Differential Phase Shift Spectroscopy in a Thallium Atomic Beam

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Joseph Kerckhoff '05
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Williams College

Poster WI.50 tomorrow for more details

postdoc available!

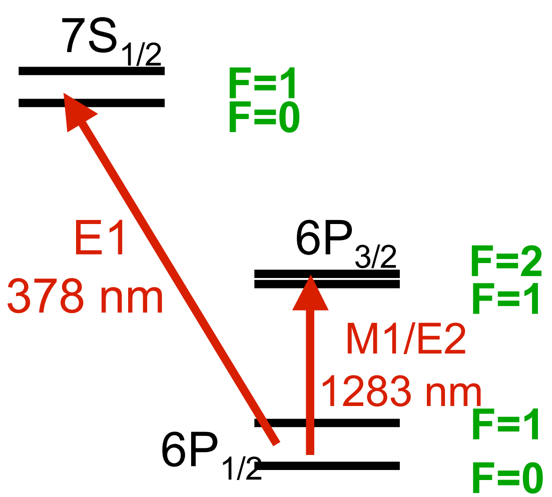
Support from:
NSF-RUI program
National Institute of Standards and Technology
Williams College

High-precision atomic structure measurements:

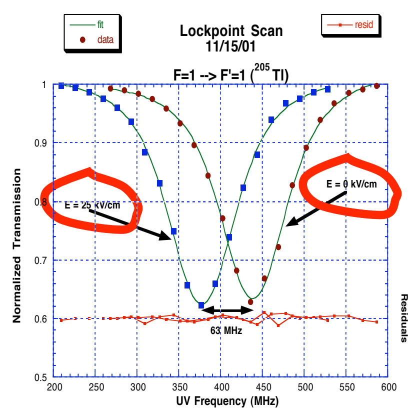
Thallium - test *ab initio* theory calculations
essential for PNC-based electroweak tests

techniques generally useful for diode laser
spectroscopy of weak atomic transitions

Example: 0.5% Atomic beam measurement of the Stark Shift in the thallium $6P_{1/2}$ - $7S_{1/2}$ 378 nm transition



Thallium (203, 205)



"Polarizability":

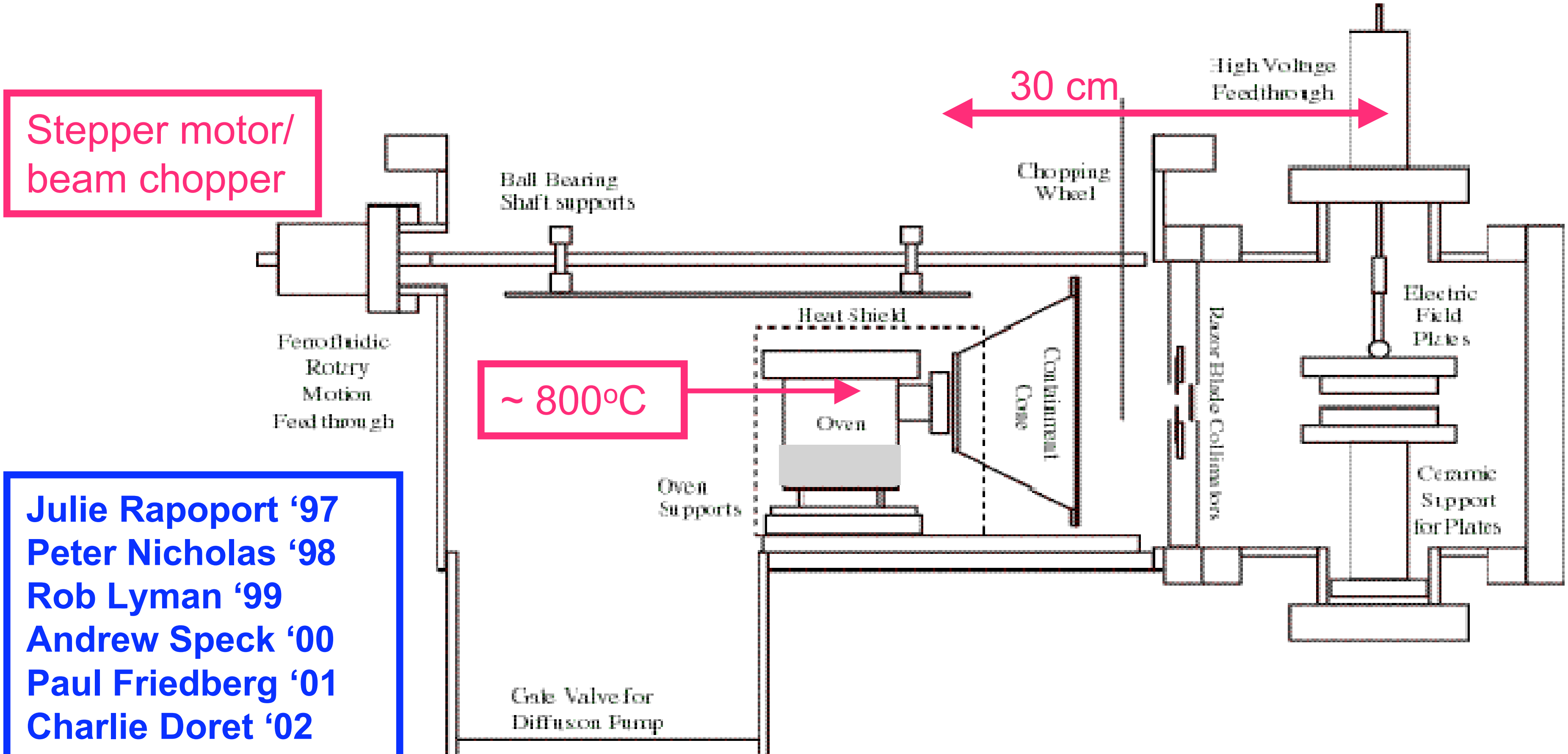
$\alpha_{7S1/2} - \alpha_{6P1/2} = 830(3)\ a_0^3$

[Doret *et al.*, PRA **66**, 52504 (2002)]

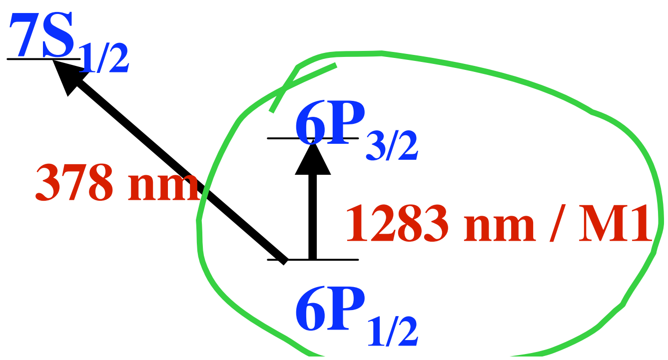
New *ab initio* Tl wavefunctions [Safronova, et al. 2006] ⟶

$\alpha_{7S1/2} - \alpha_{6P1/2} = 830\ a_0^3$!!

