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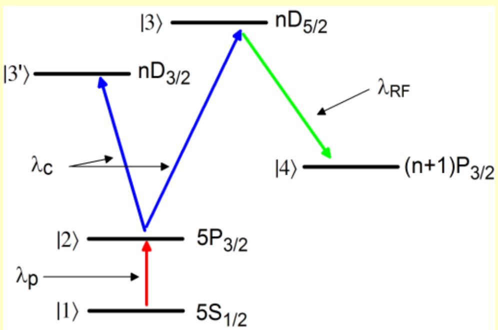
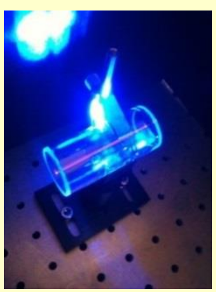
Atom-Based RF Electric Field Metrology: Direct SI Traceable Measurements and Beyond

An Exercise in Perseverance





Christopher L. Holloway

Josh Gordon and Matt Simons

What Are We Trying to Solve

Calibrating an E-Field Probe

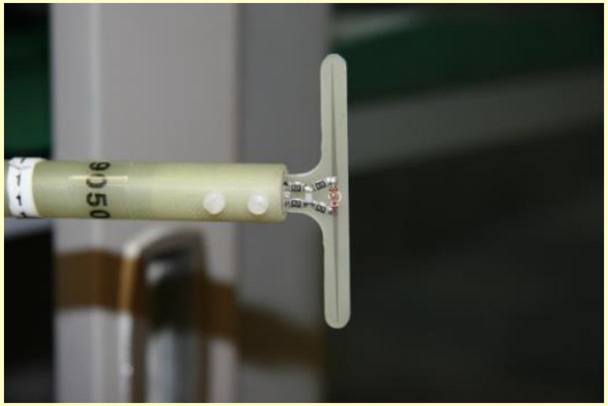
Somewhat of a "Chicken-or-Egg" dilemma

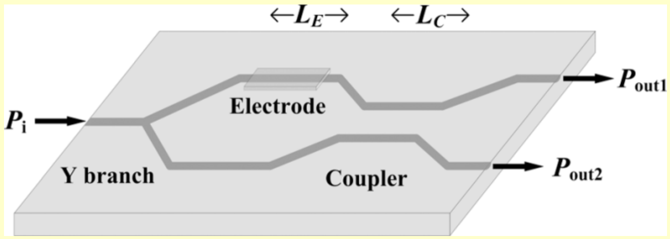
To calibrate a probe, one must place the probe (sensor) in a "known" field.

However, to know the field we need a calibrated probe.

Current Techniques

E-field Probe





Limitations:

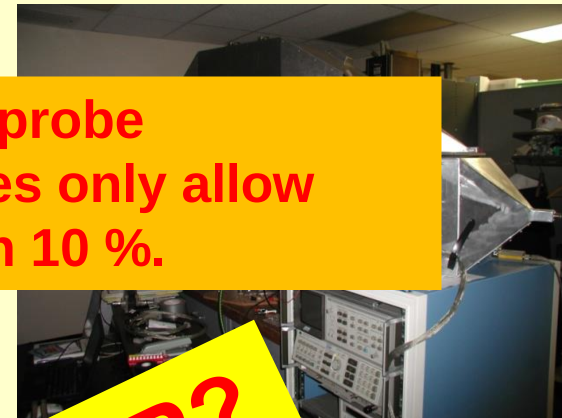
- Field-levels: about 100 mV/m
- Requires calibration
- Perturbs the field (due to metal)
- Relatively large in size

To calibrate the probe, we need a "known" field.

Current Technology for Measuring and Calibrations

Horn antenna in an anechoic chamber

TEM Cell



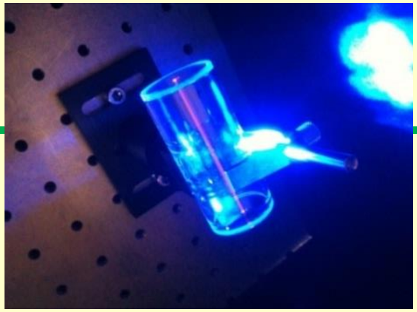
At the 2015 EMC Europe conference probe manufacturers stated that their probes only allow them to measure fields no better than 10 %.

Can We Do BETTER?

GTEM Cell

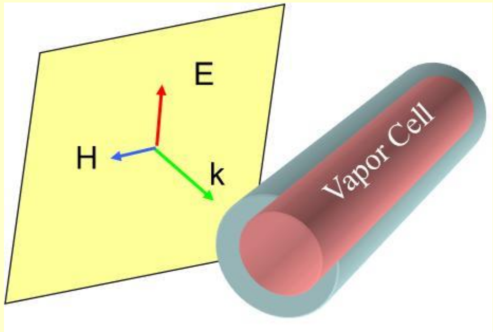
0.5 dB (or 5%) accuracy

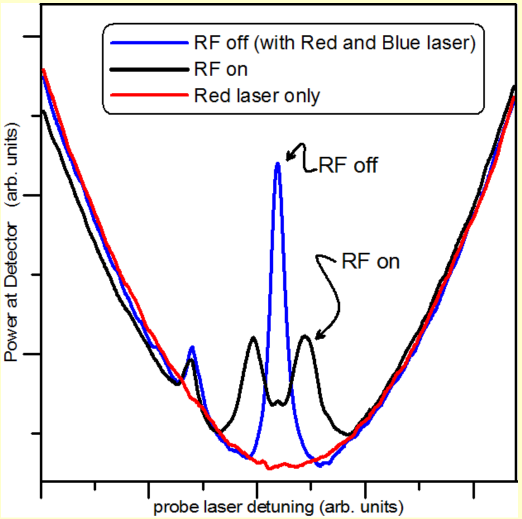
New Probe Concept

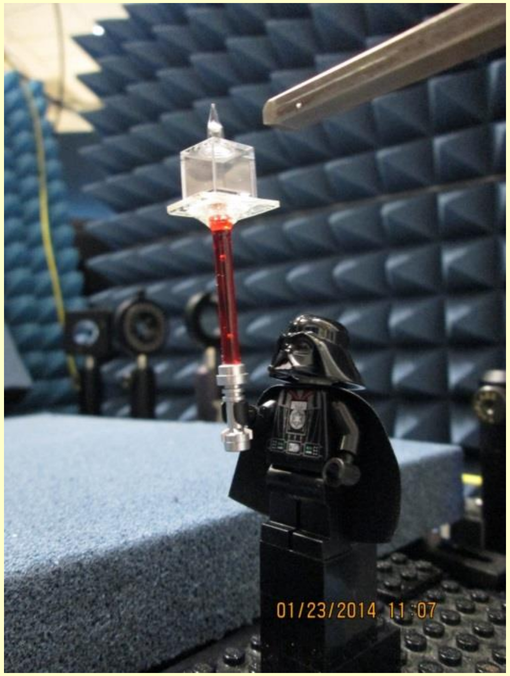


Atomic Vapor Cells:

A probe is based on the interaction of RF-fields with Rydberg atoms: where alkali atoms are excited optically to Rydberg states and the applied RF-field alters the resonant state of the atoms.





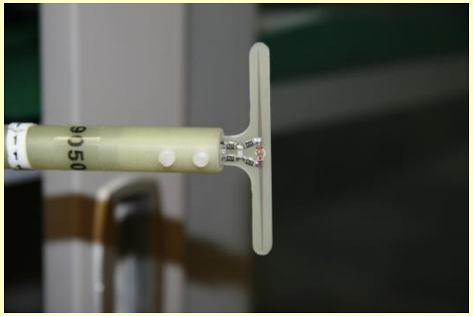


<u>In effect, alkali atoms placed in a vapor cell act like an RF-to-optical transducer, converting an RF E-field strength measurement to an optical frequency measurement.</u>

At Least 2 Orders of Magnitude Improvement in Current Technology

Current Technology

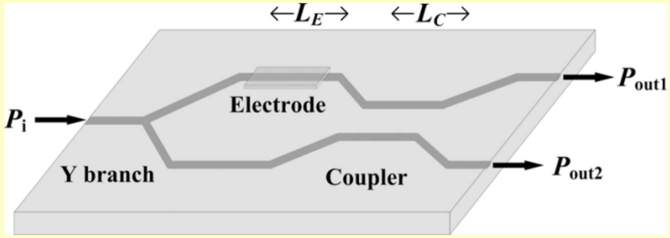
Loaded Dipole Probe



Field-levels: 100 mV/m

- Requires calibration
- Perturbs the field (due to metal)

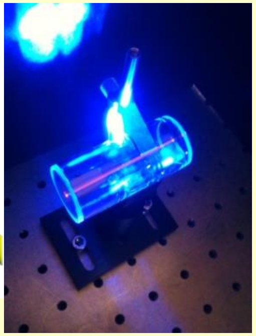
Electro-Optics Probe (lithium niobate)

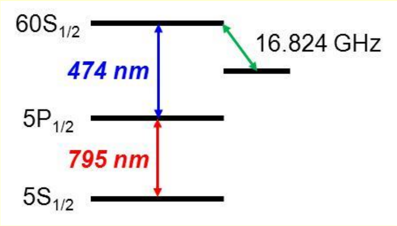


Field-levels: 10 mV/m

- Requires calibration
- Perturbs the field
  (due to metal in some designs)

Quantum Based Probe





Field-levels : <1 mV/m

- No calibration required
- Does not perturb the field
- Small spatial resolution

If successful, field levels on the order 10 μV/m and smaller should be possible.

Benefits

New approach for E-field measurements

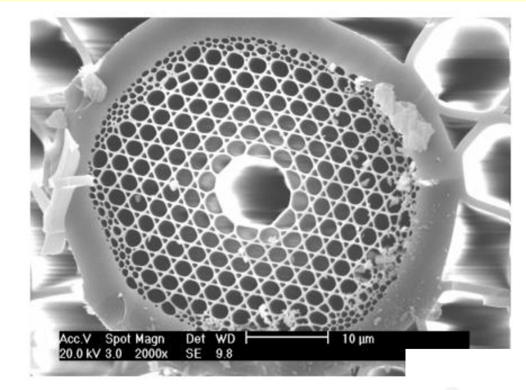
- Will allow direct SI units linked RF electric field (*E*-field) measurements
- Self calibrating due to atomic resonances
- Would provide RF field measurements independent of current techniques
- **Broadband sensor:** 400 MHz –to- 500 GHz (possible up to 1 THz)
- Measure both very weak and very strong fields over a large range of frequencies
- Potentially very small and compact probe:
  -optical fiber and chip-scale probe

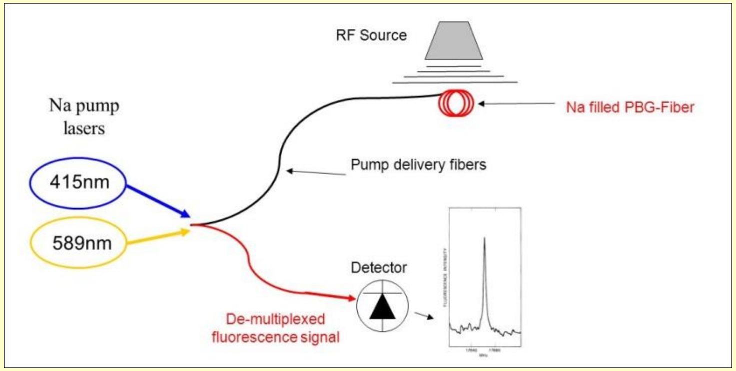
And Beyond …

- Allow for the first calibrations above 110 GHz
- In addition to E-field calibrations, the technique will allow for power calibrations
- Various other applications and uses

