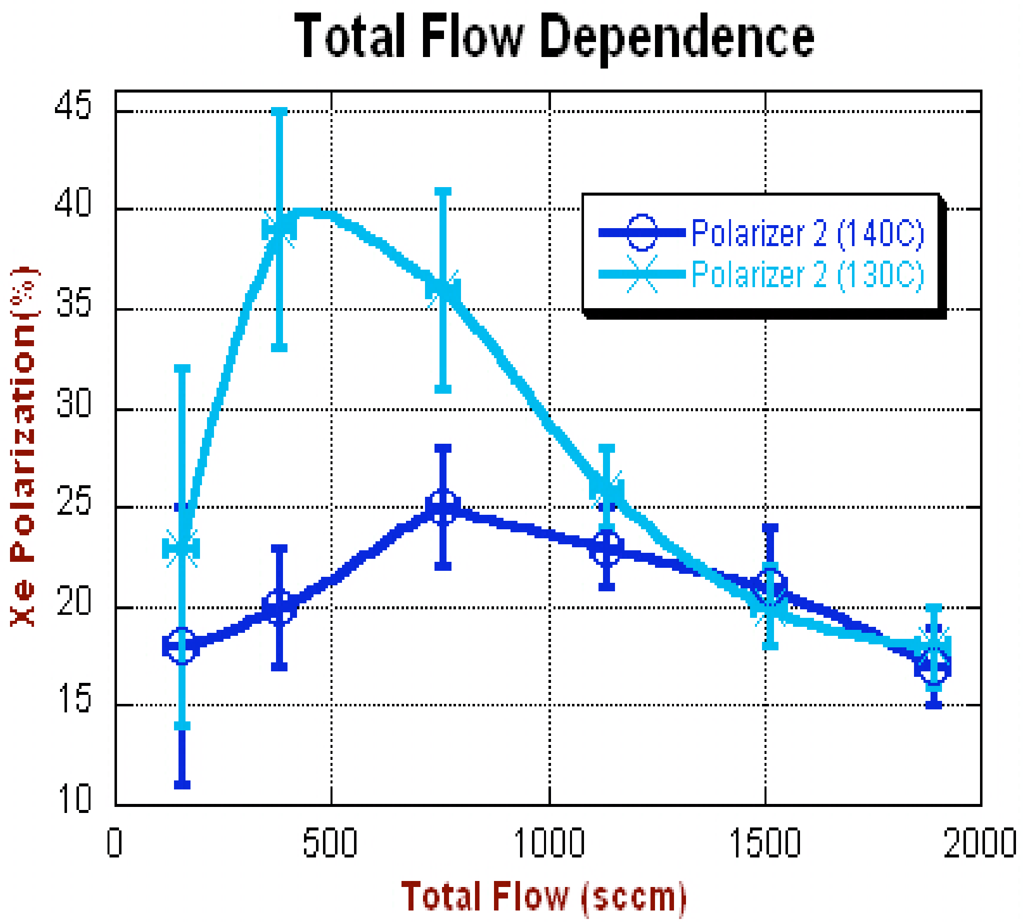
Rb Polarimetry Results

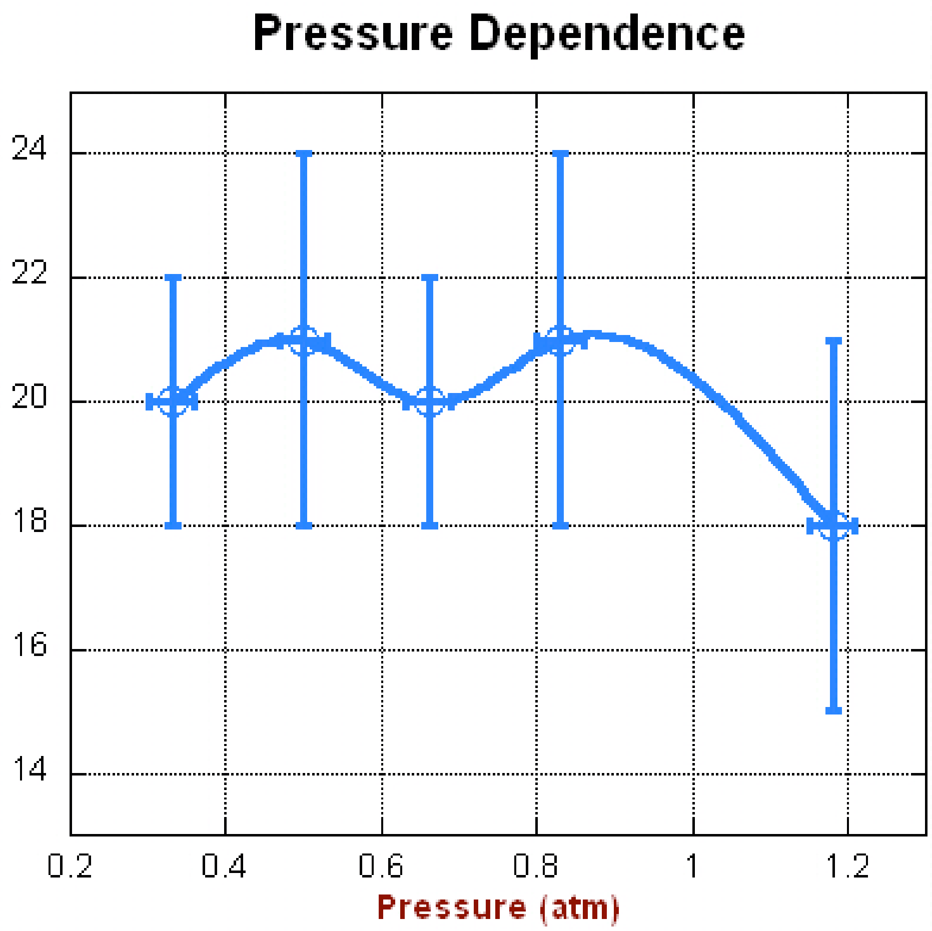


Rb Polarimetry Results