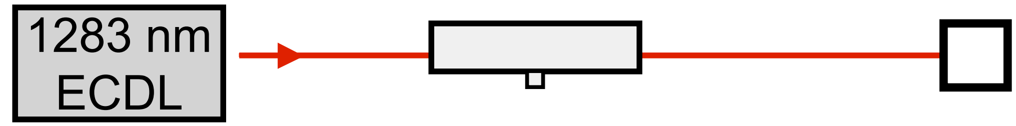
Thallium Atomic Beamline

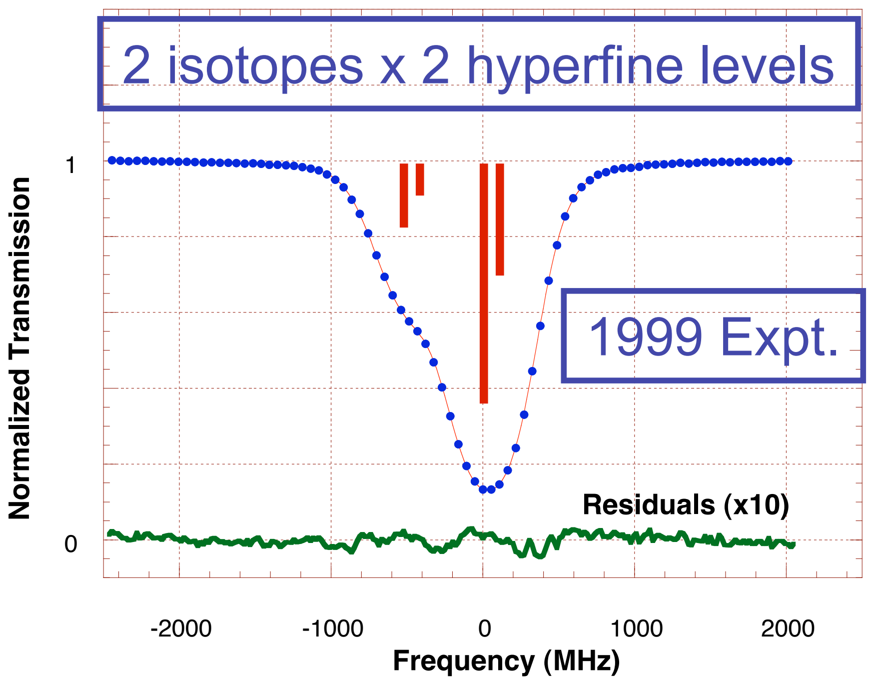


Julie Rapoport ‘97
Peter Nicholas ‘98
Rob Lyman ‘99
Andrew Speck ‘00
Paul Friedberg ‘01
Charlie Doret ‘02
Chris Holmes ‘03
Mark Burkhardt ‘04
Colin Bruzewicz ‘05
Joe Kerckhoff ‘05



Vapor cell spectroscopy @ 900 ^{o}C



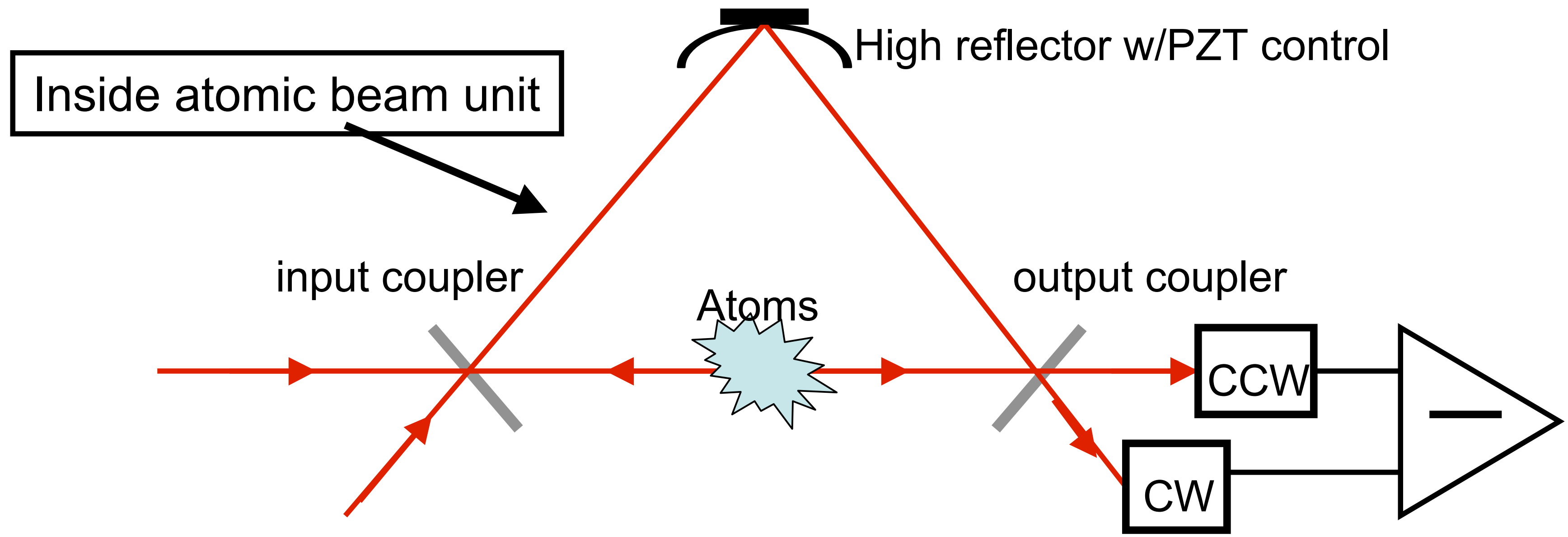


Huge number density
by heating cell, but….