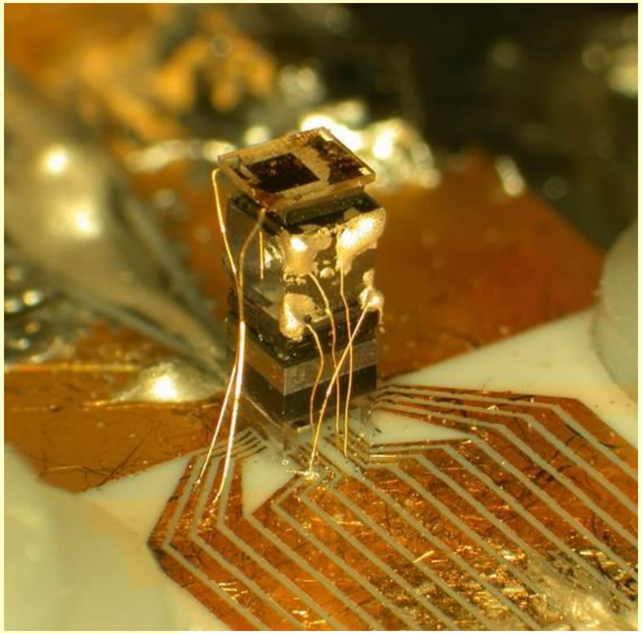
Vision of Compact Probes

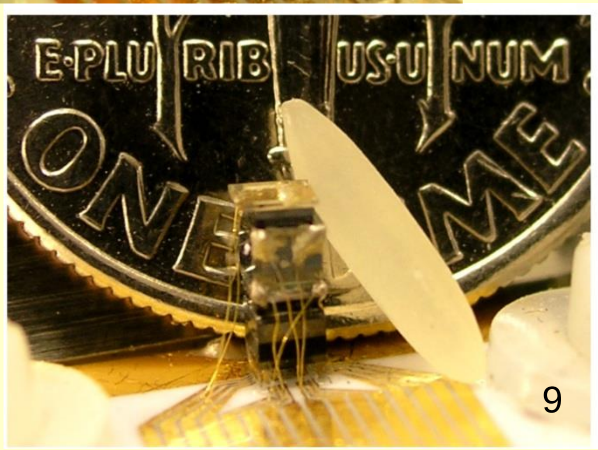
Hollow Core Photonic Crystal Fiber





Chip-Scale Probe: NIST on a CHIP



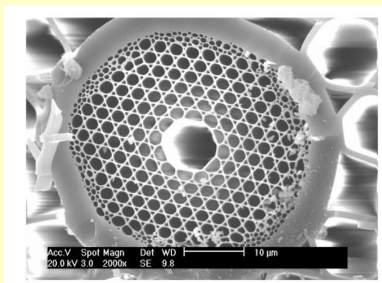


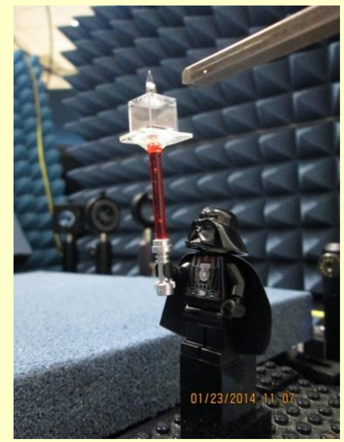
Vision of E-field Probes and Power Measurements

Outcome of this work is three-fold:

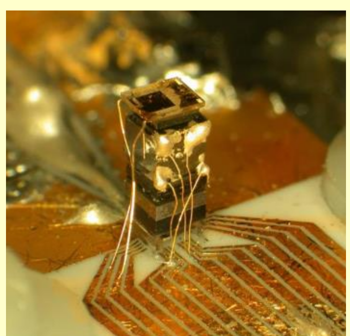
- **Broadband self-calibrating probe: one cell of atoms and two lasers to cover**
  - **400 MHz- 500 GHz (may be up to 1 THz)**

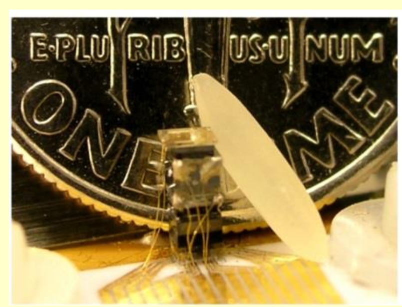
- **Compact and Movable**





- **NIST on a CHIP**

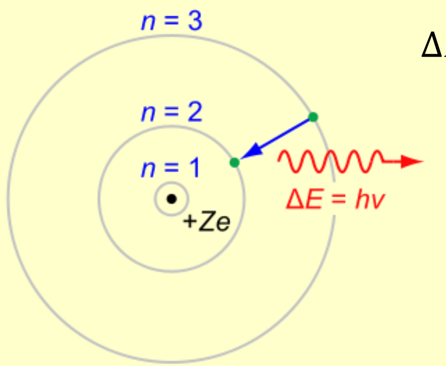




A Little Atomic Physics: The Hydrogen Atom

Bohr Model

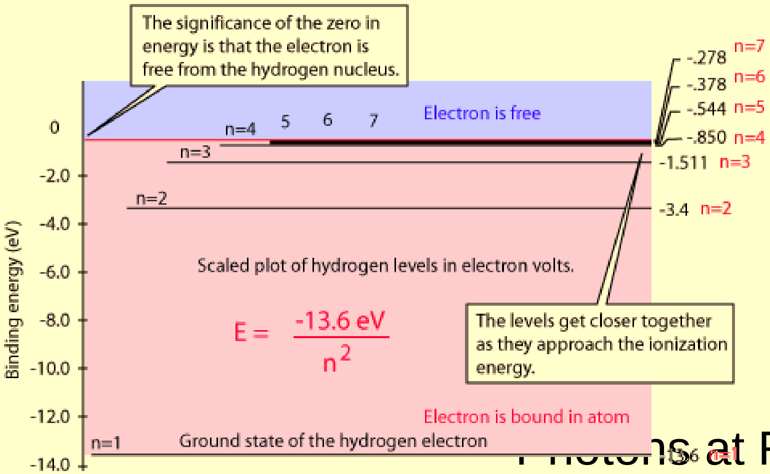
1. Electrons orbit the nucleus in discrete radius.
2. The ground state is n=1
3. Need to supply or released energy (or photons) to change state (or orbit)



$\Delta E = h\nu$ where h=6.62607x10^{-34} m^{2}kg/s and is Planck's constant

$$h\nu = -13.6\left[\frac{1}{ni^2} - \frac{1}{nf^2}\right]\ eV$$

$$\frac{1}{\lambda} = R_H\left[\frac{1}{ni^2} - \frac{1}{nf^2}\right]\ 1/m$$ R_H=1.0973731x10^{-7} m^{-1}



Transition from ground state: n=1 to n=2

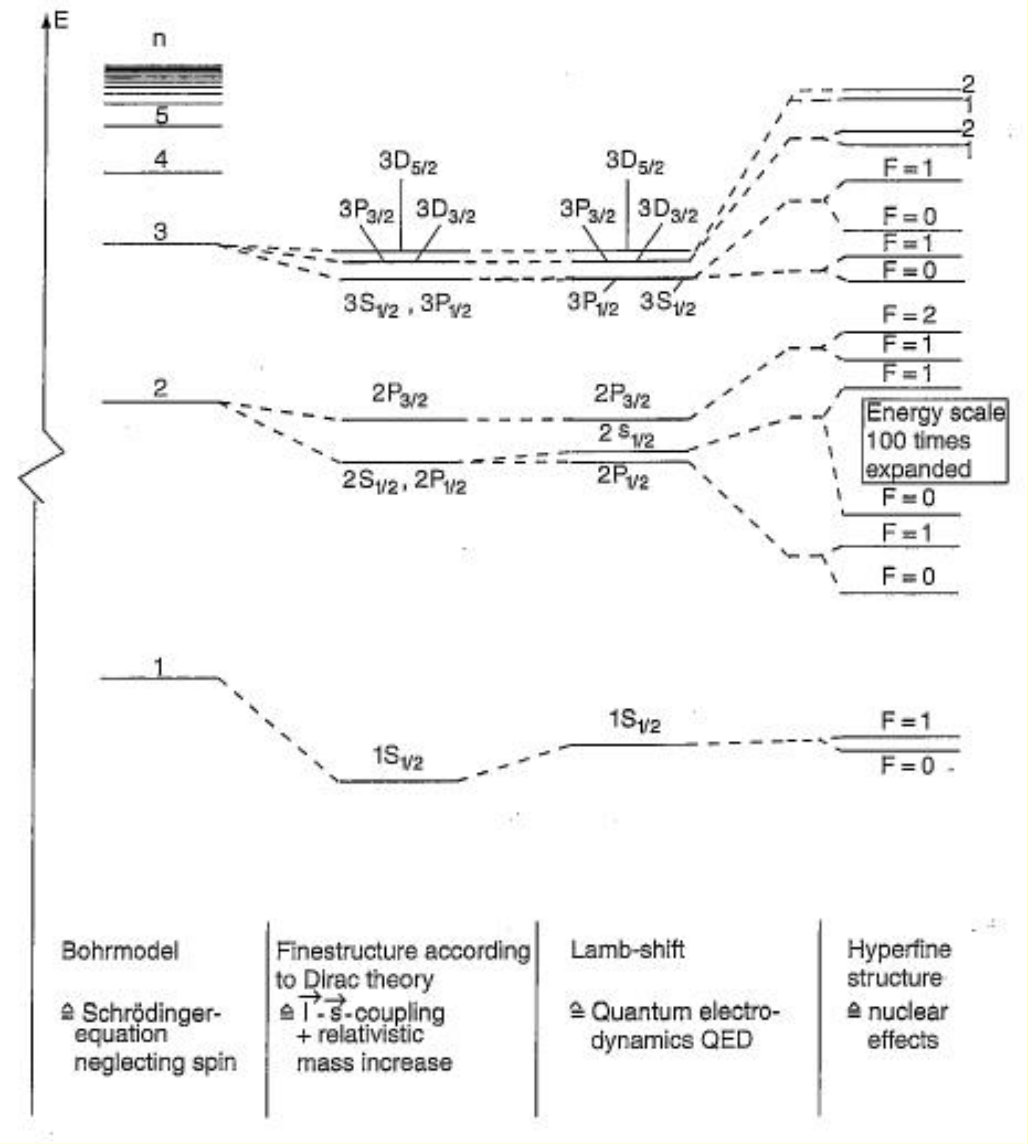
λ=121.6 nm (UV) and $\Delta E = h\nu$ = 10.2 eV

Energy in a 20 GHz photon:

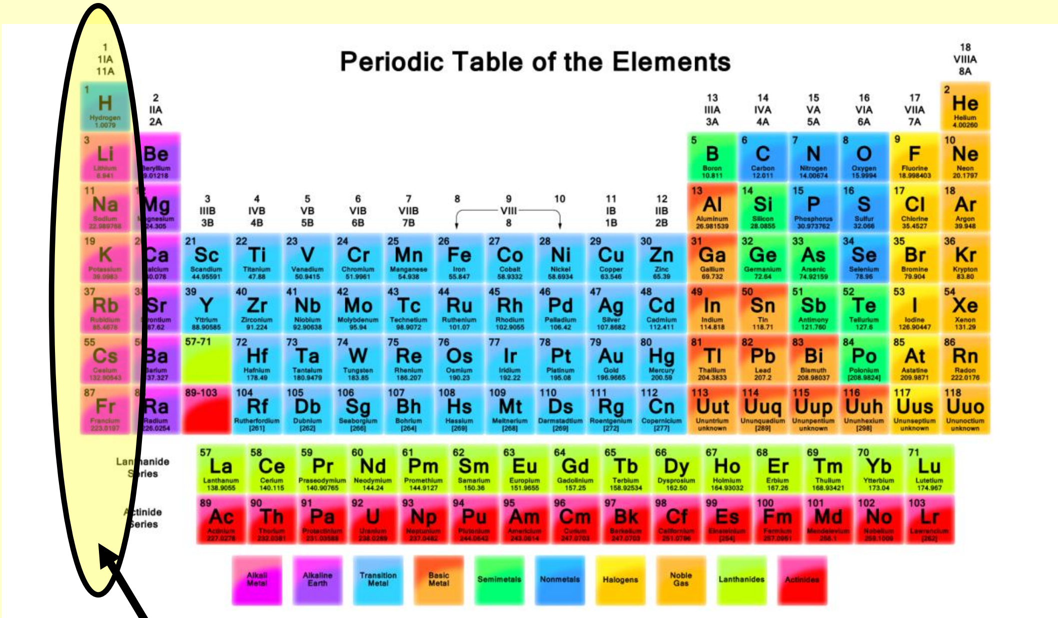
$\Delta E = h\nu$ = 8.27x10^{-5} eV

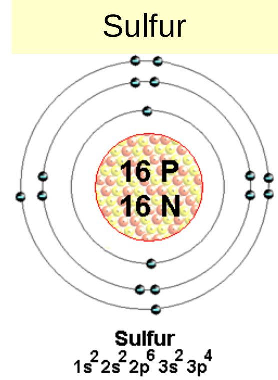
Photons at RF to lower THz will not change the state (or orbit)

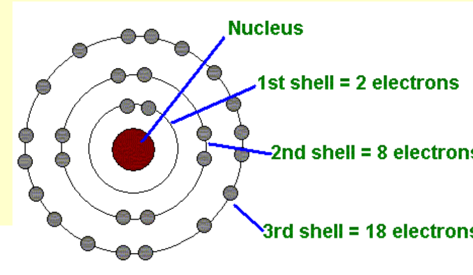
A Little Atomic Physics: Fine Structure



Alkali Atoms and Rydberg Atoms







Alkali metals or atoms

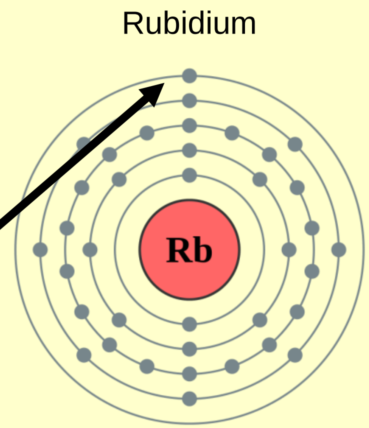
One electron in the outer shell

- The outer electron can be predictably excited
- We can use theoretical calculations of the hydrogen atom to predict interactions
- This is especially true for Rydberg Atoms (excited atoms to a very large n)

