A New Precise Measurement of the Stark Shift in the $6P_{1/2}$->$7S_{1/2}$ 378 nm Transition in Thallium

Apker Award Finalist Talk

September 4, 2002

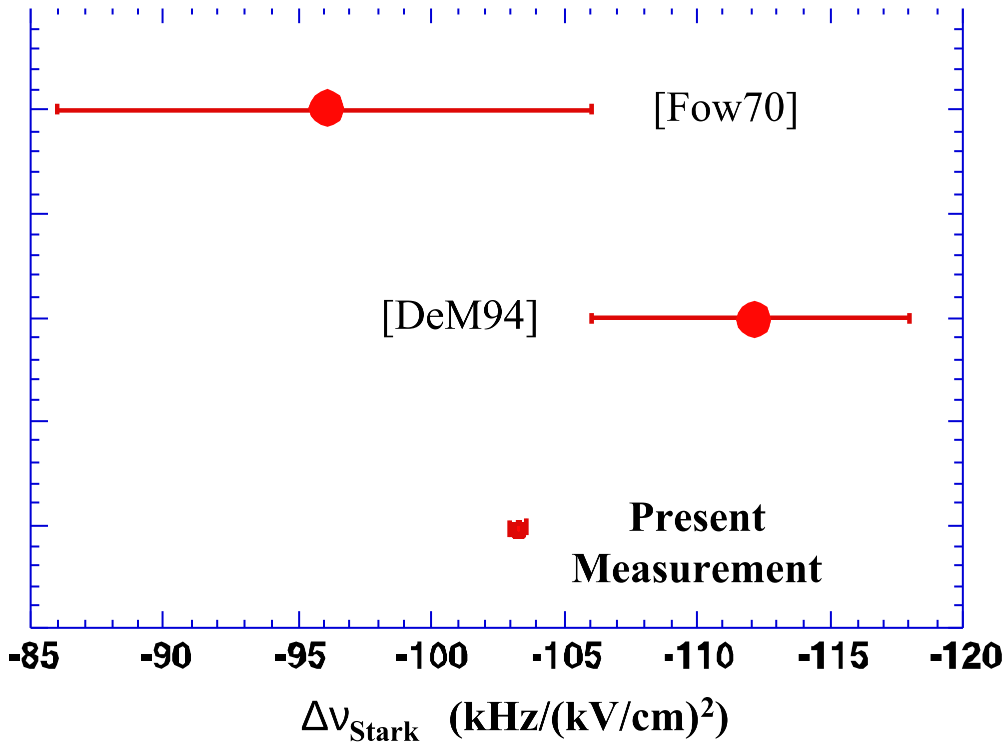
S. Charles Doret

Earlier work by Andrew Speck Williams ’00, Paul Friedberg ’01, D.S. Richardson, PhD

Summary of Tl Stark Shift Measurements

$W_{\mathbf{Stark}} = -\_\,\alpha_o E^2$; $\Delta\nu_{\mathbf{Stark}} = -{}^1/_{2h}\,[\alpha_o(7S_{1/2}) - \alpha_o(6P_{1/2})]\,E^2$

(α_o is scalar polarizability; $\alpha_2 = 0$ for J= _ -> J= _)



Our Measurement: $\Delta\nu_{\mathrm{Stark}} = 103.23(39)$ kHz/(kV/cm)^2

Key Contributions

- Worked on vacuum and laser frequency stabilization systems

- Rebuilt entire optical system for improved laser power and greater stability

- Planned and implemented two data collection schemes, including software

- Built chopping system for improved signal-to-noise and reduced statistical error, including mechanical components, electronics, and software

- Collected and analyzed all data, including an exhaustive search for potential remaining systematic effects

- Co-authored formal paper:

Measurement of the Stark shift within the $6P_{1/2} \rightarrow 7S_{1/2}$ *378-nm transition in atomic thallium*, Doret et al. (To appear in Phys. Rev. A)

Motivation –
Tests of Standard Electroweak Model with Atoms

- Atomic Parity Non-conservation measurements give both evidence for and tests of fundamental physics

- Of interest here: Q_w, predicted by elementary particle theory

According to Atomic Physics:

$$E_{PNC} = Q_w * C(Z)$$

Group	Element	Experimental Precision	Atomic Theory Precision
Oxford '91	**Bismuth**	**2%**	**8%**
UW '93	**Lead**	**1.2%**	**8%**
UW '95	**Thallium**	**1.2%**	**2.5% (new, 2001)**
Colorado '97	**Cesium**	**0.35%**	**~ 1% (or less)**

- Precision matters: { > 5% - not so interesting; < 1% - very important }

- Independent tests of atomic theory – separate from PNC measurements

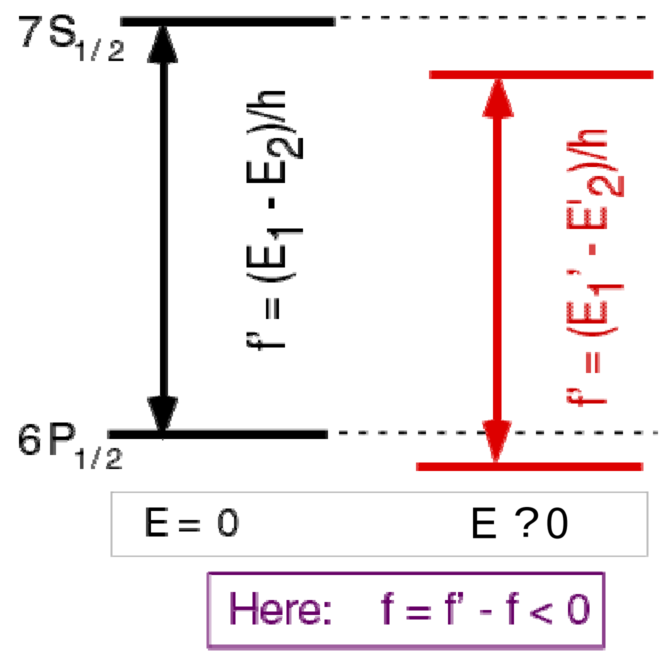
- Improve on existing limits beyond the Standard Model

How to measure?

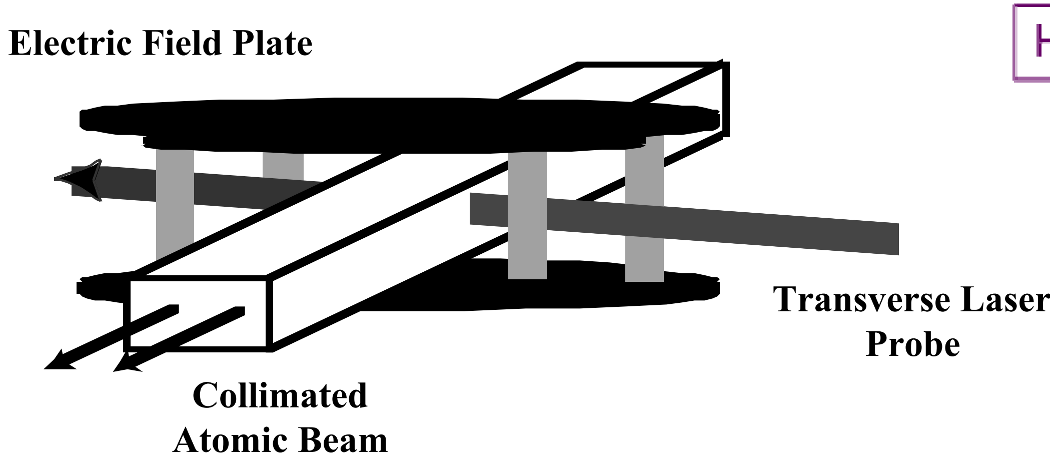
2nd order Perturbation Theory:

$\Delta\nu_{Stark}$ E^2

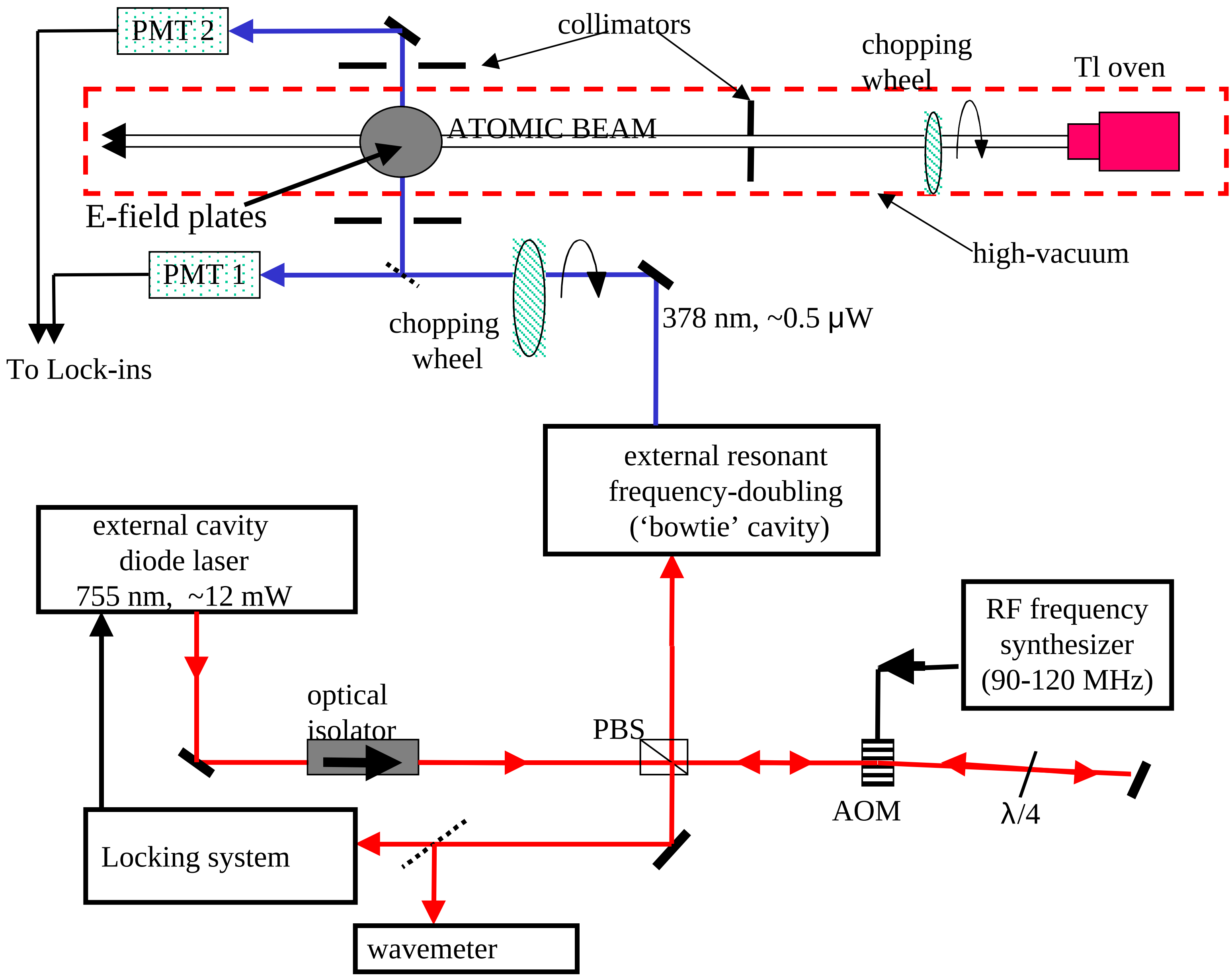
-Proportionality constant based on an infinite sum of E1 matrix elements, similar to C(Z)



Interaction Region:



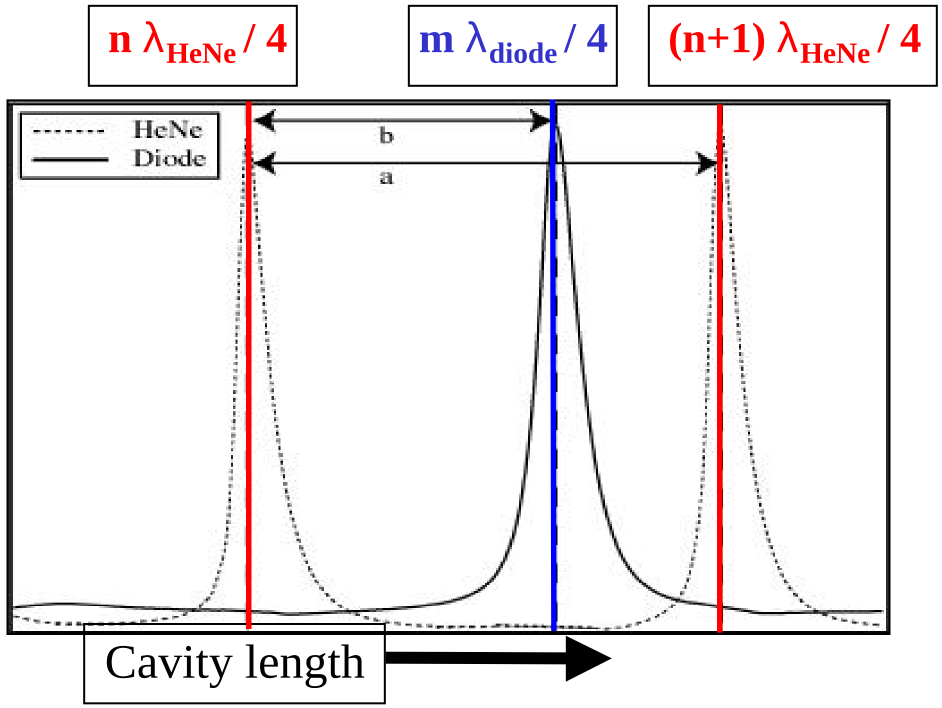
Atomic Beam and Optical System Layout



Locking System:

Frequency Stabilization:

$\rho = b/a$



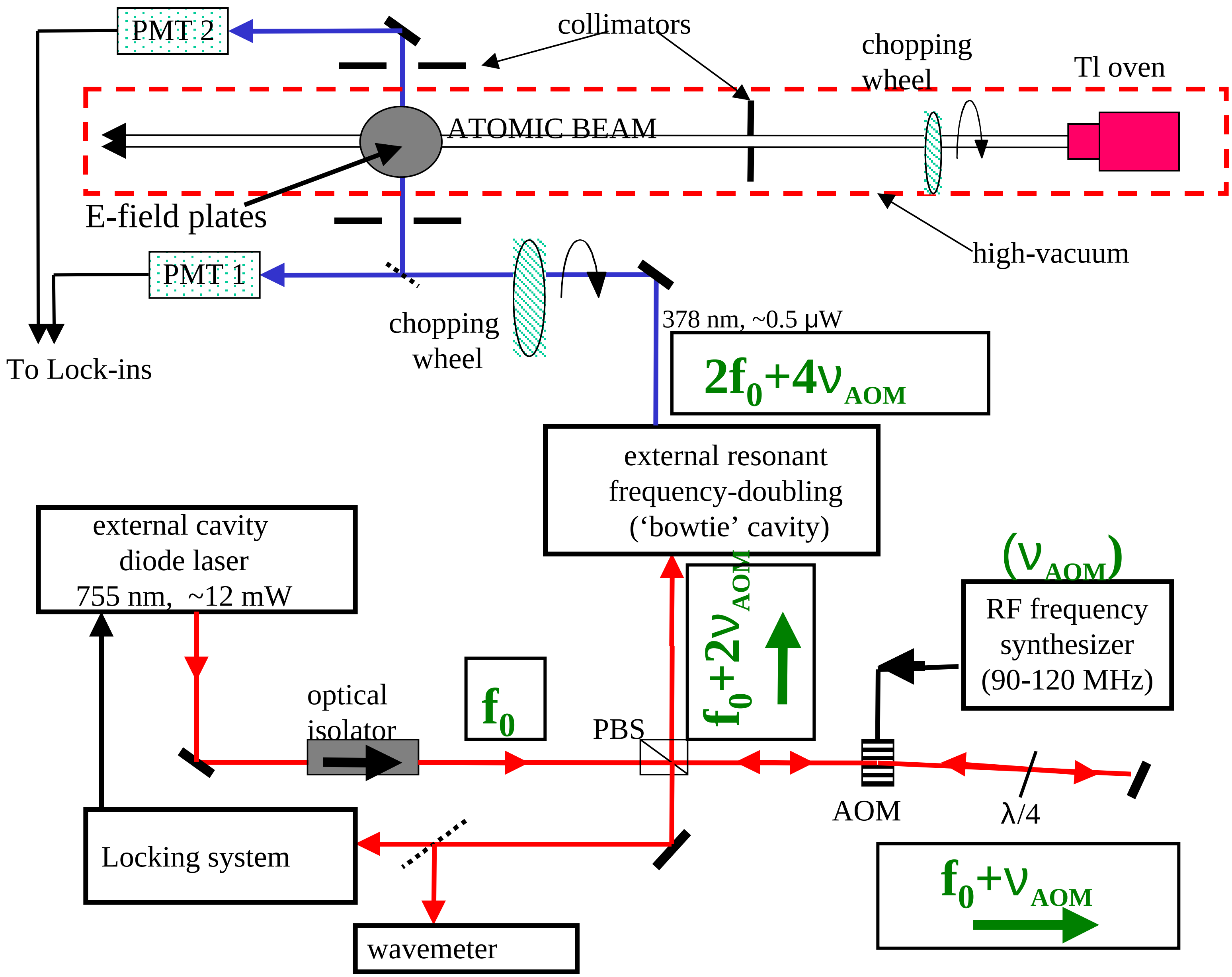
$0 < \rho < 1$

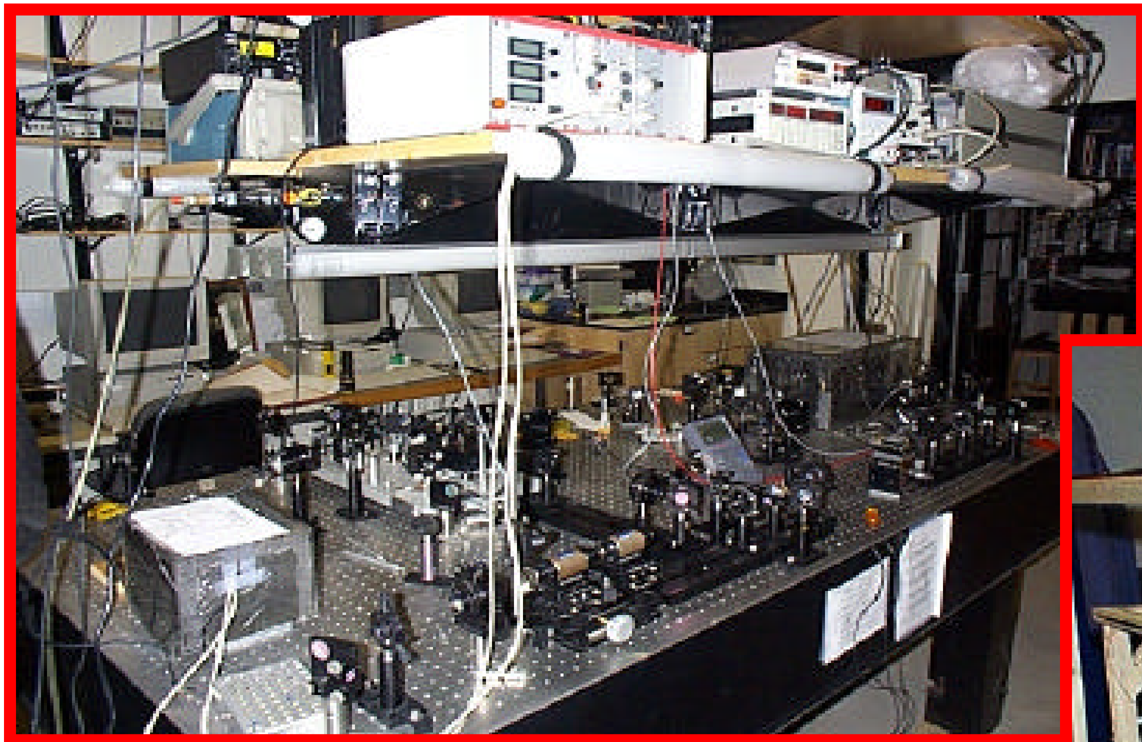
$0 < \nu < 838.2\,\text{MHz}$

Frequency Tuning:

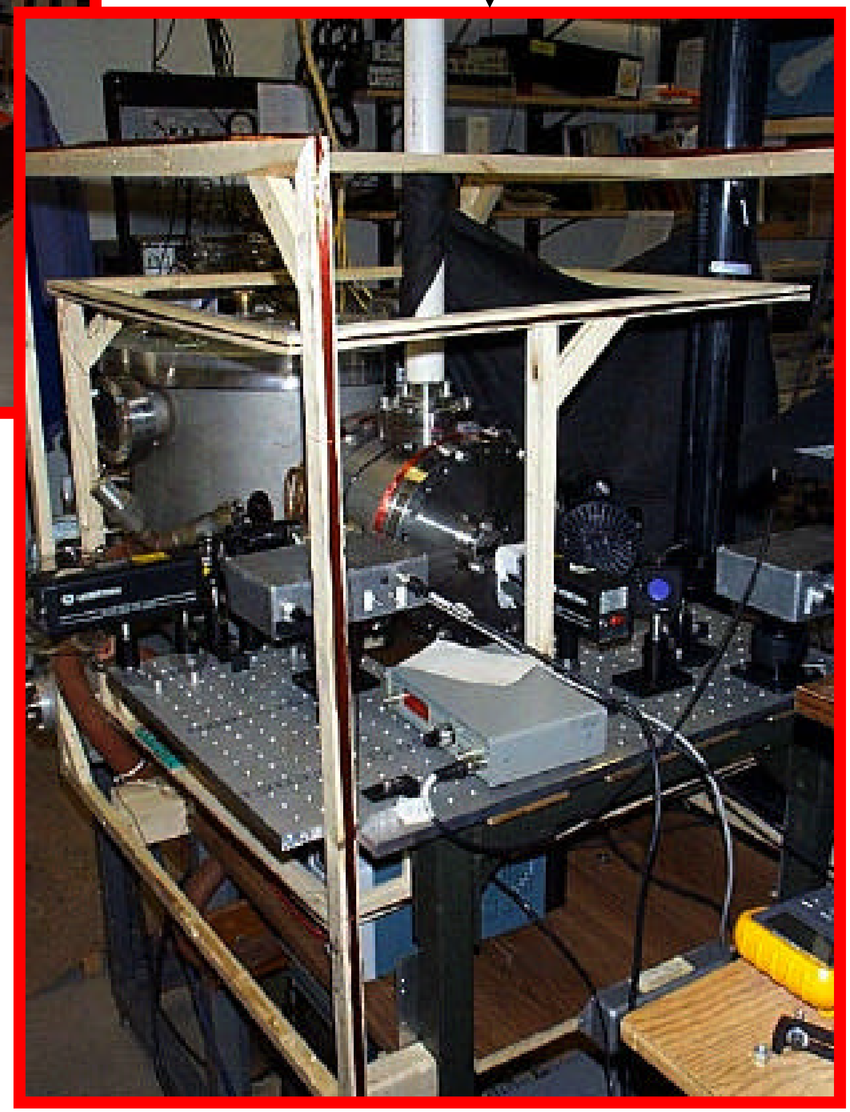
- Adjust $0 < \rho < 1$ ~ 800 MHz range
- requires precise calibration of free spectral range; tuning is SLOW, manual