- Can't apply E-field
- Unresolved structure
  (Doppler broadening)

Atomic beam apparatus affords clean, controlled,
spectrally-resolved laser/atom interaction
(at expense of much-reduced density -- OD ~ 10^{-5})

"Ring-Cavity / Differential Phase Shift Technique"



- Lock cavity - high sensitivity to small optical phase shifts
  due to high finesse

- Separate CW, CCW beam detection allows
  differential measurement, common-mode noise rejection

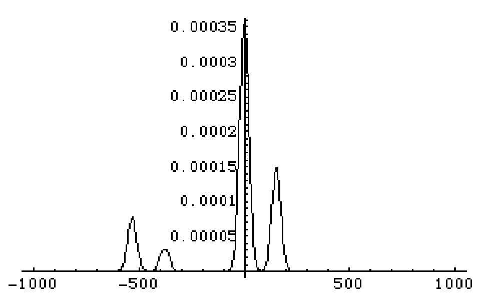
Atom-induced Index of Refraction -

$$\boxed{\mathbf{n}(\nu) \sim \Sigma\, |\langle f|V|I\rangle|^2 \;\Big/\; [\,(\nu-\nu_0) + i\Gamma/4\pi\,]}$$

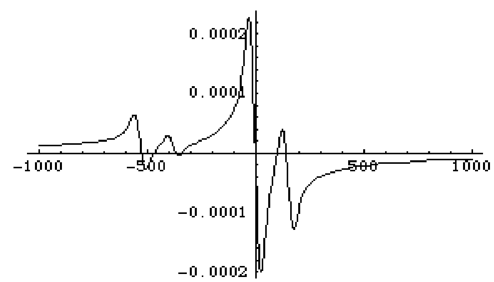
- Atoms cause both absorption and optical phase shifts
- Real, imaginary parts of '$\mathbf{n}(\nu)$' related in well-known way
- Experimentally scaled by measured 'optical depth'

Realistic Atomic Beam spectrum for 1283 nm (F=1 ➜ F'=1,2):

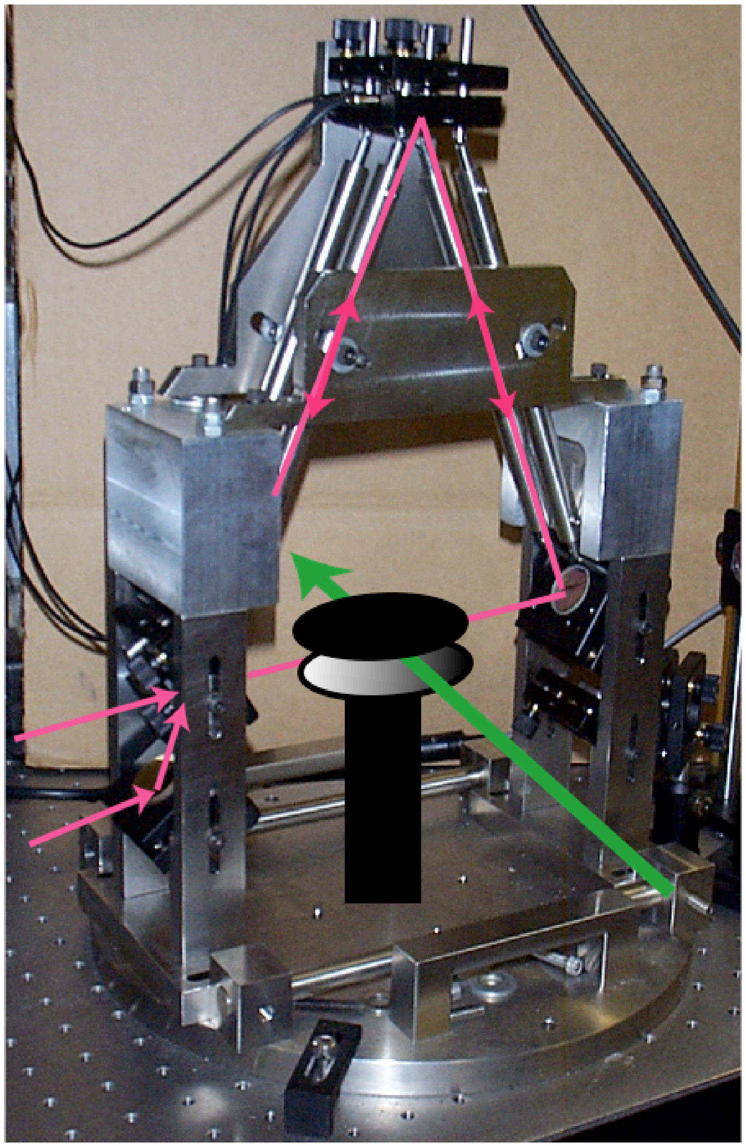
A(ν) looks like:



ϕ(ν) looks like:



The first-generation 3-mirror ring cavity



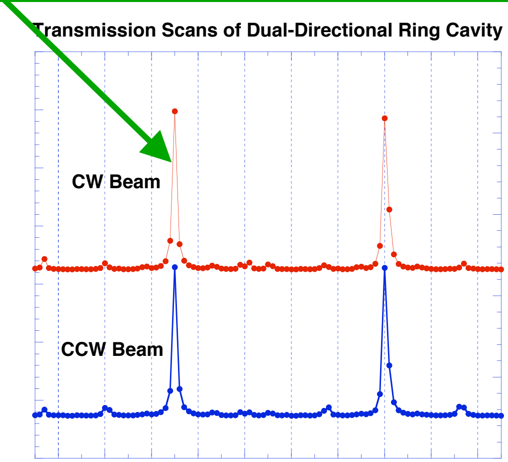
- Finesse ~ 70
- FSR = 440 MHz

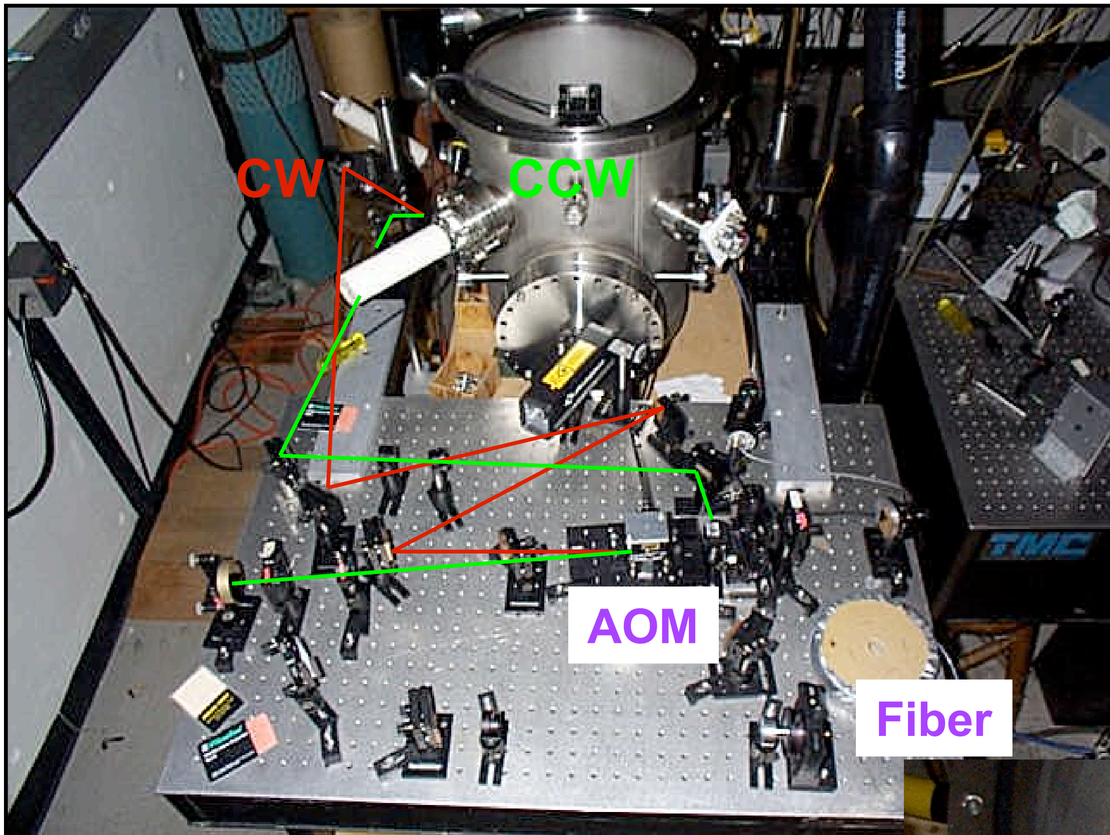
- Introduce relative freq. shift via double-passed AOM @ 220 MHz