Transition for ground state of Rb: $5S_{1/2}$-$5P_{1/2}$

λ=780.24 nm (UV) and $\Delta E = h\nu$ = 1.59 eV

20 GHz: $\Delta E = h\nu$ = 8.27x10^{-5} eV



one electron in outer shell

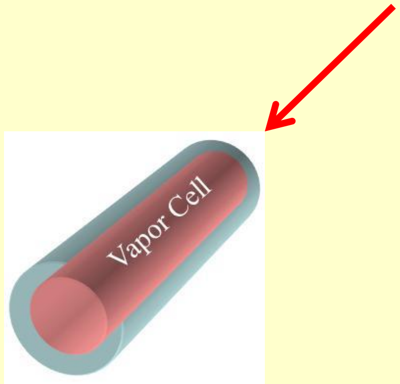
ground state: n=5

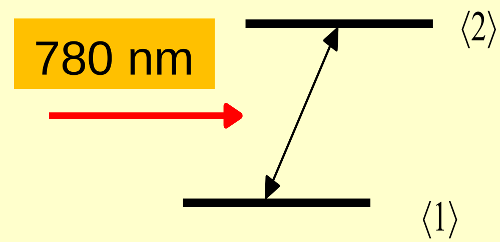
RF Source on a cells

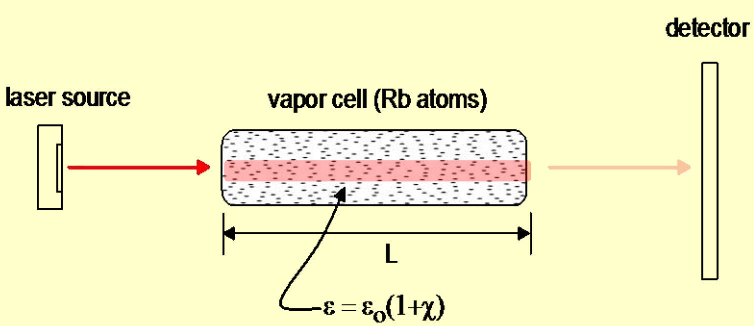
However, if we precondition the atom (with two different color lasers), we can then use RF photons to change the atom to a different state, and use this effect to determine the E-field strength of the applied RF energy.

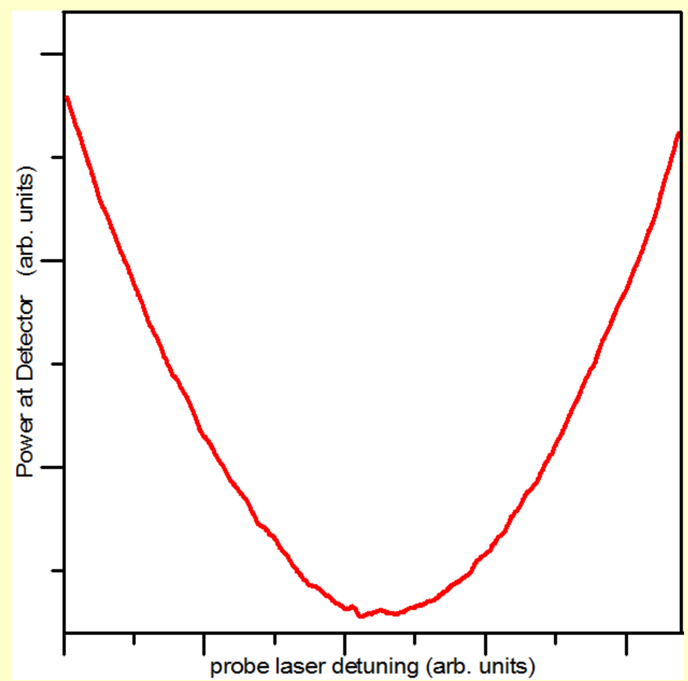
On Resonance

A laser tuned to resonance of the ground state transition

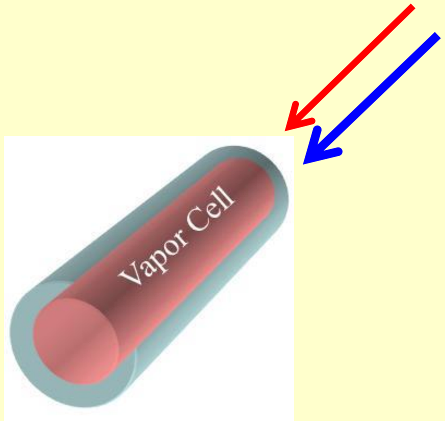


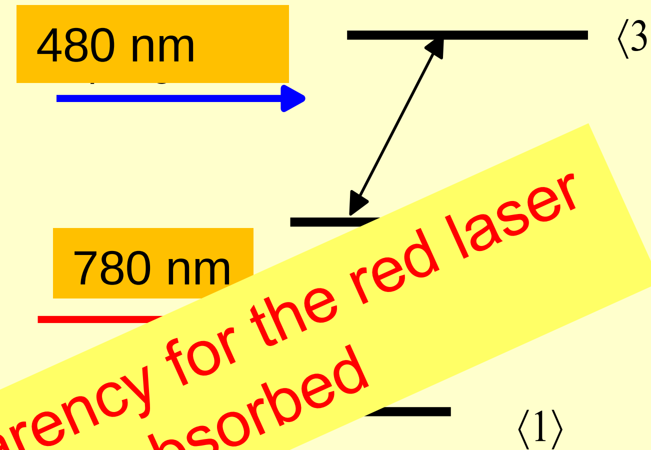






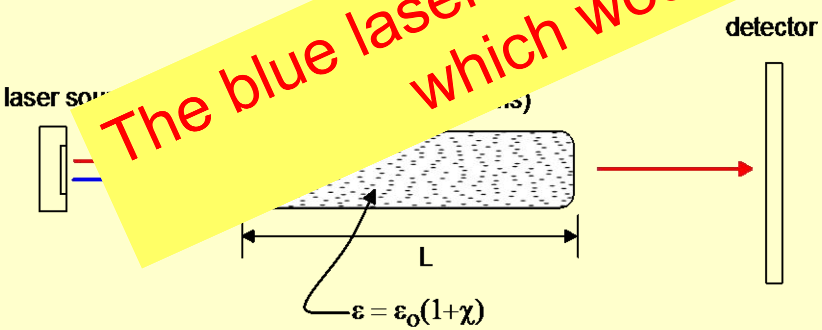
EIT: Electromagnetically induced transparency

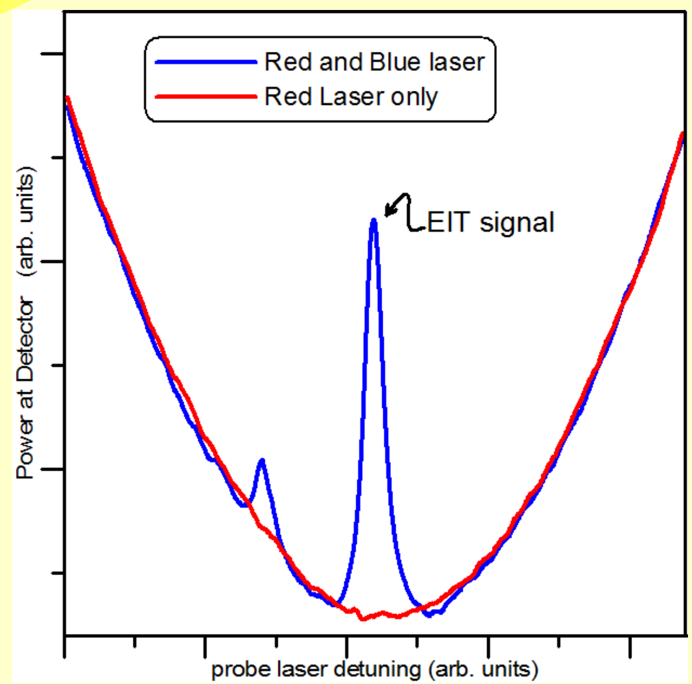




The blue laser induces a transparency for the red laser which would normally be absorbed

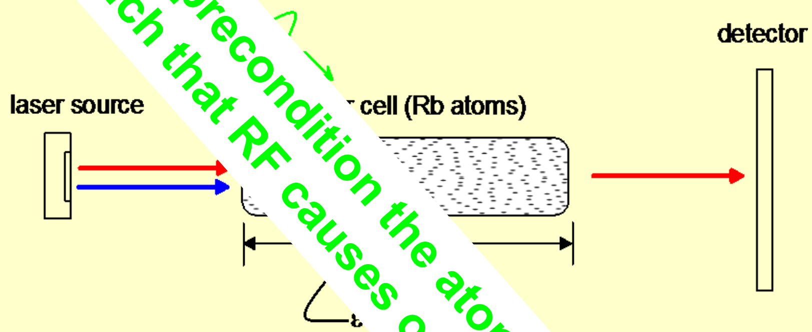
…erence between the two state

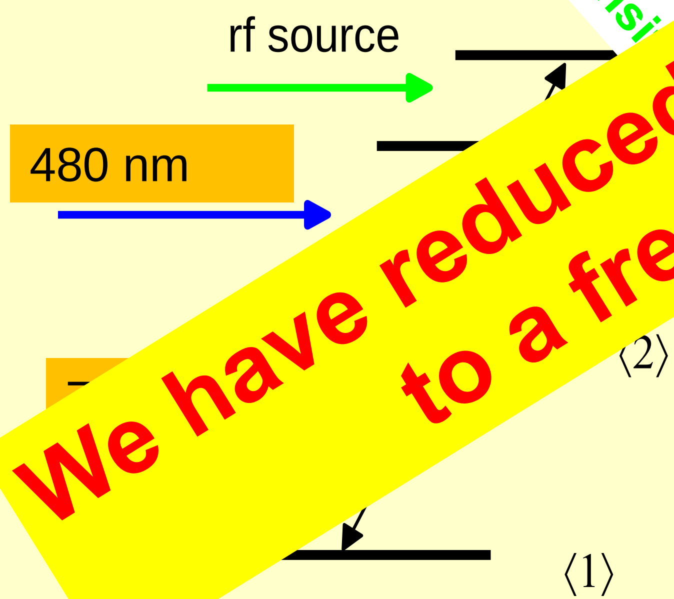


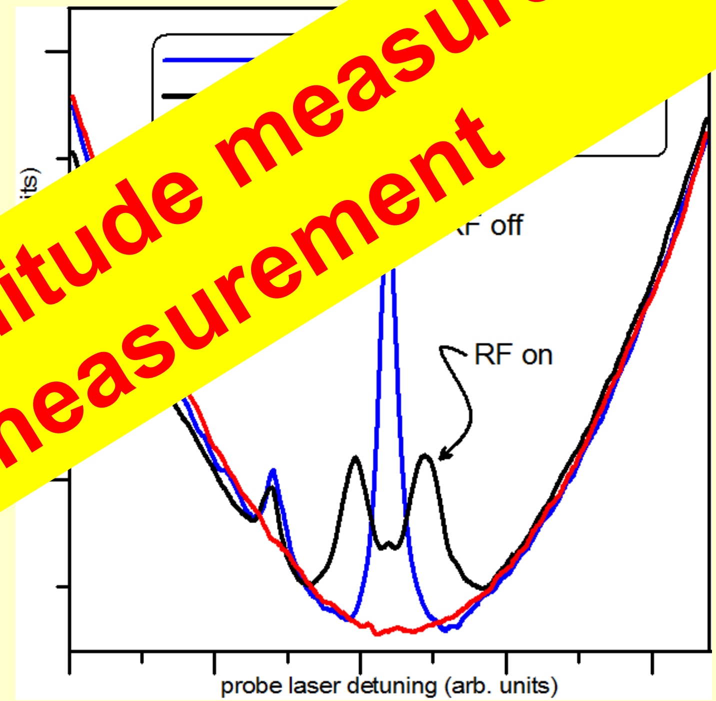


EIT with an RF source

The blue laser gets us high-ene…
next transition can be m…







Splitting in the EIT signal
(Autler-Townes Splitting)