Atomic Beam and Optical System Layout

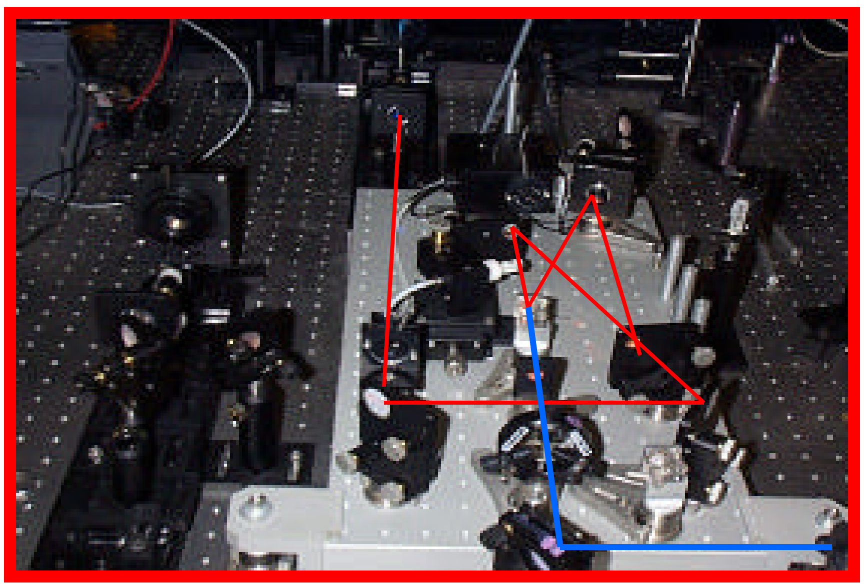




Optical Table

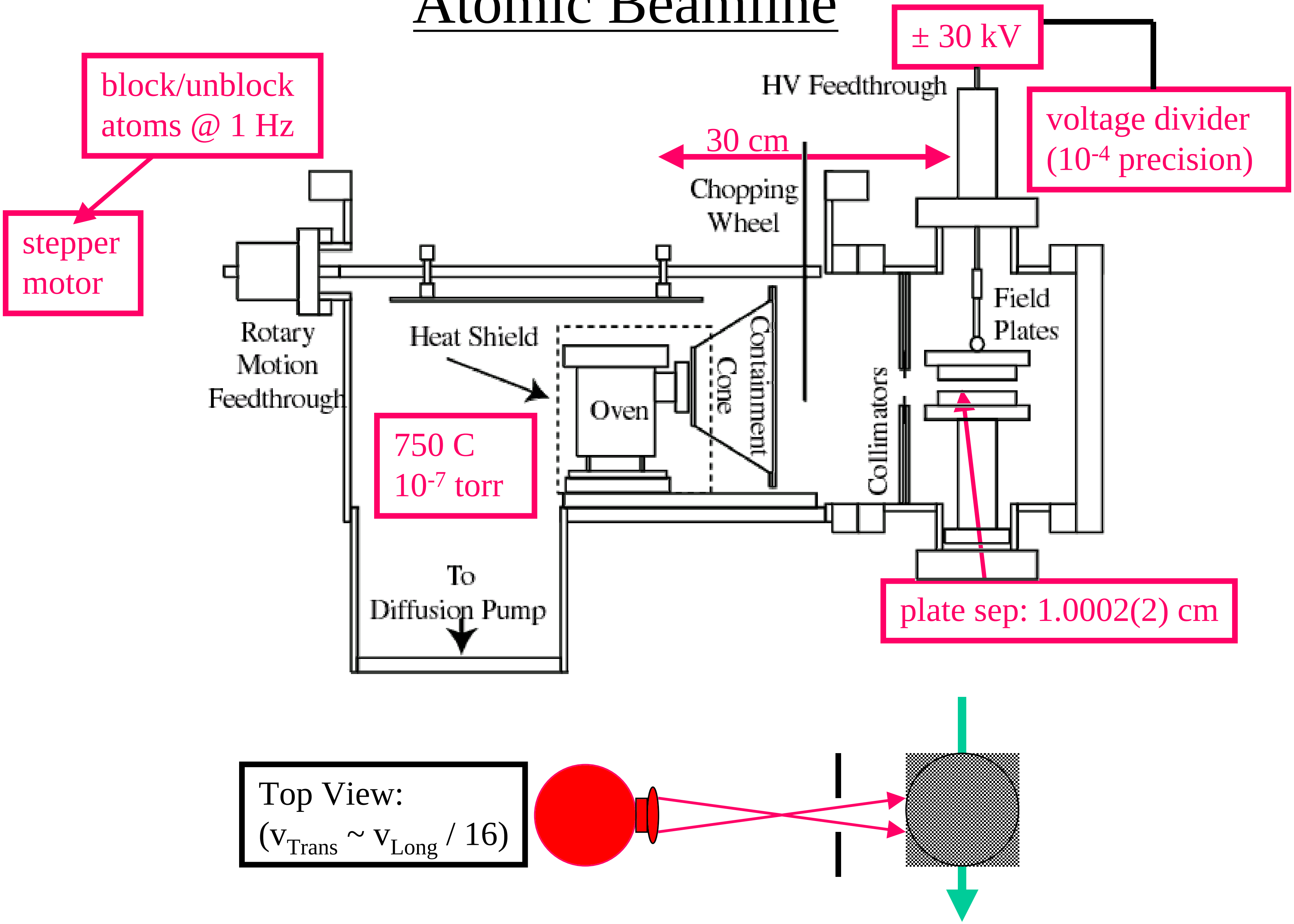


Interaction Region



Doubling Cavity

Atomic Beamline



Data Collection/Signal Processing

Chopping System:

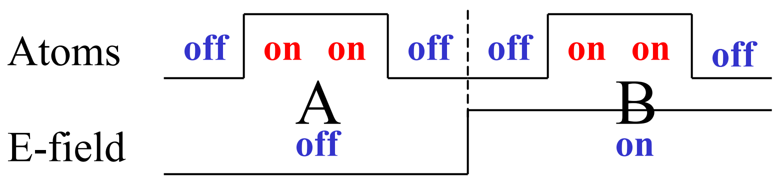
- Laser Beam chopping rejects any noise with frequency components other than the modulation frequency – 1400 Hz

- Atomic Beam chopping to correct for optical table drifts, beam density fluctuations, etc. – 1Hz

Division/Subtraction Schemes:

- Extra PMT for laser beam intensity normalization

- Interested in difference signals A-B:

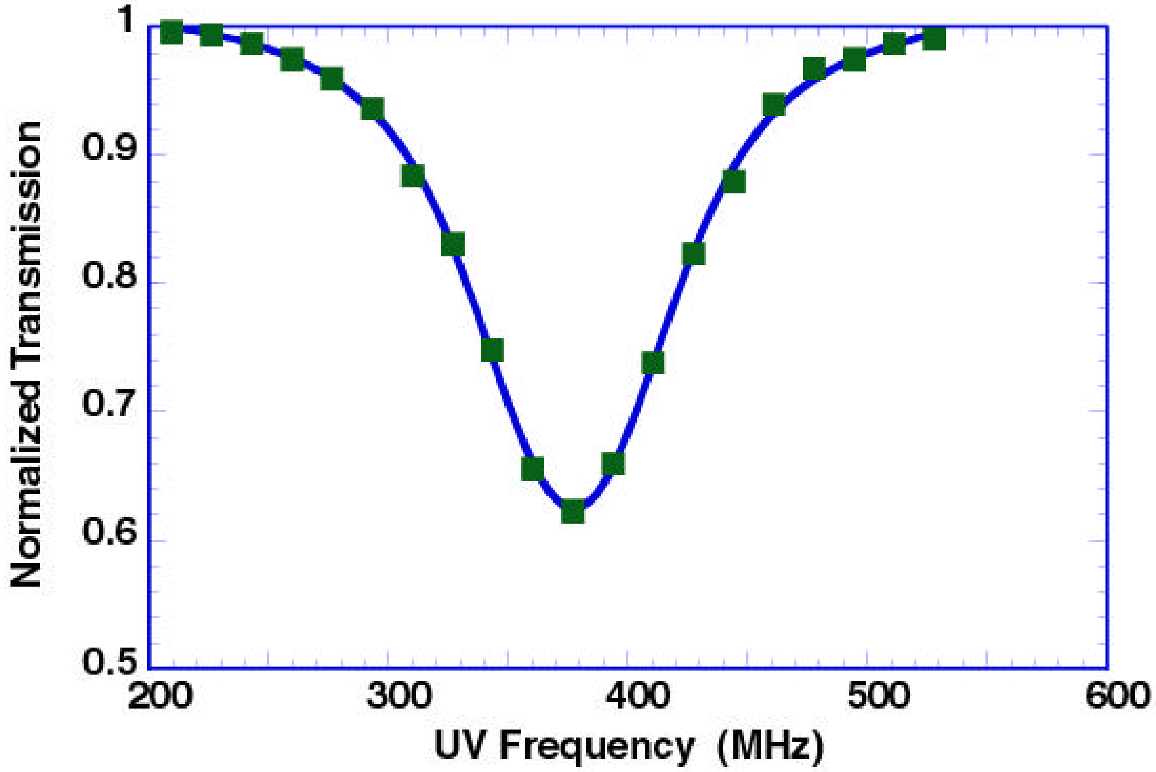


- Collect data in ABBA format to minimize the effects of linear drifts

Transmission Profile

T(ν) = exp[-βV(γ,Γ;ν)], V a normalized Voigt profile

(same for all 6 peaks in transition)

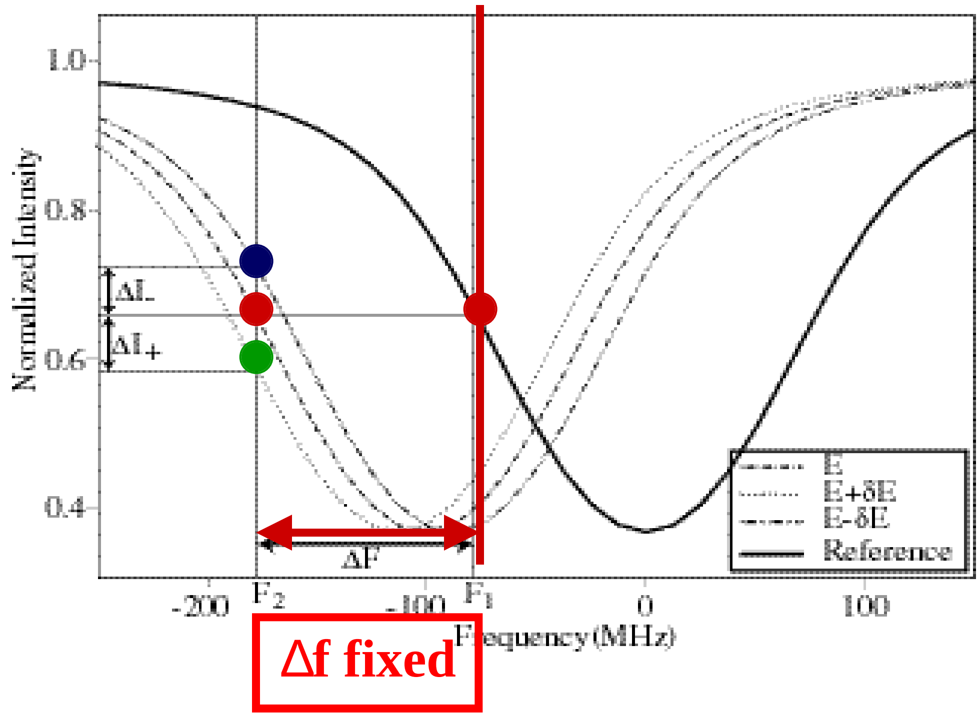


β = 0.5

γ = 20MHz

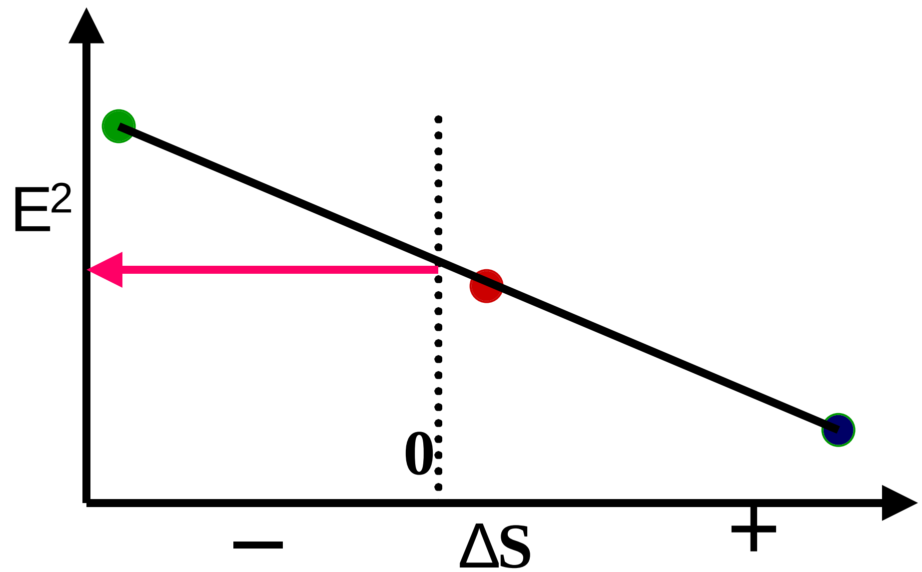
Γ = 100MHz

Transmission Change:



(1) Lock laser to inflection point of transmission curve (dip), measure S = T/N (E = 0)