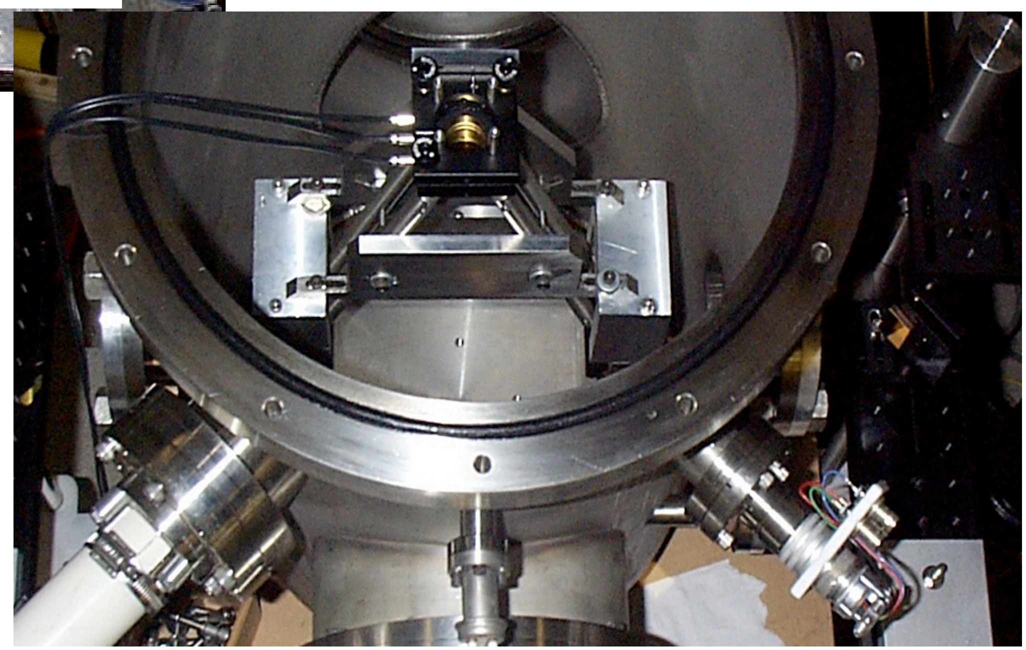
- Cavity doesn't care about frequency shift,

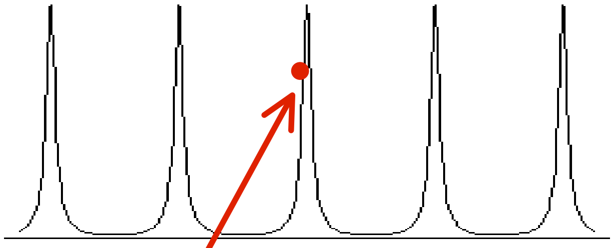
  BUT ATOMS DO …

This beam shifted by exactly one F.S.R.




CW
CCW
AOM
Fiber



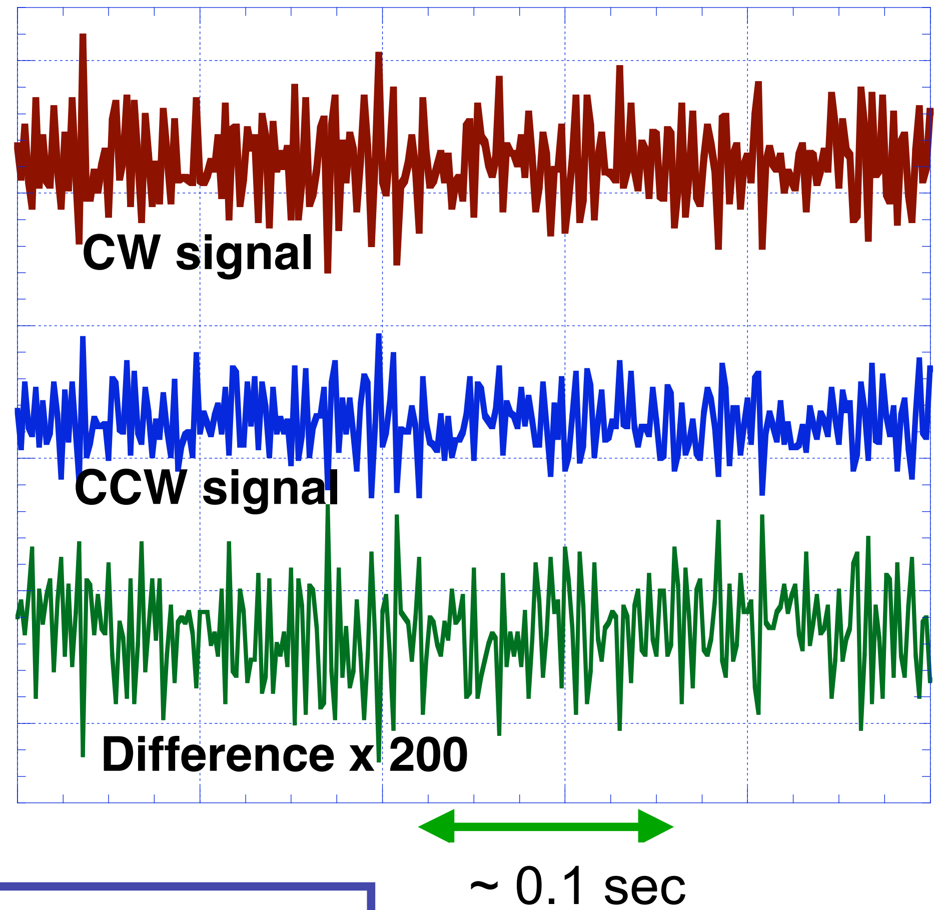


- LOCK one cavity signal to inflection point of F-P fringe

- Tune AOM, adjust differential amplifier to subtract optimally here

- Independently, lock laser to this ‘forbidden’ transition…. [See **poster**, recent pub. ⇐]