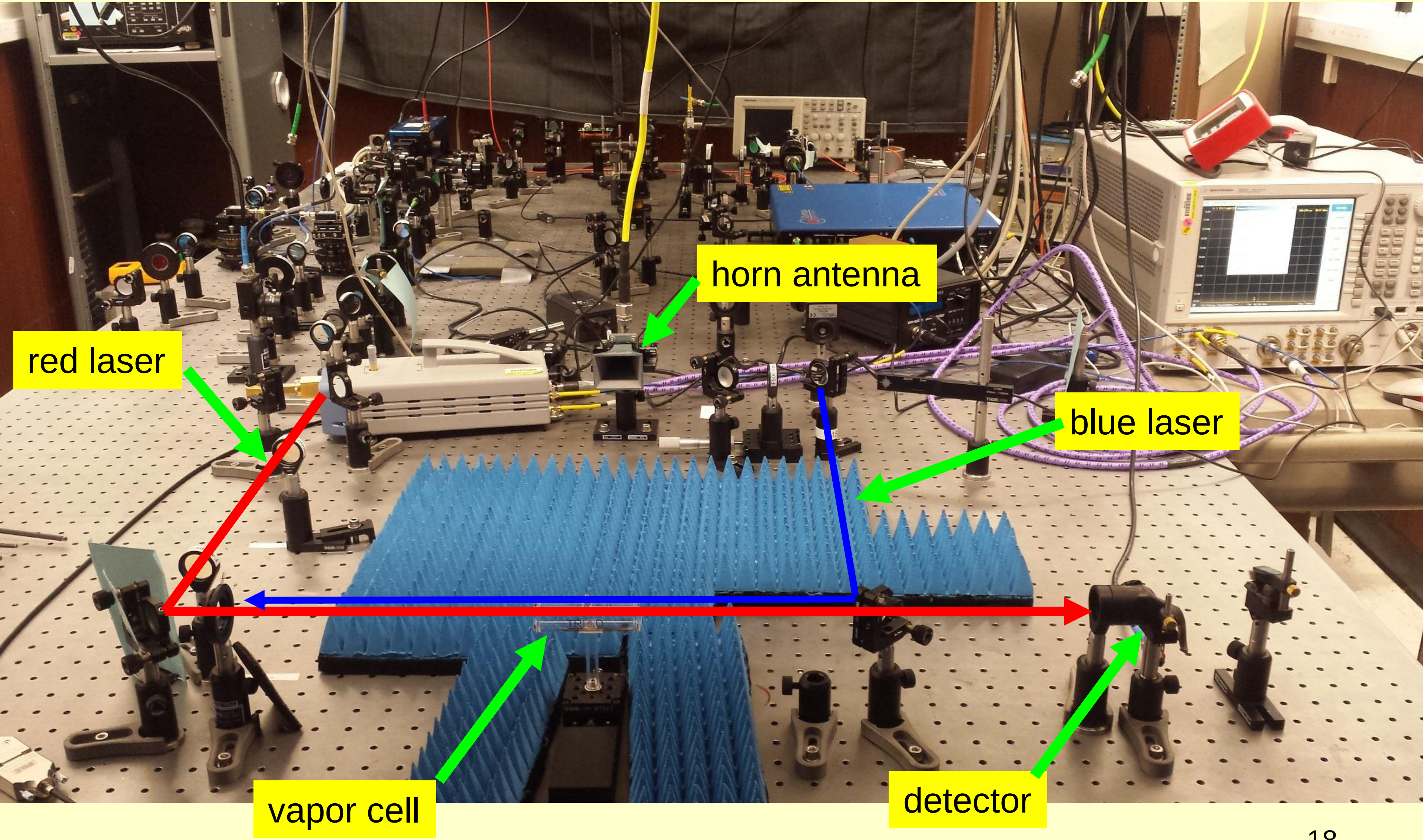
$$\Omega_{rf} = |E|\frac{\wp}{\hbar}$$

$$|E| = \Omega_{rf}\frac{\hbar}{\wp}$$

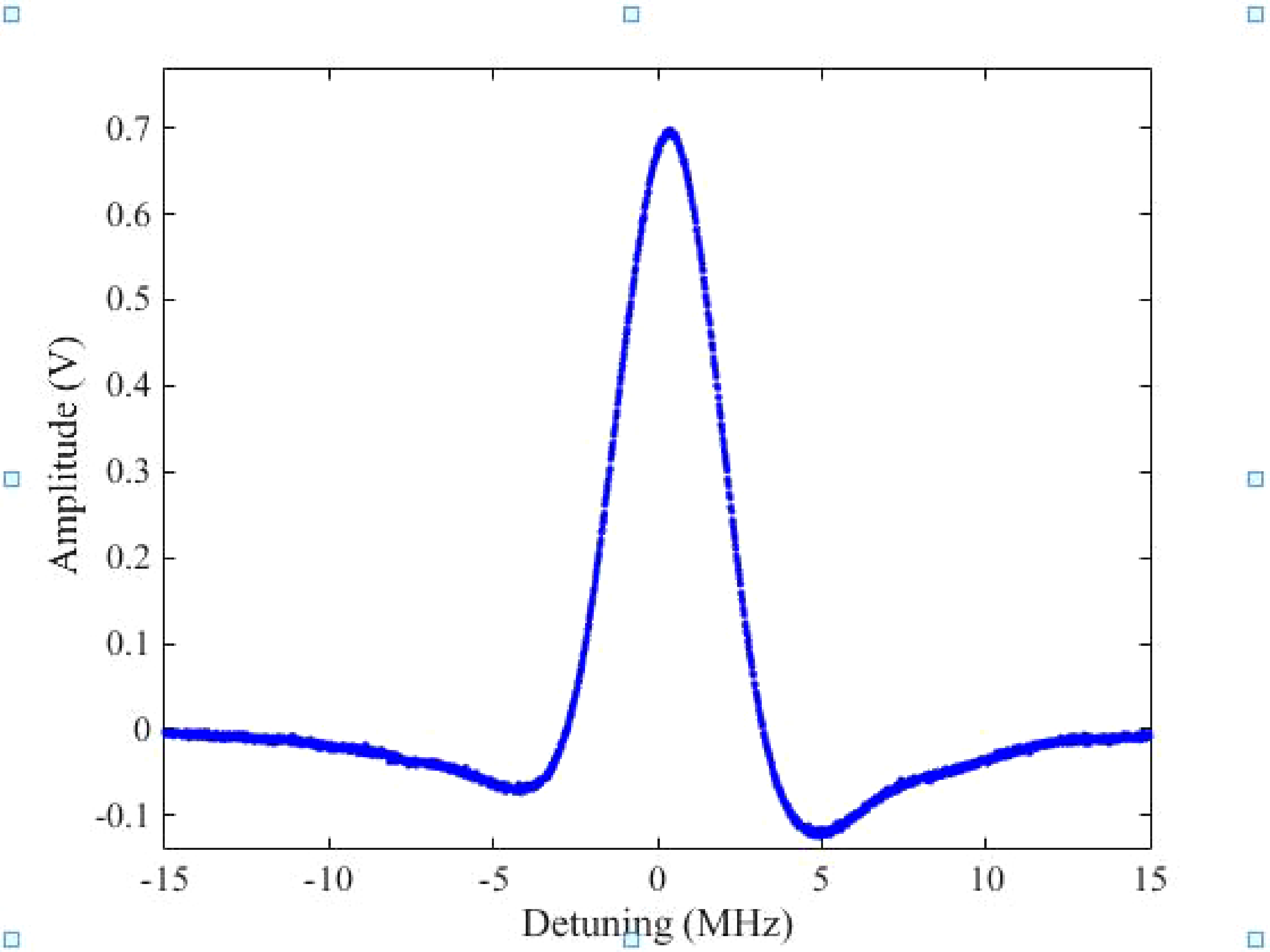
We precondition the atoms with two la…
such that RF causes on atomic transi…

We have reduced an amplitude measurement to a frequency measurement

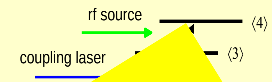
Measurement Setup (very simple, YES. But is it, ChipScale??)

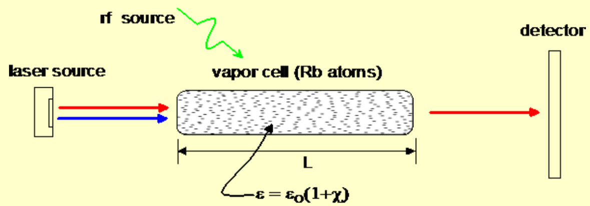


Signal on the Detector: Typical Experimental Result for the Splitting



Four-Level EIT: RF E-field Measurement



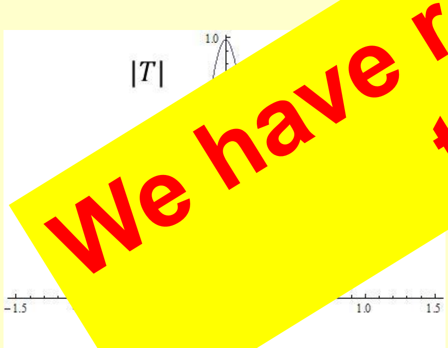


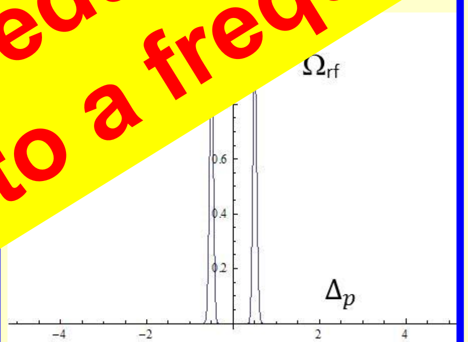
$$\chi = \frac{N\,|\wp_{12}|\,\Omega_p}{|E_p|\;\varepsilon_o}\;\frac{(\gamma_{13} - j\,\Delta_p)\,(\gamma_{14} - j\,\Delta \ldots}{(\gamma_{12} - j\,\Delta_p)\left(\frac{\Omega_{rf}}{2}\right)^2 + (\gamma_{14} - j\,\Delta \ldots}$$

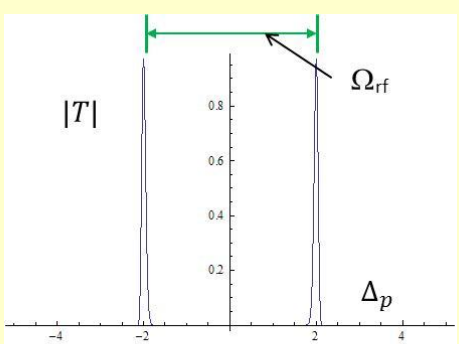
[illegible]

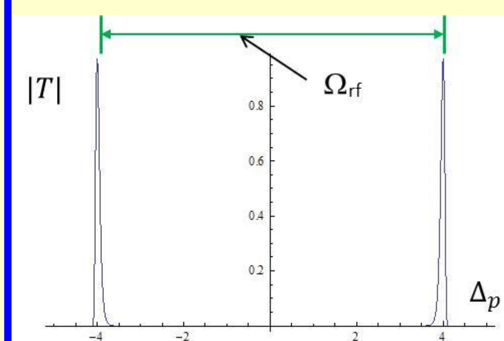
Ω_{rf} =0 | Ω_{rf} =1 | [illegible] | Ω_{rf} =4

$|E$ [illegible] $\wp$ Ω_{rf}



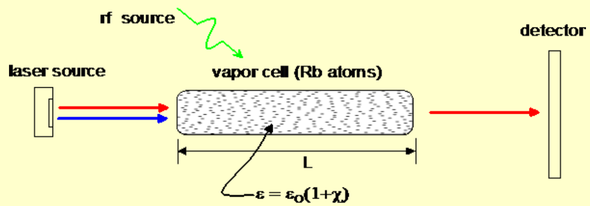






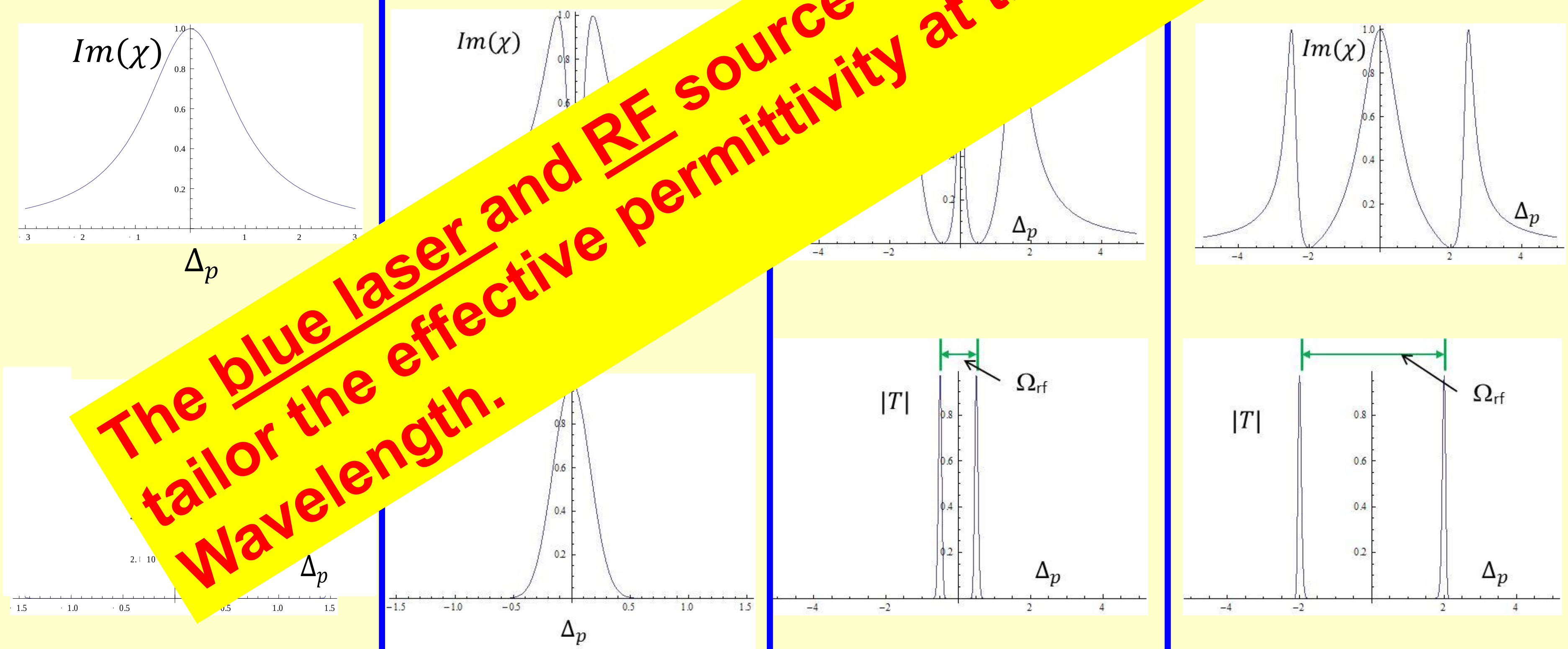
We have reduced a amplitude measurement to a frequency measurement