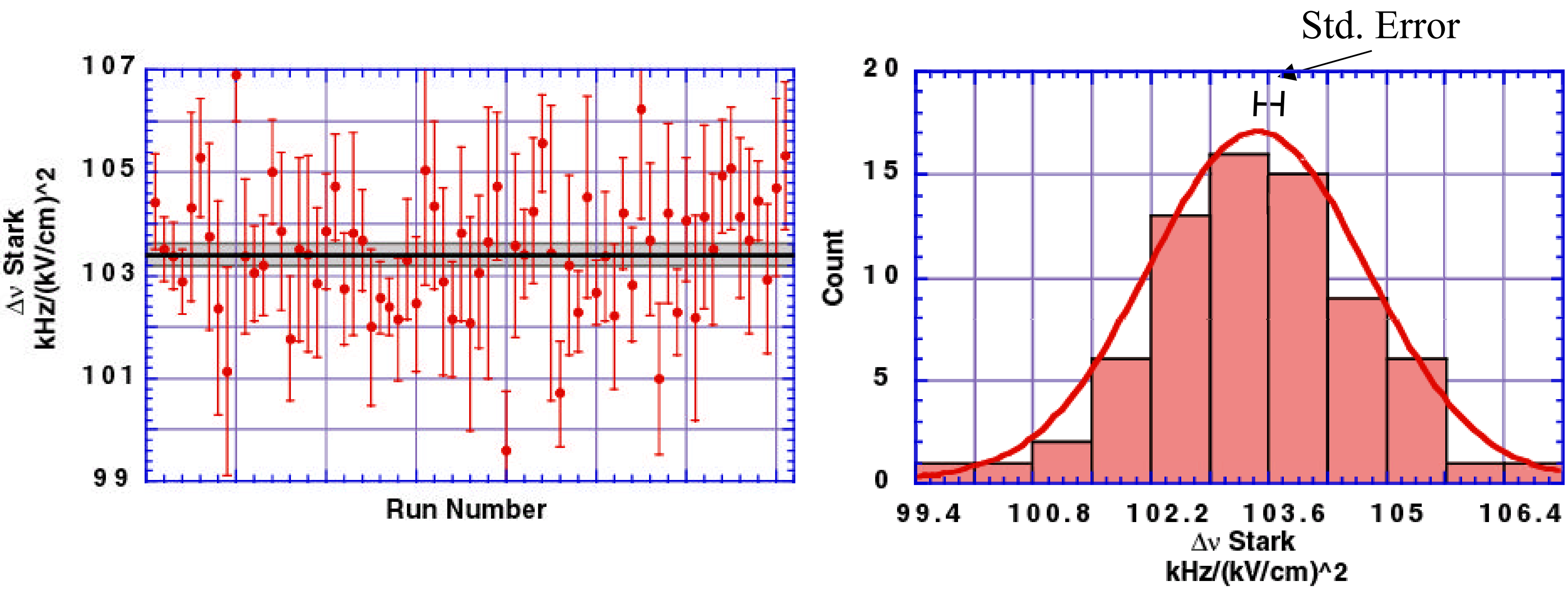
(2) - Turn on Electric field ($E = E_0$)
- Shift AOM frequency by appropriate amount (Δf);
- Determine S' and ΔS = S' - S



(3) Repeat sequence with altered Electric field values, <u>but same Δf</u>.

(4) Find y-intercept of linear fit -- value of E^2 which exactly matches Δf

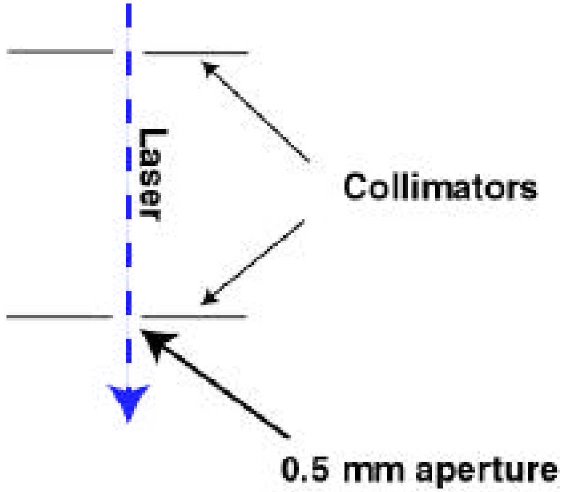
Statistical Analysis



Final Statistical Error: 0.20 $kHz/(kV/cm)^2$ (0.19%)

Systematic Error Analysis

Doppler Shifts:



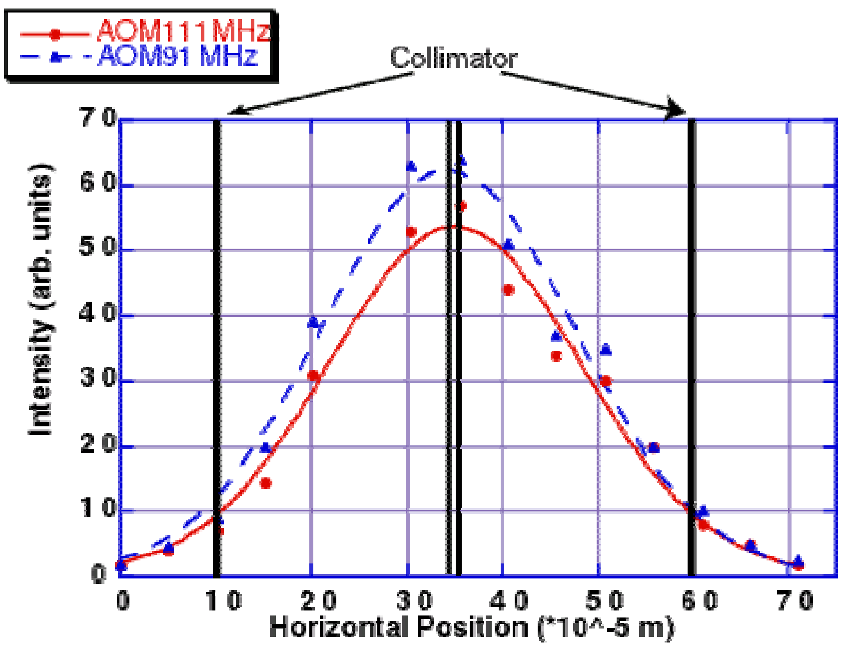
$\delta f = f \quad v/c$

$= 4*10^{14}(300 \text{ m/s} / 3*10^{8} \text{ m/s}) * 10^{-3} \text{ rad}$

$= 0.4$ MHz (0.38%)

$\leq 4*10^{14}(300 \text{ m/s} / 3*10^{8} \text{ m/s}) * 10^{-4} \text{ rad}$

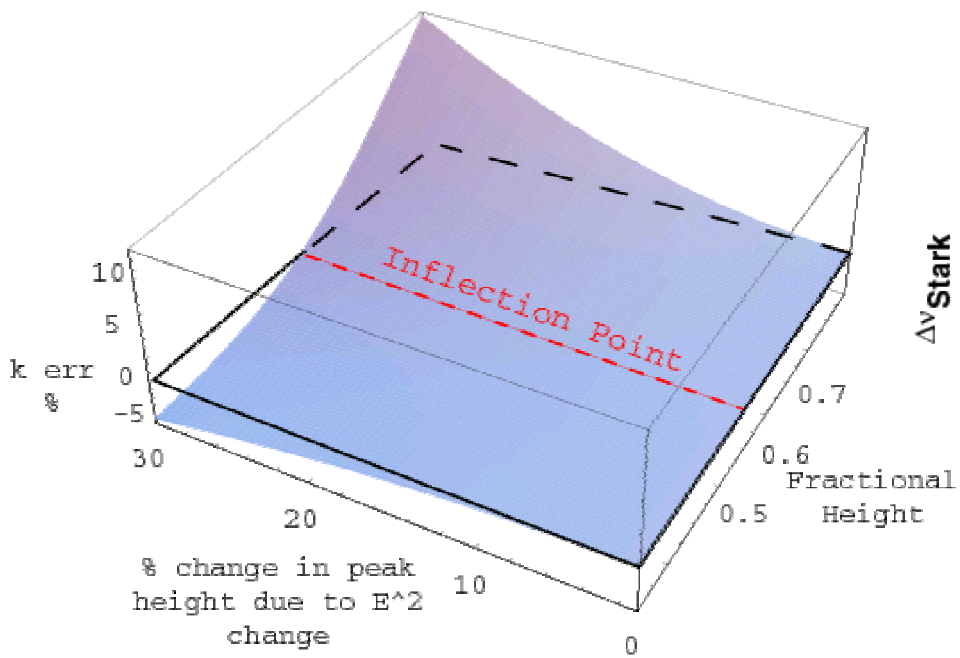
≤ 40 kHz (0.04 %)