Dual directional ring cavity transmission
Cavity locked to CCW transmission signal



REVIEW OF SCIENTIFIC INSTRUMENTS 76, 093108 (2005)

A frequency stabilization method for diode lasers utilizing low-field Faraday polarimetry

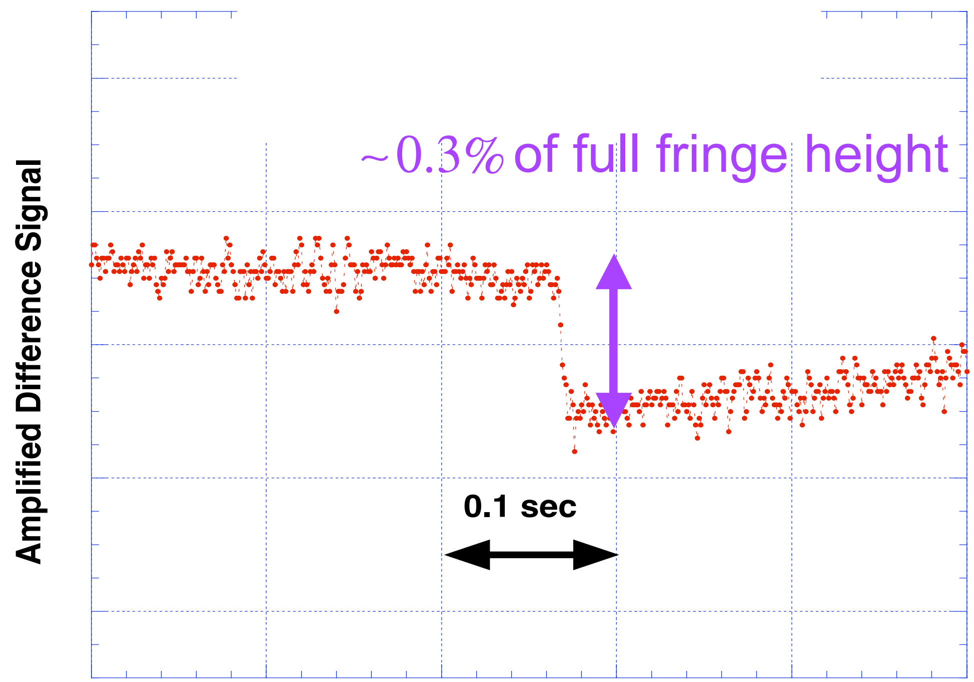
J. A. Kerckhoff, C. D. Bruzewicz, R. Uhl,[a] and P. K. Majumder
Physics Department, Williams College, Williamstown, Massachusetts 01267

Explore differential phase shift resolution using AOM

20 kHz step to AOM-shifted beam $\vee$ $\Delta\phi \approx 3 \times 10^{-4}$ rad
Study differential cavity transmission signal

Differential phase resolution limit:

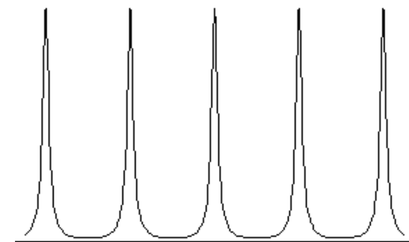
$\phi_{noise} \approx 5 \times 10^{-6}$ rad/$\sqrt{\text{Hz}}$



[Lock to both sides of FP fringe to insure true phase shift vs. amplitude change]

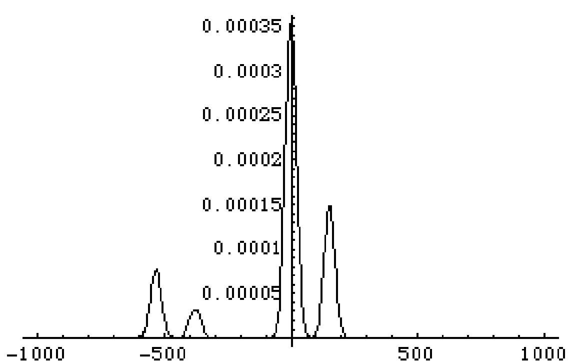
- **Mathematica**…simulation generates Airy functions
- Includes **atoms** as additional (known) frequency-dependent complex ‘cavity element’

$$\mathrm{T}_{\mathrm{CCW}}(\delta,\nu)=\frac{(1-r)^2}{\left(1-r\sqrt{1-A(\nu)}\right)^2}*\frac{I_0}{1+\dfrac{4r\sqrt{1-A(\nu)}}{\left(1-r\sqrt{1-A(\nu)}\right)^2}\mathrm{Sin}[\delta+\phi(\nu)]^2}$$