MetaMaterial Viewpoint



$$\chi = \frac{N\,|\wp_{12}|\,\Omega_p}{|E_p|\,\varepsilon_o}\;\frac{(\gamma_{13} - j\,\Delta_p)\,(\gamma \ldots}{(\gamma_{12} - j\,\Delta_p)\left(\frac{\Omega_{rf}}{2}\right)^2 + (\gamma_1 \ldots j\,\Delta_p)}$$

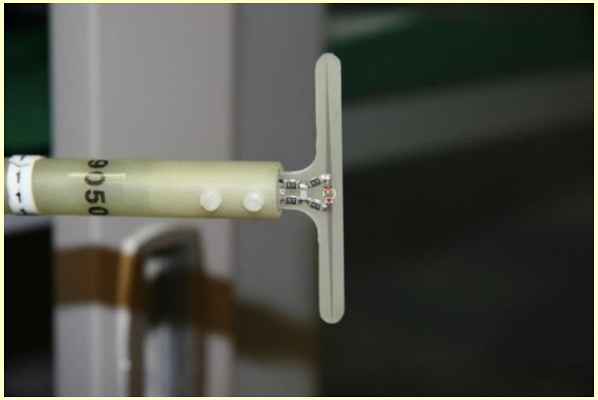
Blue Laser Off | RF Off | on: Ω_{rf} =4

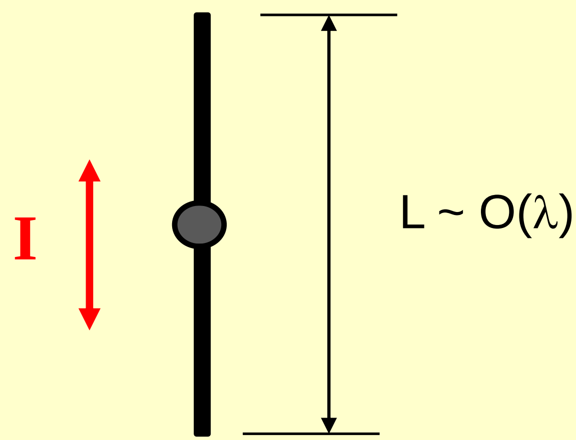


The <u>blue laser</u> and <u>RF</u> source is used to tailor the effective permittivity at the probe-laser Wavelength.

Broadband Nature of Probe/Sensor

Conventional Probe/Sensor

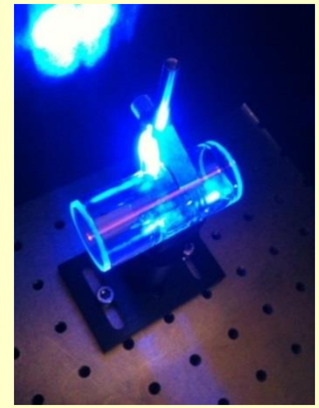




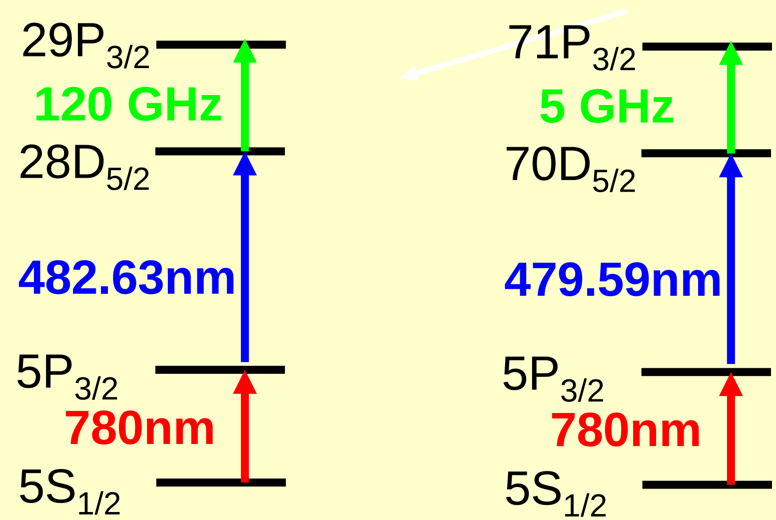
Change L for desired frequency

Atom-Based Probe/Sensor

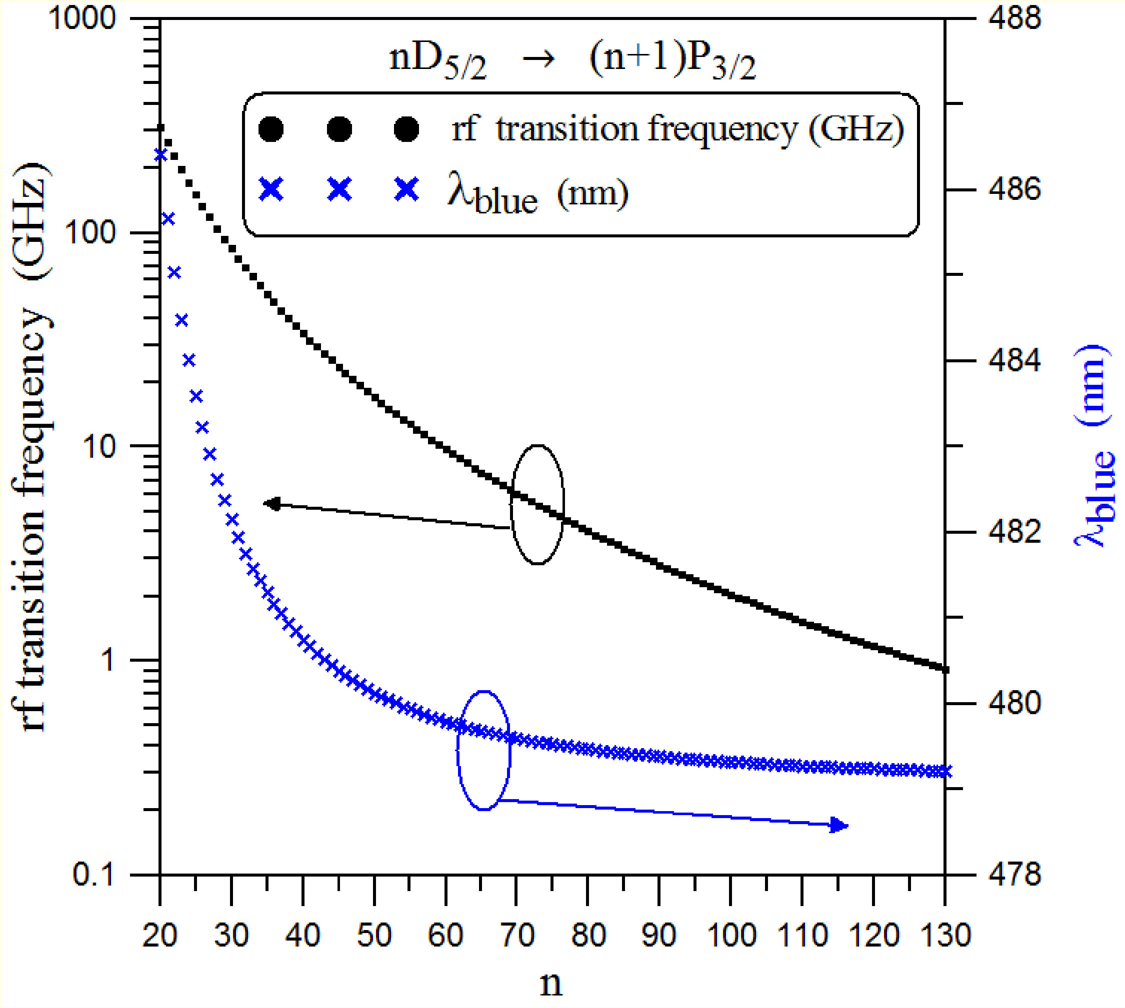
(the atom is a **<u>“RICH”</u>** resonant structure)

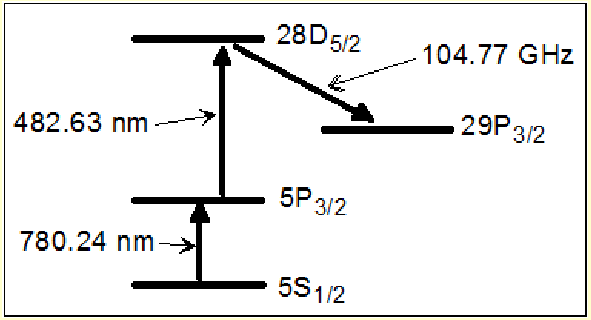


Change Blue laser for desired frequency



Broadband Nature of Probe/Sensor





With one vapor cell, red-laser and a tunable blue-laser, we can measure an E-field ranging from 1 GHz to 500 GHz (may be as high as 1 THz)

Sensitivity

rf source detector rf source (4)