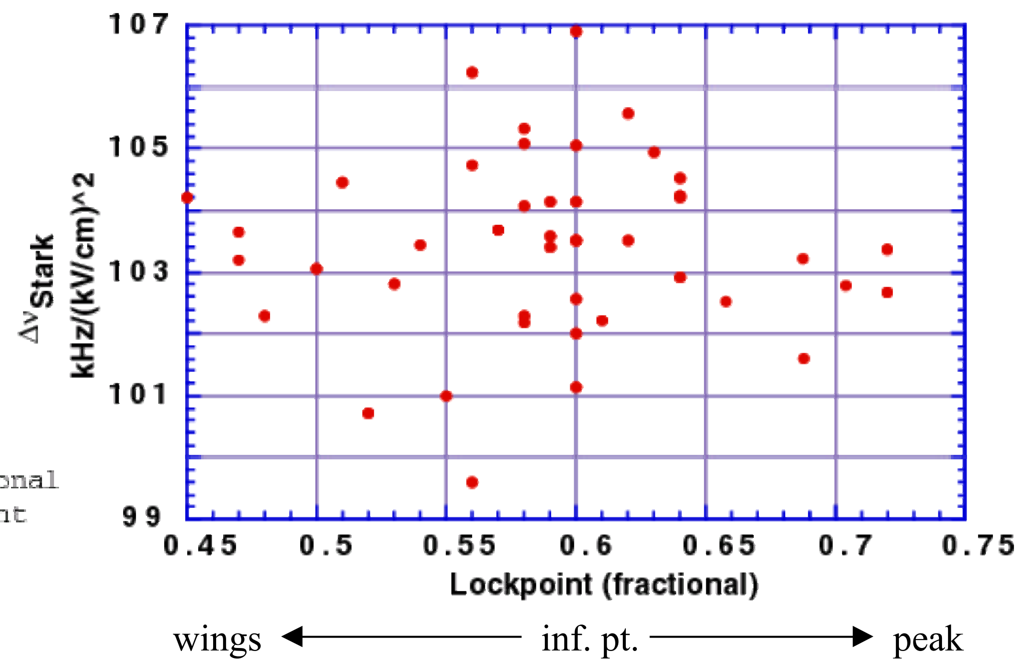
Correlation Plots

- Concerns about linear fit used to extract k_{Stark} with Transmission Change method

Simulation:



Measured:

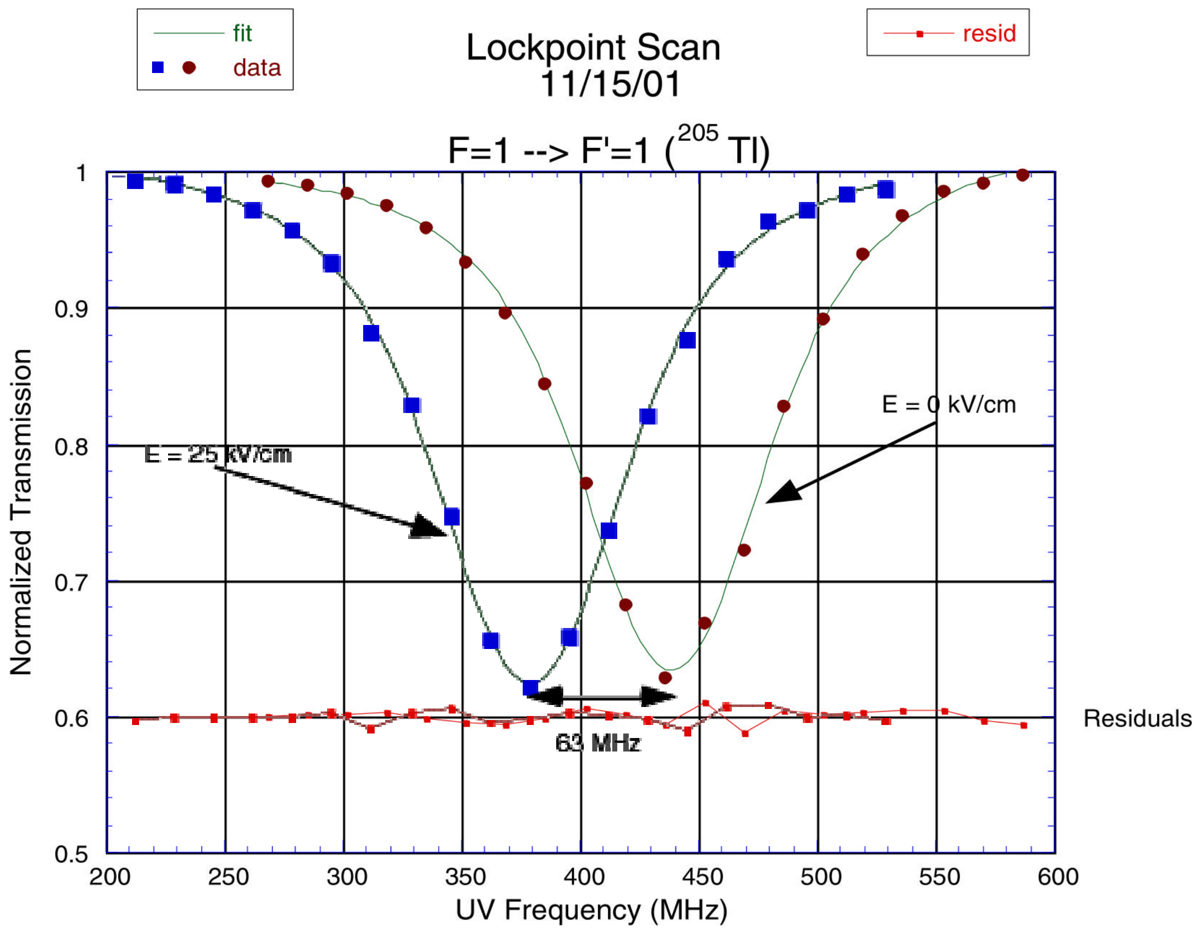


- Symmetric data collection on both sides since opposite effect

Transmission Change Analysis	$\Delta\nu_{Stark}$ (kHz/(kV/cm)^2)
Final mean value	103.39
Statistical Error	0.20
Systematic Error Sources:	
Curve linearity	0.30
Oven Temperature	0.26
Residual Doppler Shift	0.16
E^2 Step size	0.04
E-field calibration	0.01
Hi/Lo side lock	0.01
Quadrature Sum	0.43

"ρ" Frequency Scan:

- **Sequentially lock the diode laser, calibrate "ρ"**
- **Scan over single line of ^{205}Tl. Fit data to Voigt transmission profile**