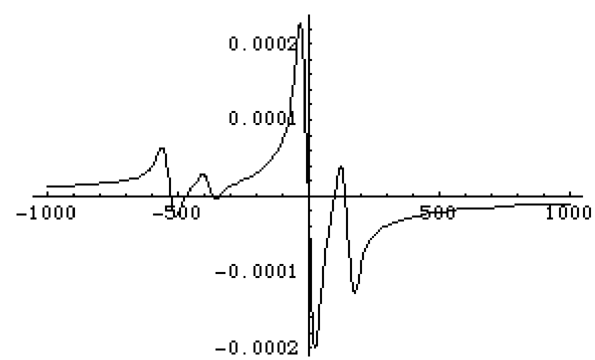


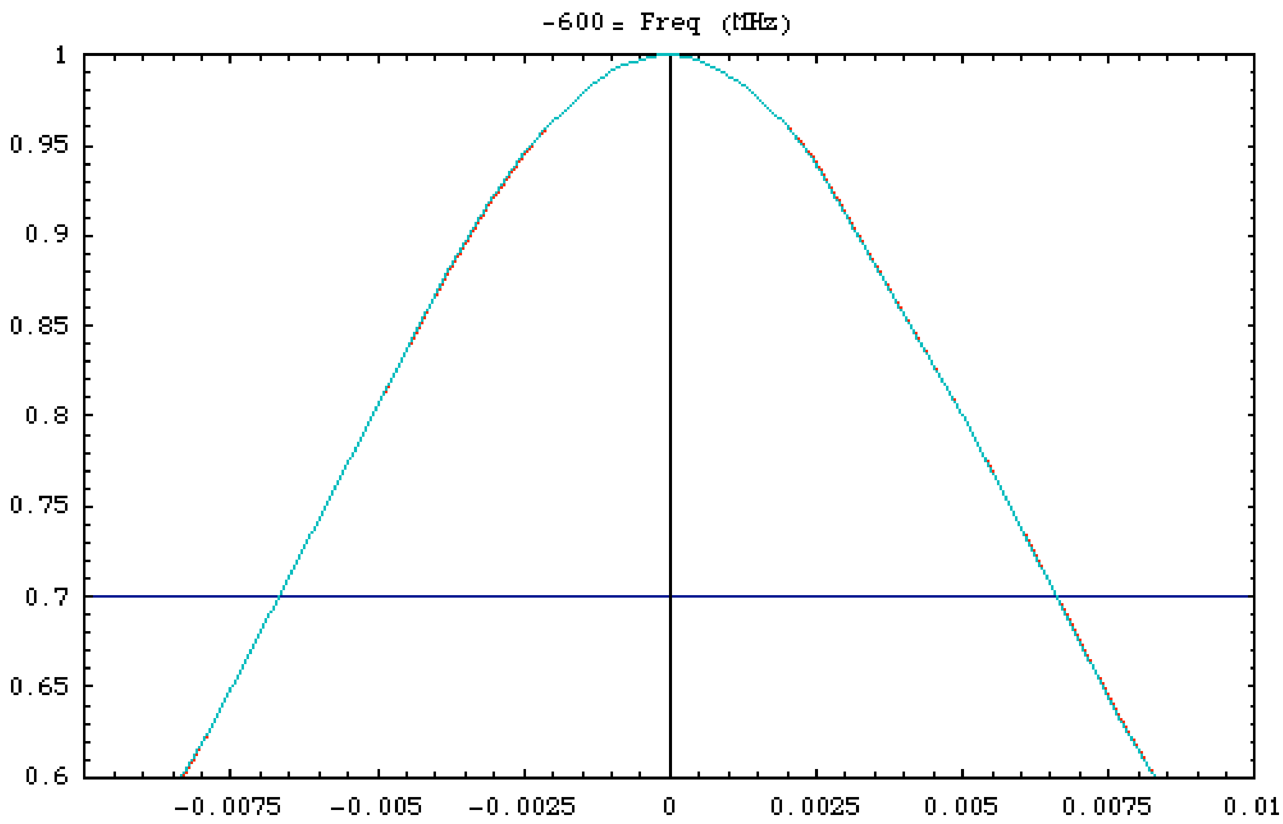
$$\mathrm{T}_{\mathrm{CW}}(\delta,\nu_{\underline{+FSR}})=\frac{(1-r)^2}{\left(1-r\sqrt{1-A(\nu_{\underline{+FSR}})}\right)^2}*\frac{I_0}{1+\dfrac{4r\sqrt{1-A(\nu_{\underline{+FSR}})}}{\left(1-r\sqrt{1-A(\nu_{\underline{+FSR}})}\right)^2}\mathrm{Sin}[\delta+\phi(\nu_{\underline{+FSR}})]^2}$$

A(ν) looks like:



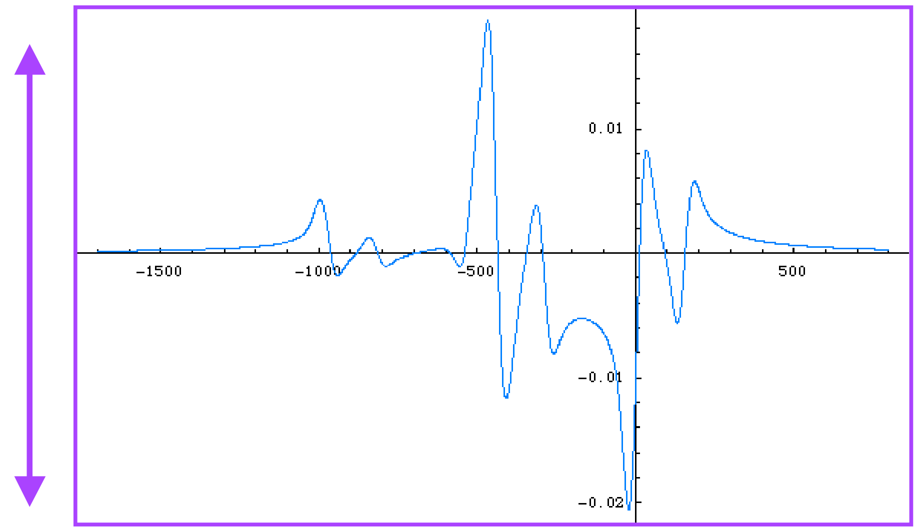
φ(ν) looks like:





<u>Differential Transmission:</u>

Predicts ~2% fractional change in peak height for $OD_{M1} = 1 \times 10^{-4}$

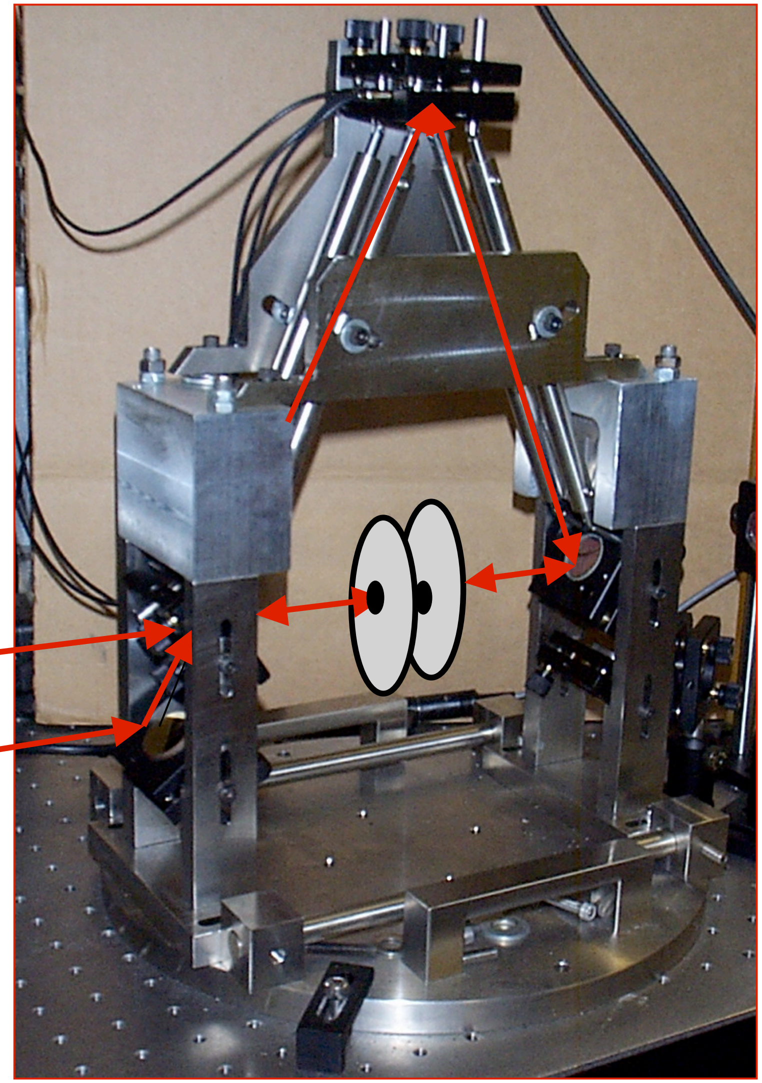


Summarizing…

- Have constructed, tested an in-vacuum ring cavity for differential phase shift spectroscopy
- Predicted lineshape is complicated (good), and has “built-in” frequency calibration via AOM shift
- Given resolution demonstrated, simulation predicts that we can detect absorption down to 1 part in 10^5
- Expected Stark shift @40 KV/cm more than full linewidth in atomic beam (~ 50 MHz)
- Resolution sufficient for sensitive new Time-reversal (T-odd, P-even) symmetry test **using same system**
  - same frequency for both counterpropagating laser beams
  - introduce E-field parallel to laser propagation direction