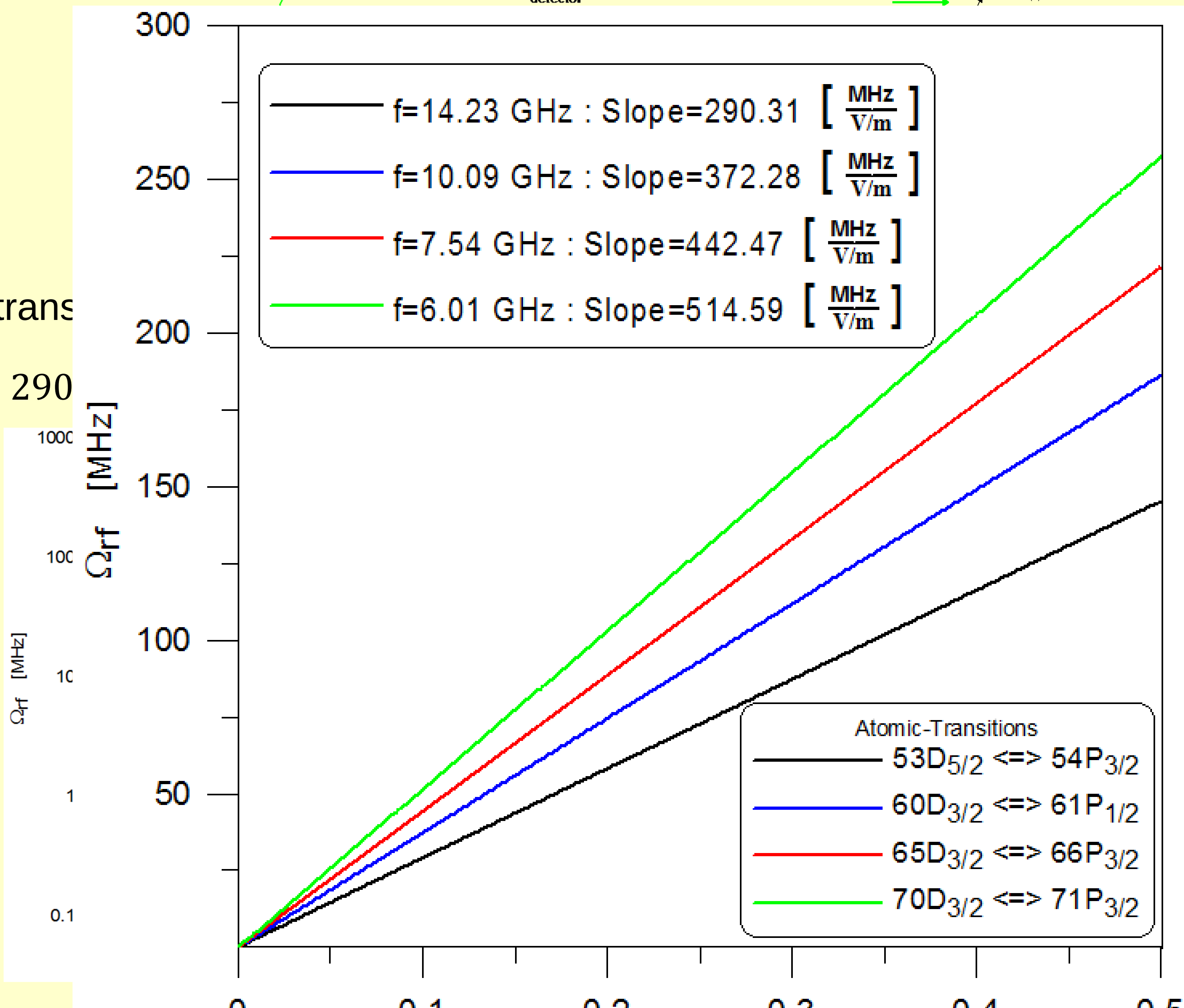
RF-trans

$\Omega_{rf} \approx 290$

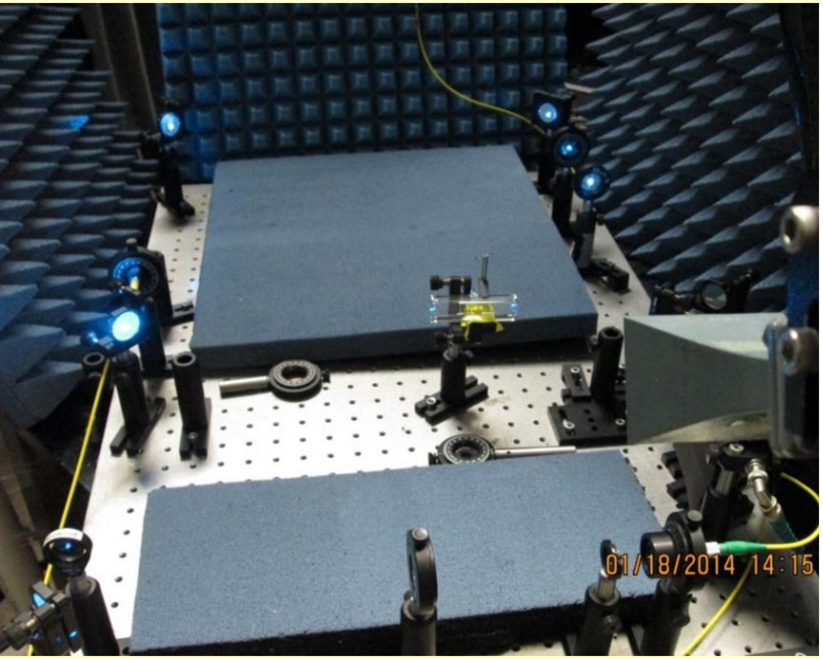
$C \cdot m]$

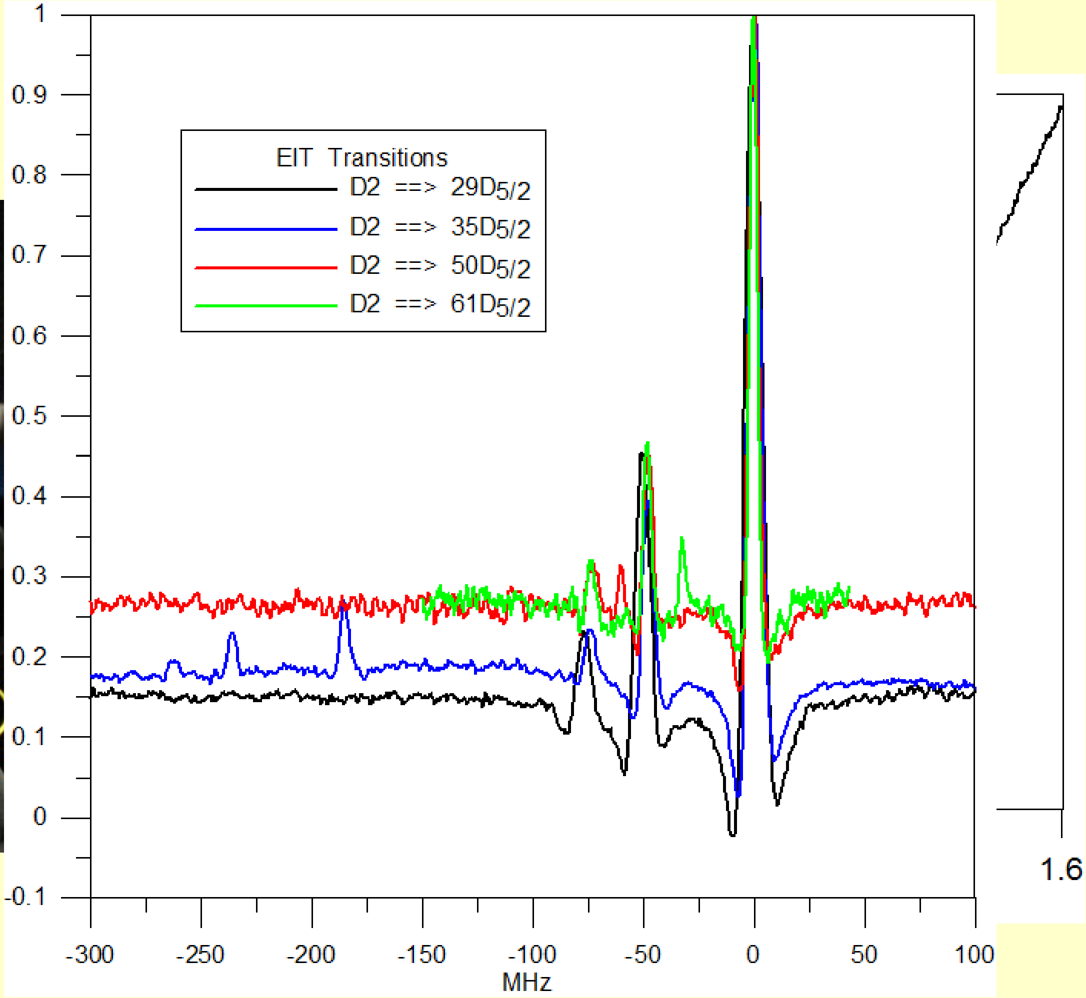
$^{-10}$ $[m]$

^{19} $[C]$

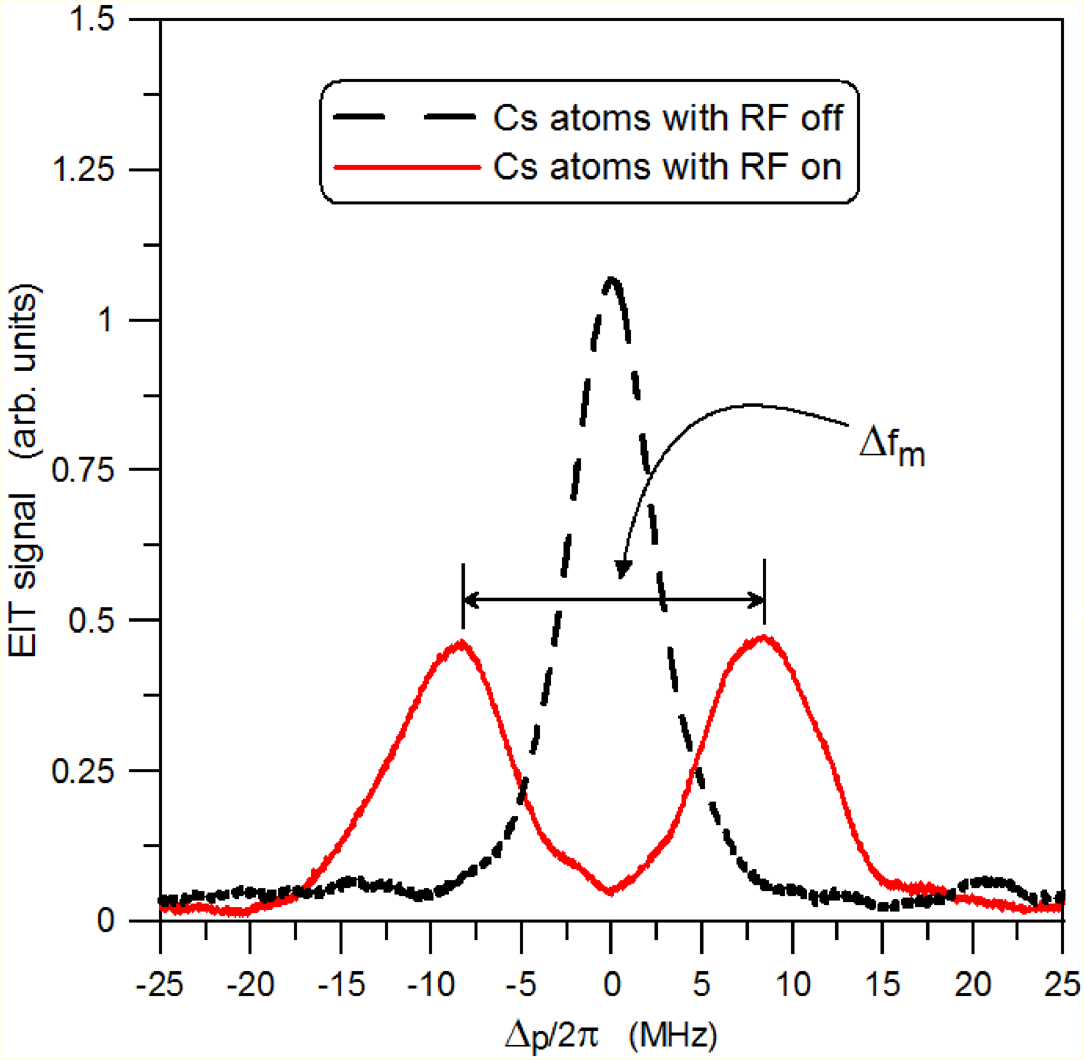


Demonstrate EIT for large number of D2 transitions: from 26D-to-68D

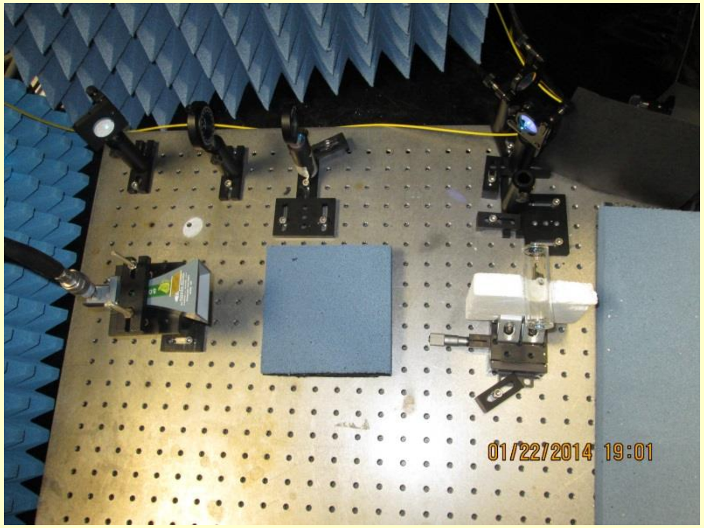


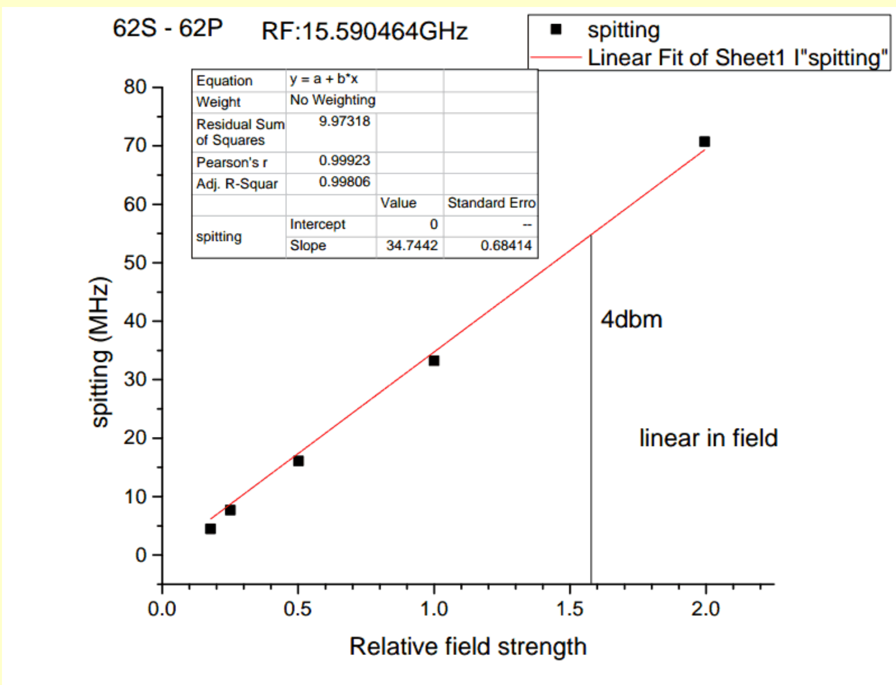


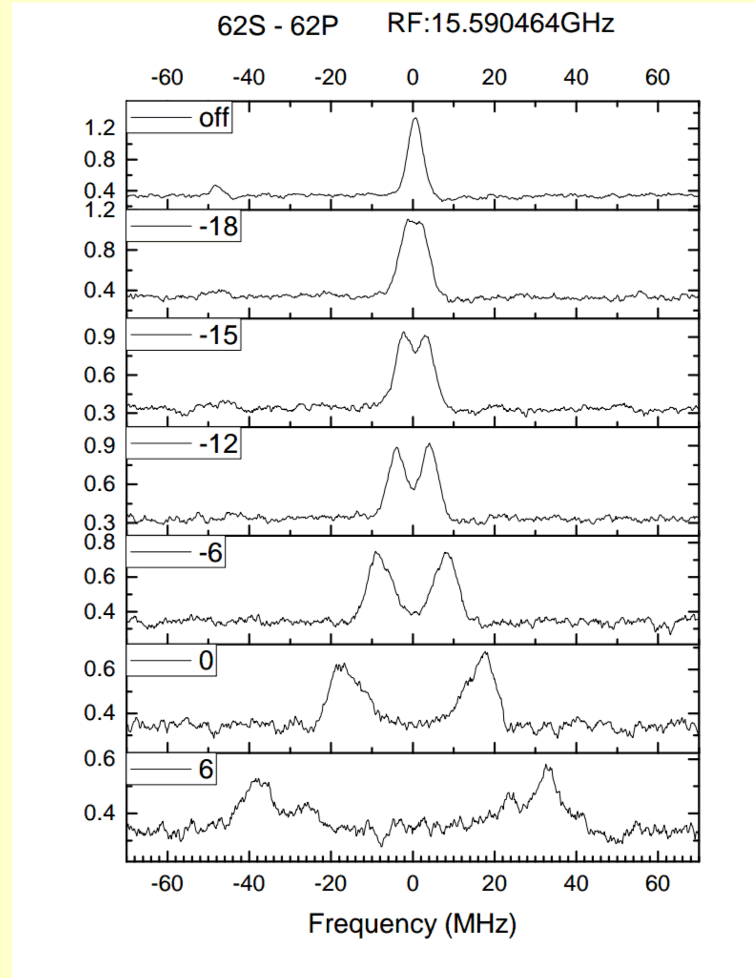
Typical EIT Signal



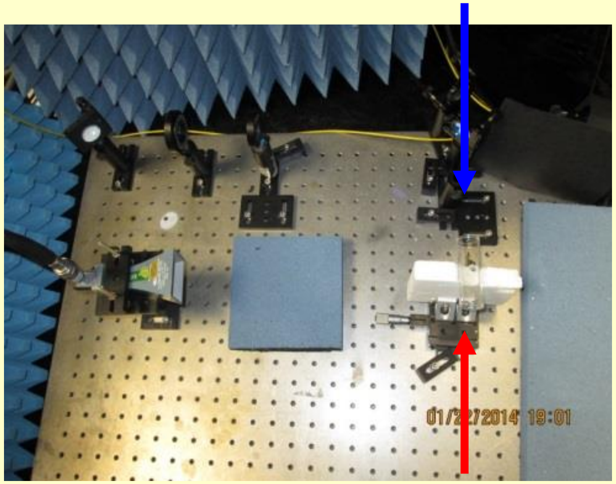
E-field Measurements at 15.56 GHz



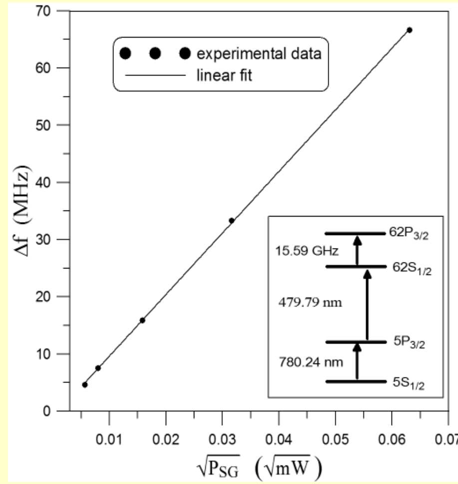




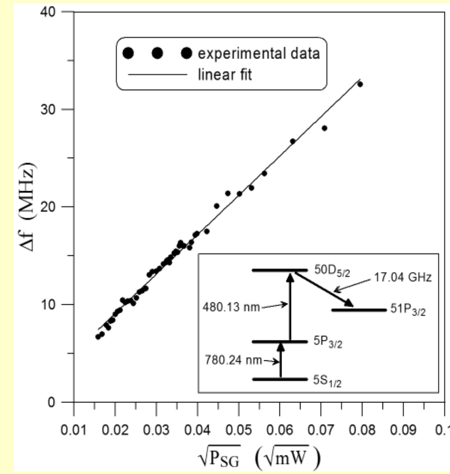
Broadband E-field Measurements



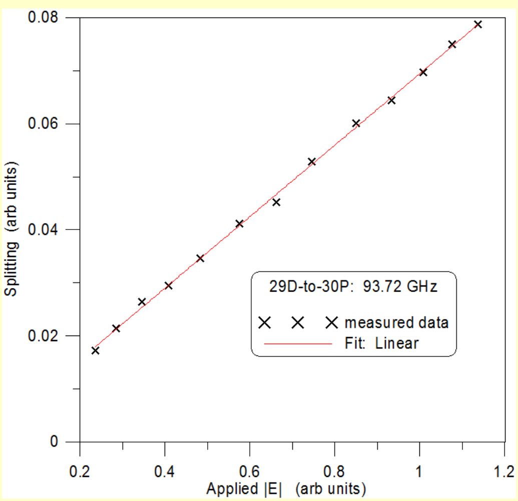
15.56 GHz



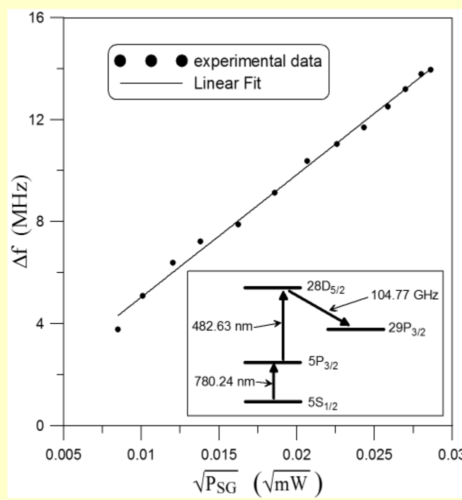
17.04 GHz



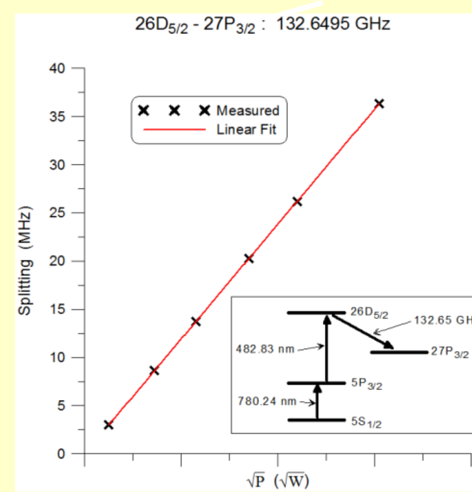
93.73 GHz



104.77 GHz



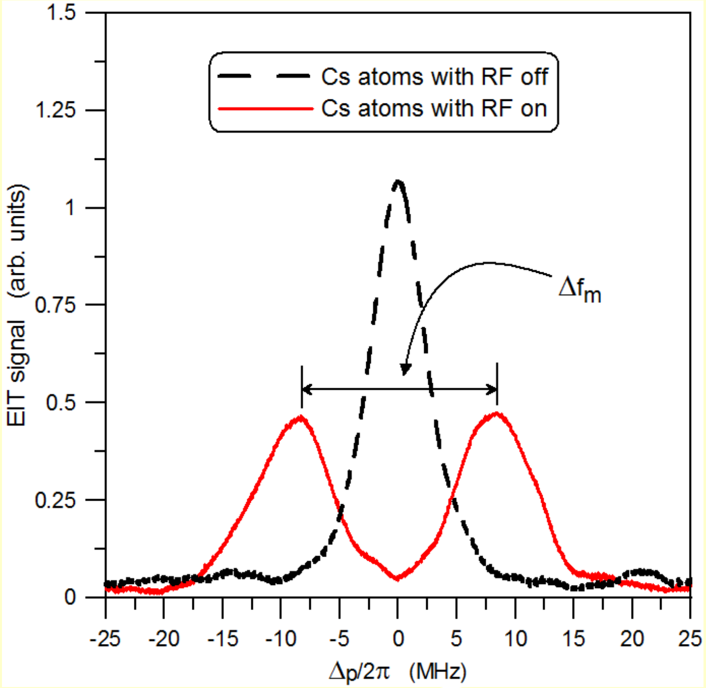
132.65 GHz



Determining the E-Field Strength

Recall:

$$|E| = 2\pi \frac{\hbar}{\wp} \Delta f$$



1) we just measured Δf

2) $\hbar$ is known : 1.054571596x10^{-32} J s