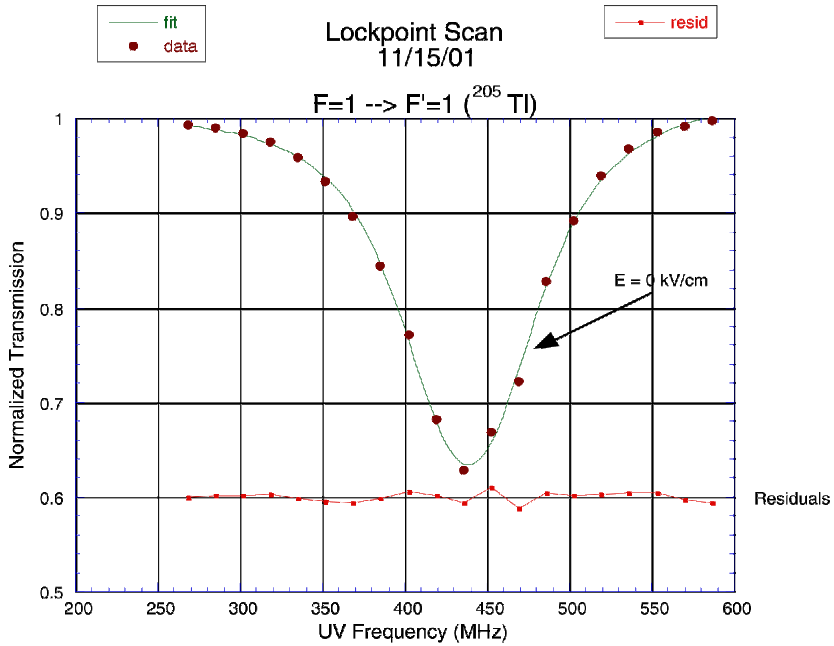


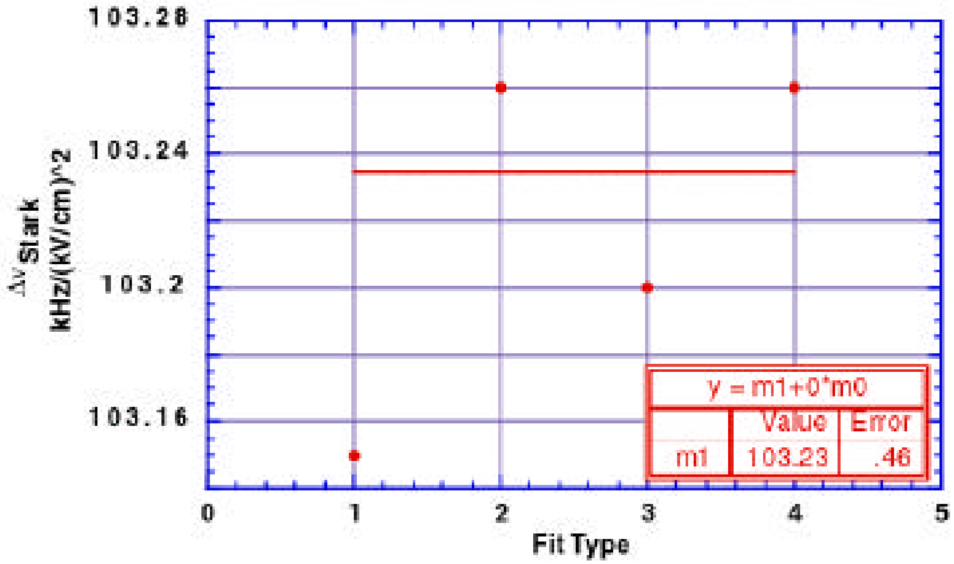
$$\Delta\nu_{Stark} = \frac{63MHz}{(25kV/cm)^2}$$

$$= 101 kHz/(kV/cm)^2$$

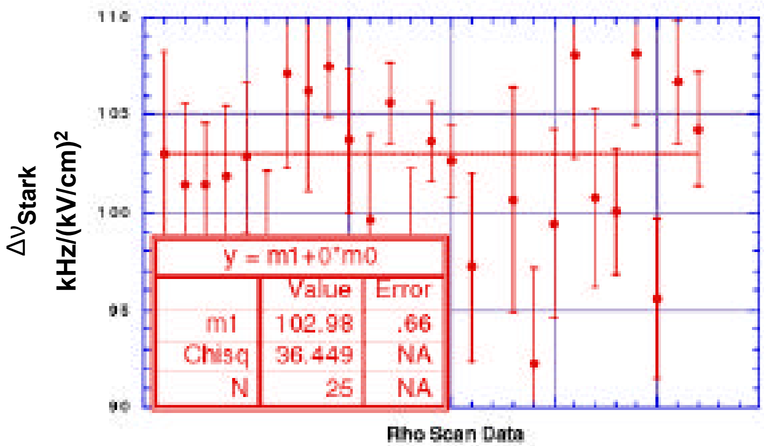
Some ρ Scan Errors

Fitting Errors:





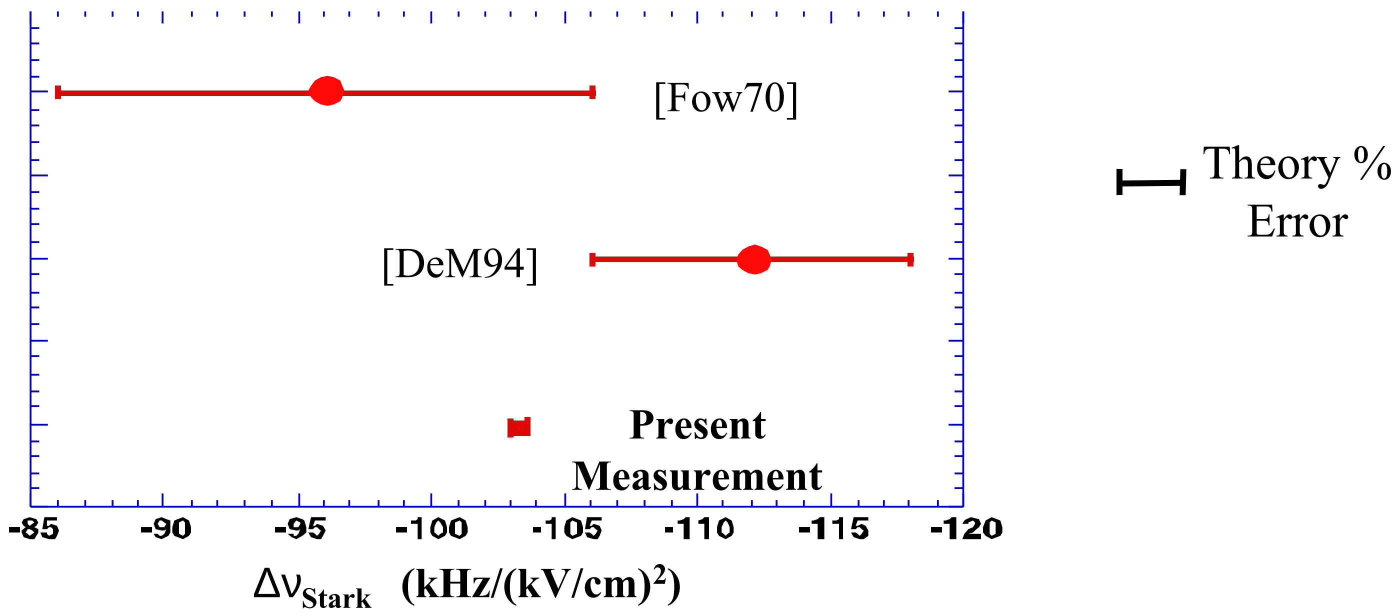
Statistics:



Conclusions

Frequency Scan: -103.02(62) kHz/(kV/cm)^2 **Transmission Change**: -103.39(43) kHz/(kV/cm)^2

Combined Value: 103.23(39) kHz/(kV/cm)^2



- Factor of 15 improvement over previous measurement
- $[\alpha_o(7S_{1/2}) - \alpha_o(6P_{1/2})] = 122.96(47) \times 10^{-24}$ cm^3