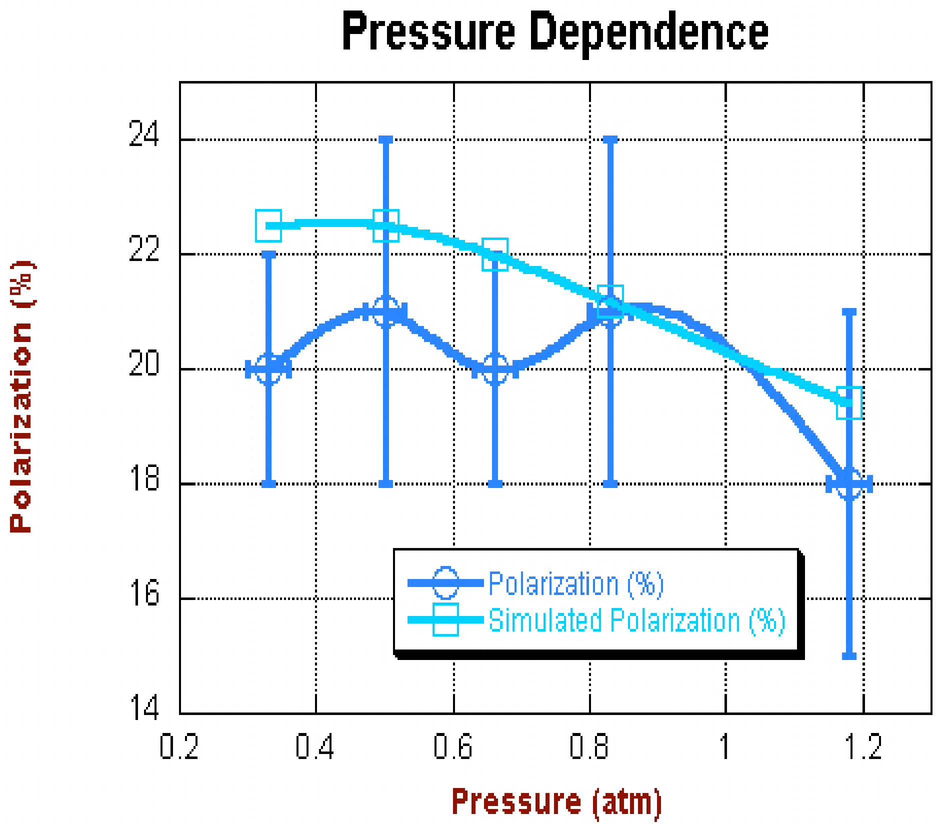


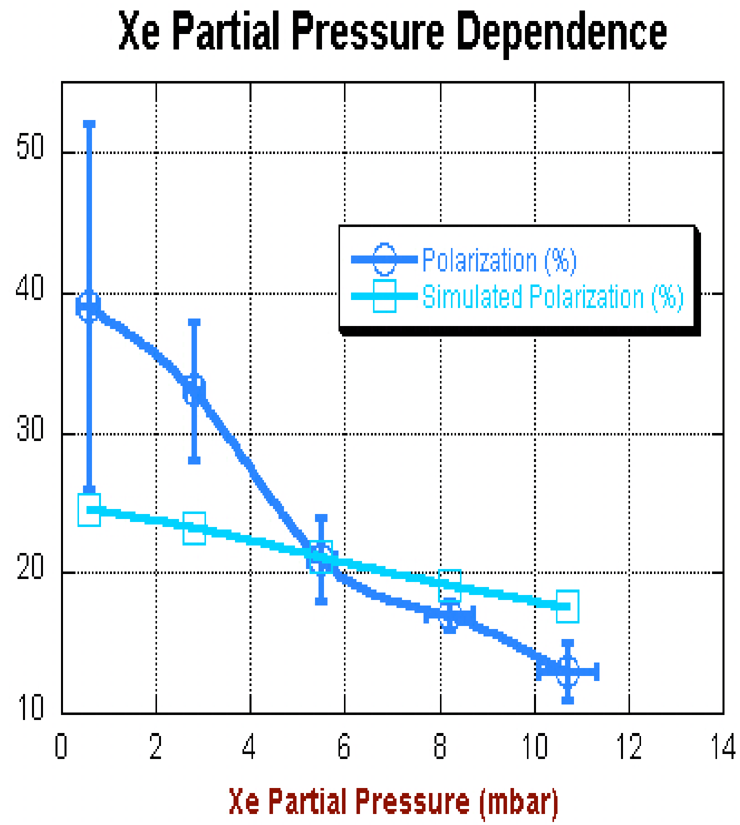
U of U Flow-Through Polarizer Performance





Numerical Results





Numerical Results