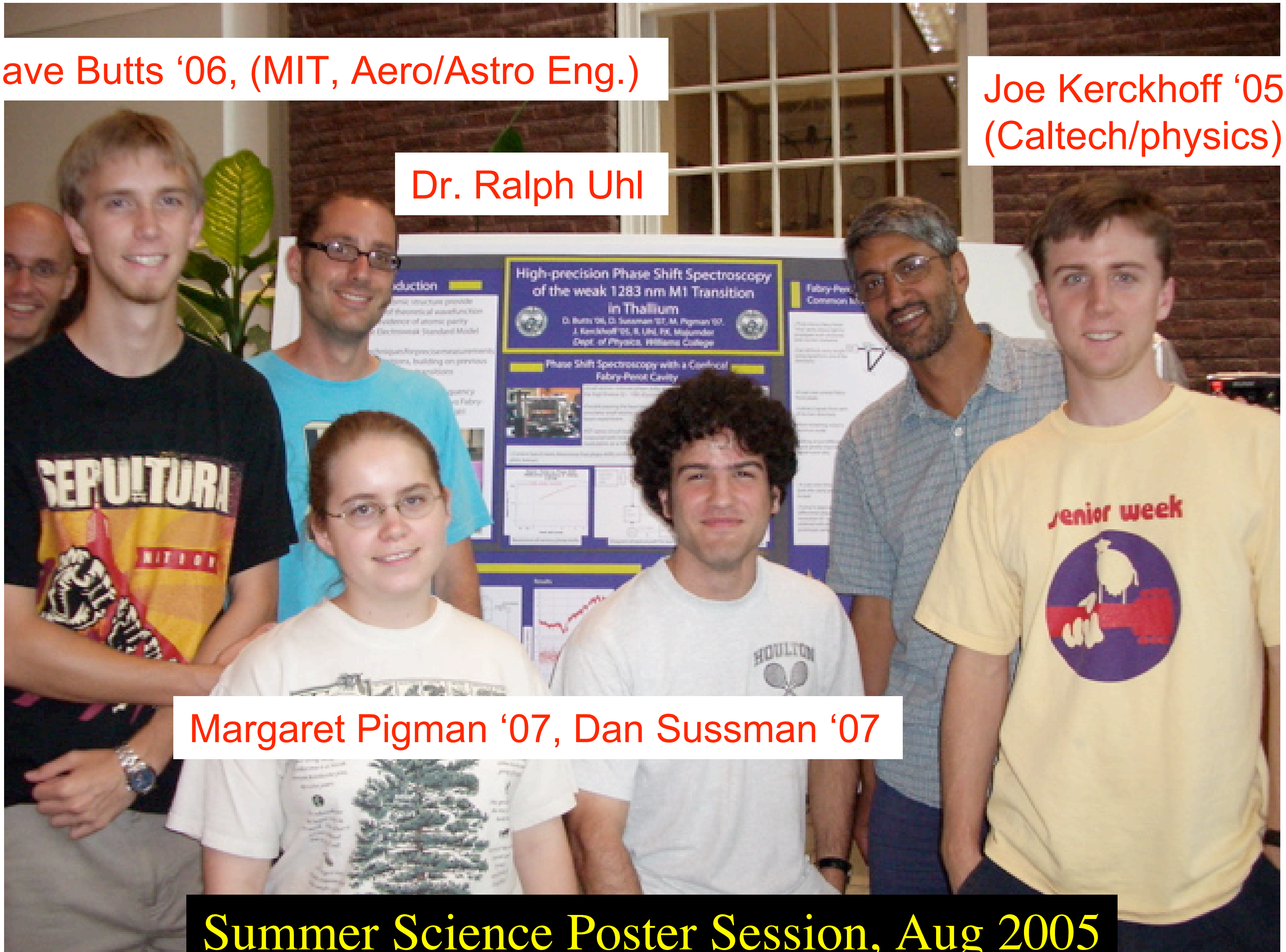
Straightforward re-design for T-Violation experiment:

- Remove relative frequency shift
- Install E-field plates to provide co-linear field