3) we need $\wp$

Dipole Moment

Since the dipole moment is directly related to the field we can measure, it is one of parameters that govern the uncertainty of the E-field measurement. We need accurate values of the dipole moment.

We have written a numerical code to first determine the wavefunction for a given set of states. These wavefunction were then numerical integrated to give the desired dipole moment.

We follow the technique of Numerov as discussed in Gallagher's book, in which the wavefunction is obtained from a finite-difference technique. We start with:

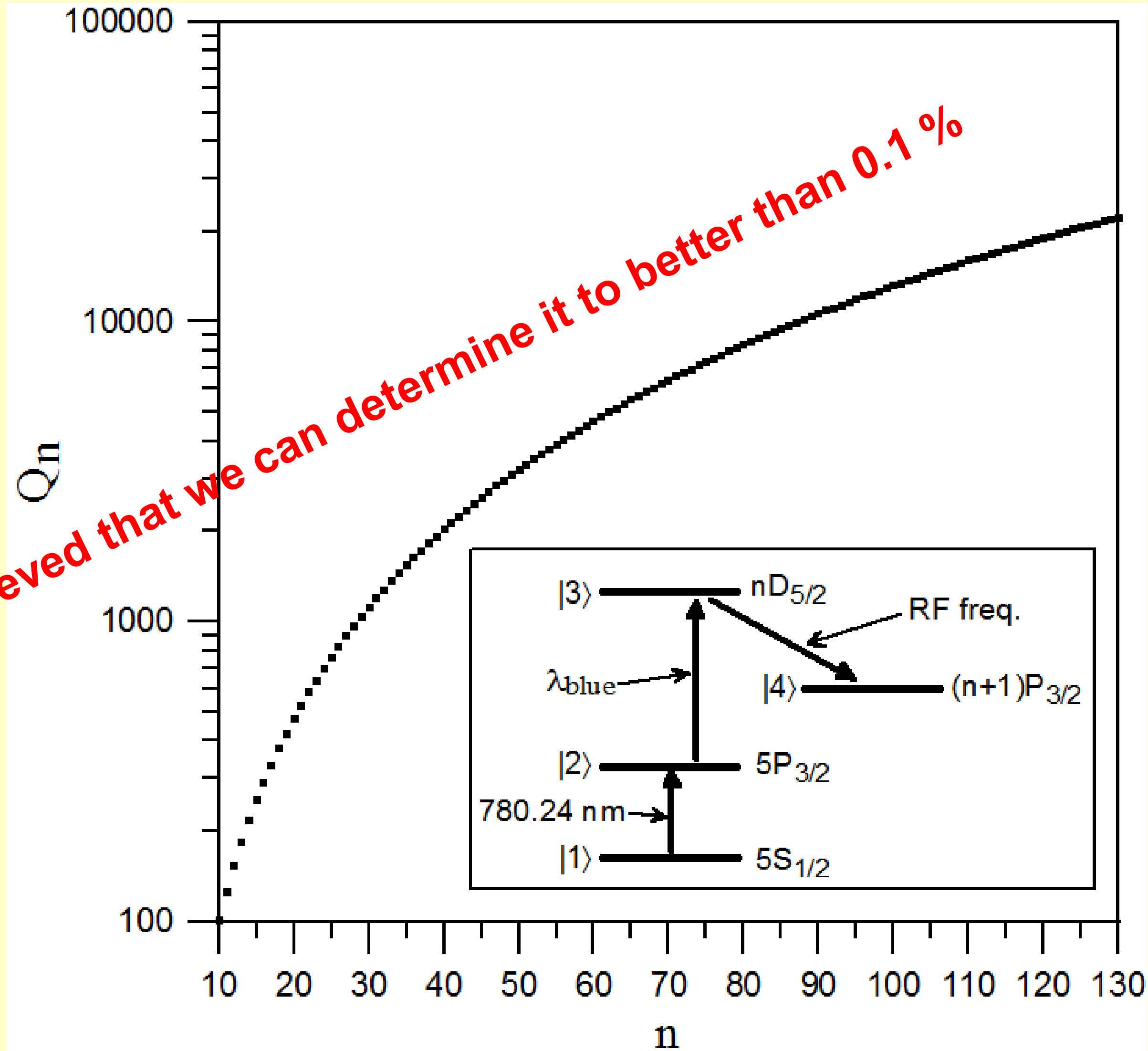
$E_{n,l,j} = \frac{-R_y}{(n-\delta_{l,j})^2}$ and $\left(\frac{\nabla^2}{2} + \frac{1}{r} + E_{n,l,j}\right)\psi = 0$ *where* $\delta_{l,j}$ *is the empirically quantum defect*

we need $\wp_{12} = e\langle\psi_1|\, r \,|\,\psi_2\rangle$ which we get from a numerical integration of the wavefunctions

After writing the program, we compared the dipole moment to various values in the literature for both H and Rb atoms.