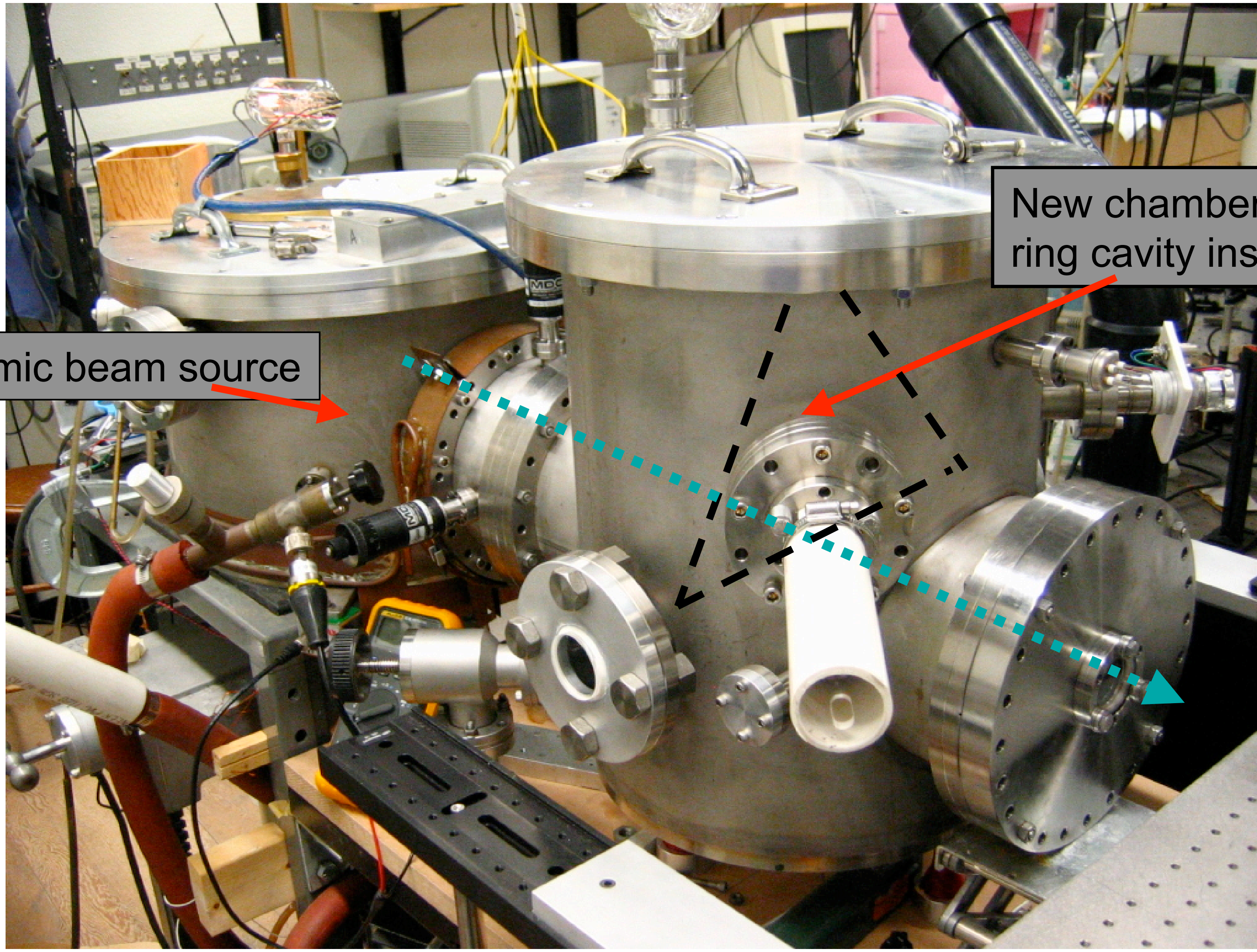
Continue to detect differential phase shift for interaction of counter-propagating beams with atoms in **reversable E-field**

Current/recent students and postdoc



Summer Science Poster Session, Aug 2005

New interaction region (2005)

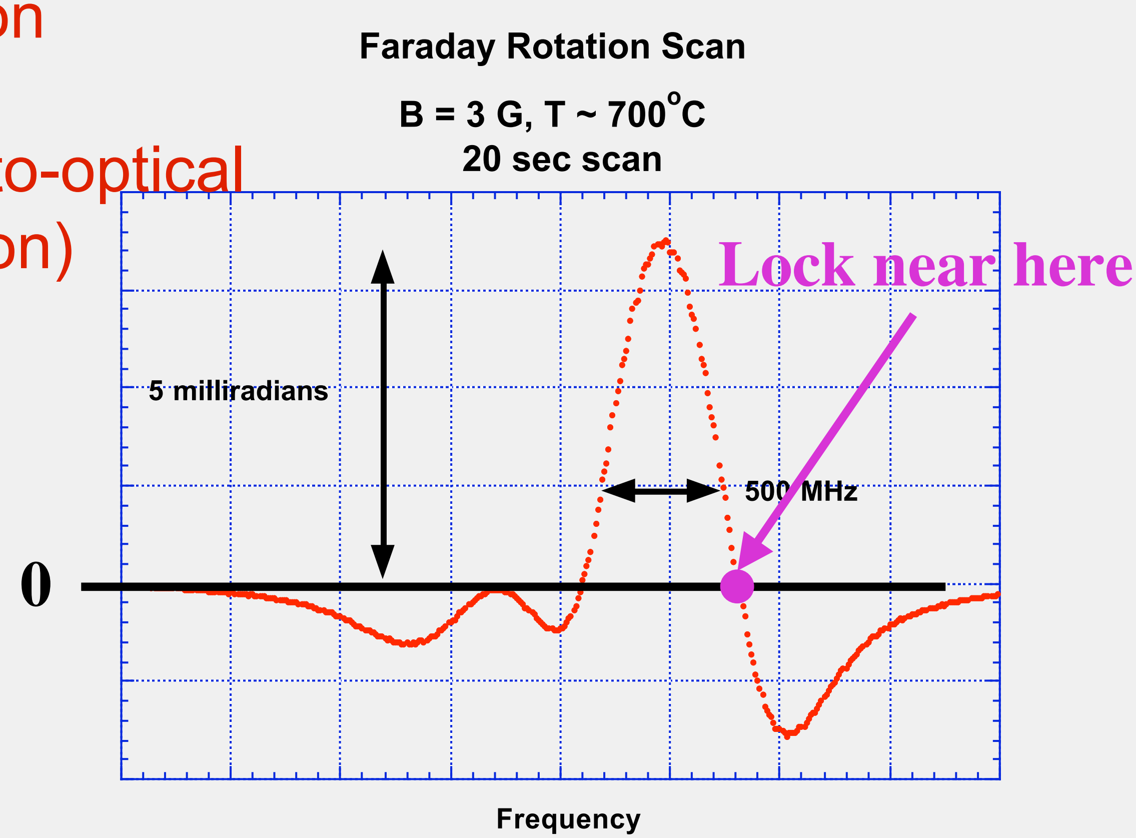


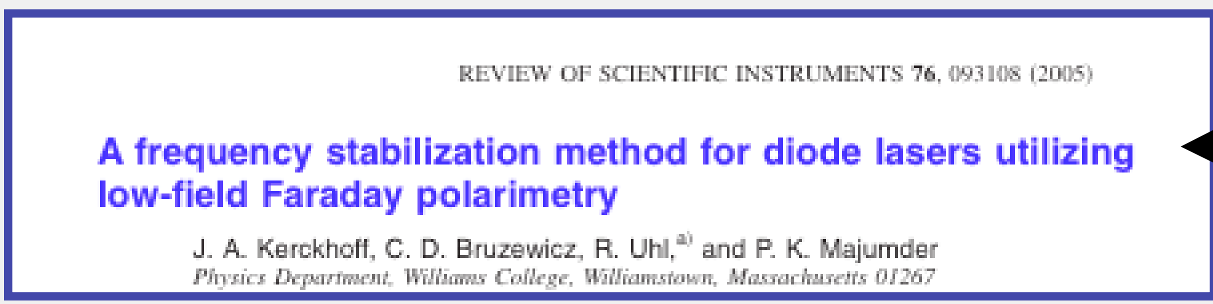
To limit overall drift and improve stability

Lock diode laser near
'forbidden' M1/E2 transition

Use new low-field magneto-optical
technique (Faraday rotation)

Sub-MHz residual noise
within ~300 Hz bandwidth

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Rev. Sci. Instrum.
(Sept. '05)