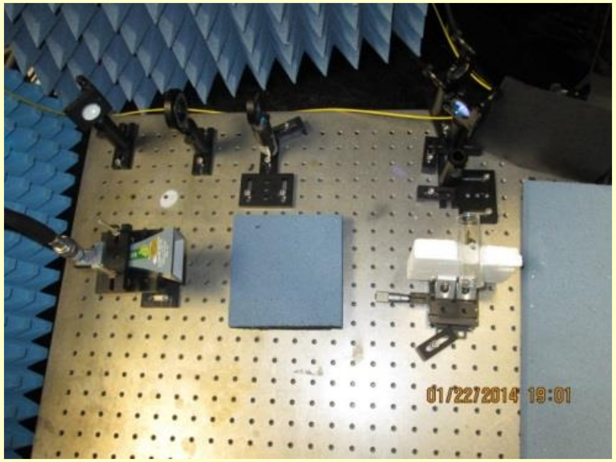
Dipole Moment

$$\wp = 0.4899\, e\, a_0\, Q_n$$

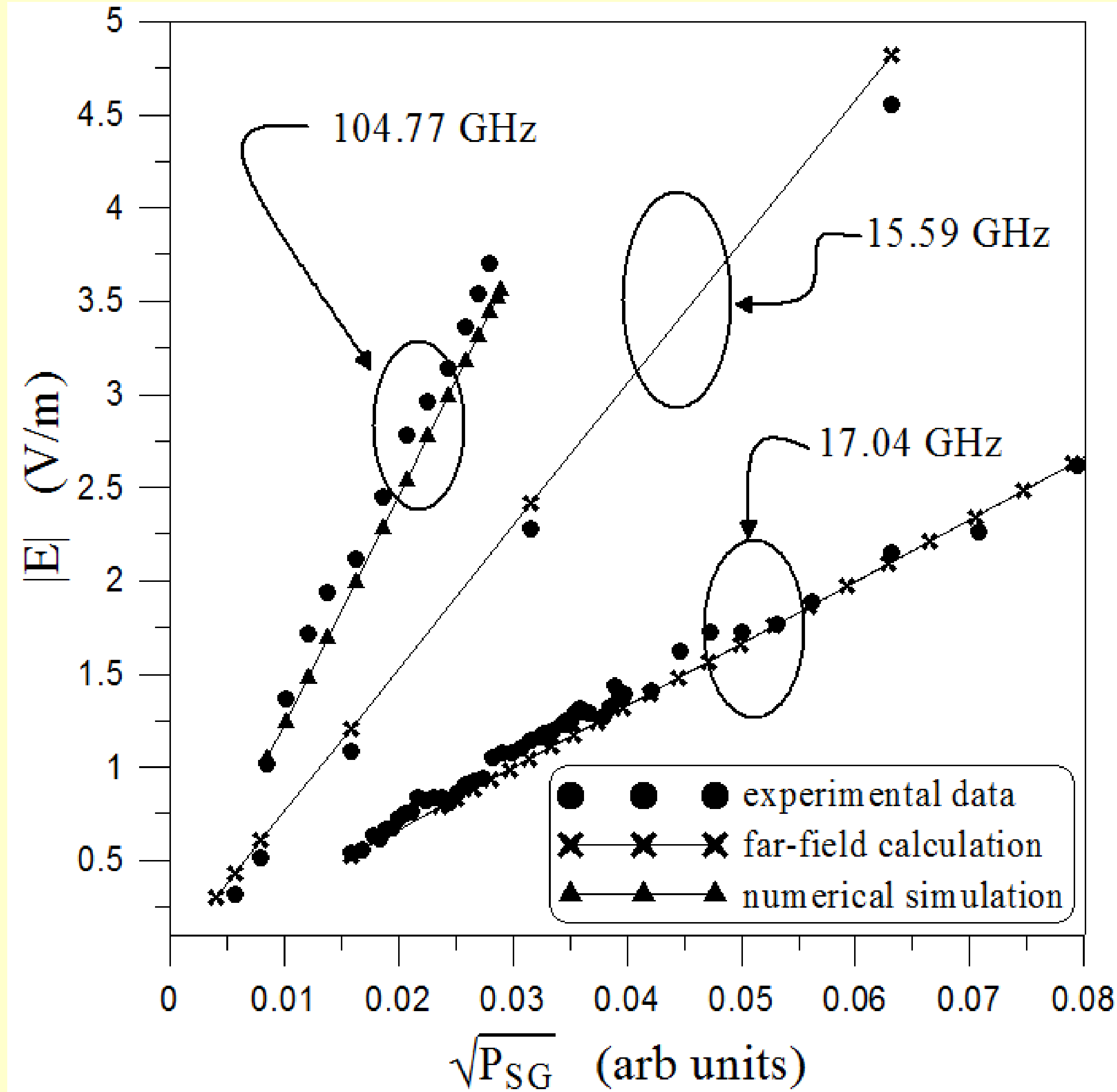


It is believed that we can determine it to better than 0.1 %

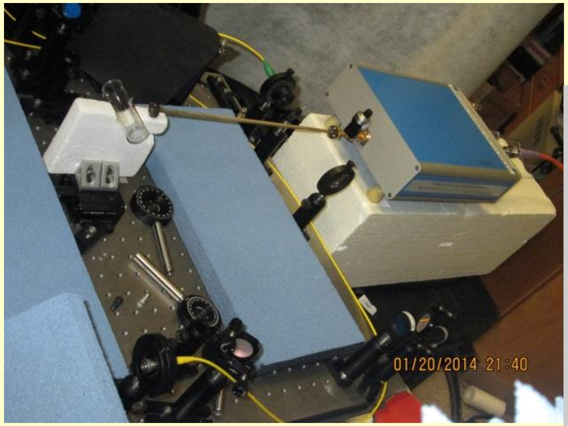
Correlation to Simulation and Far-field Calculations

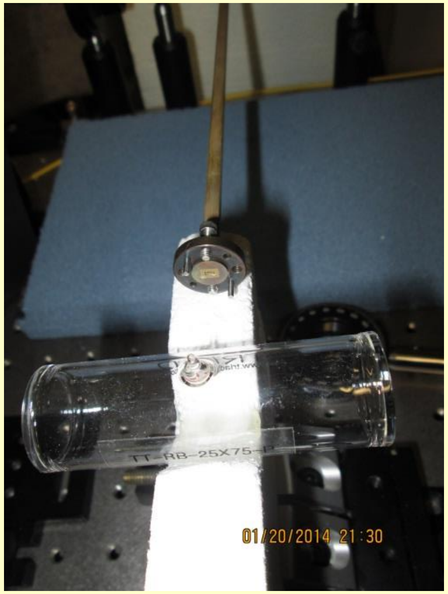


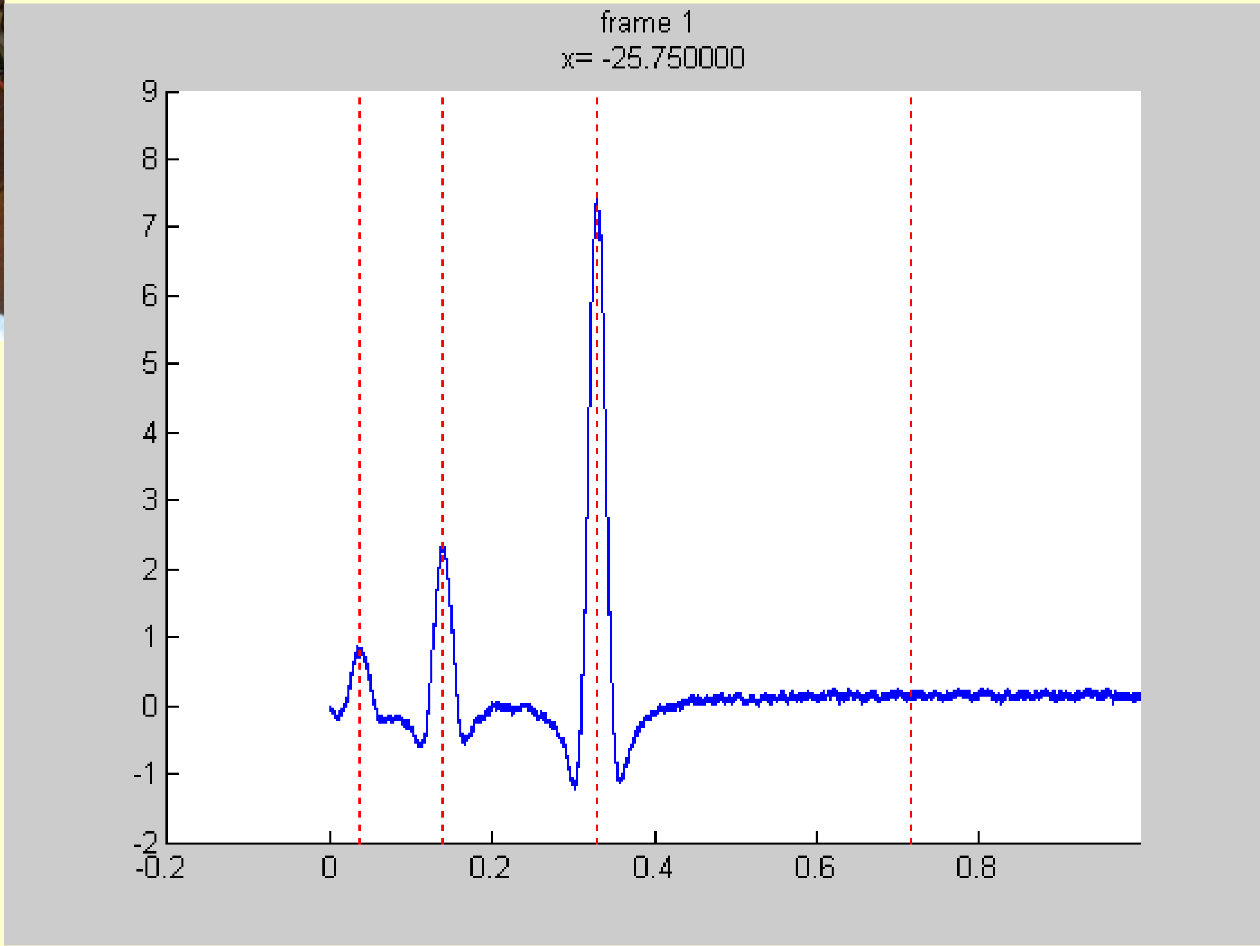
$$|E| = 2\pi \frac{\hbar}{\wp} \Delta f$$



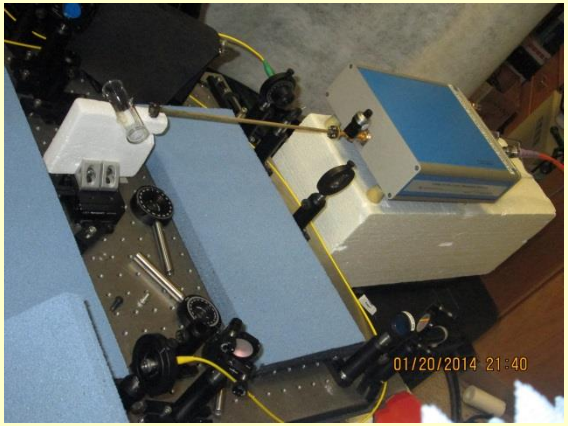
E-field Measurements at 93 GHz

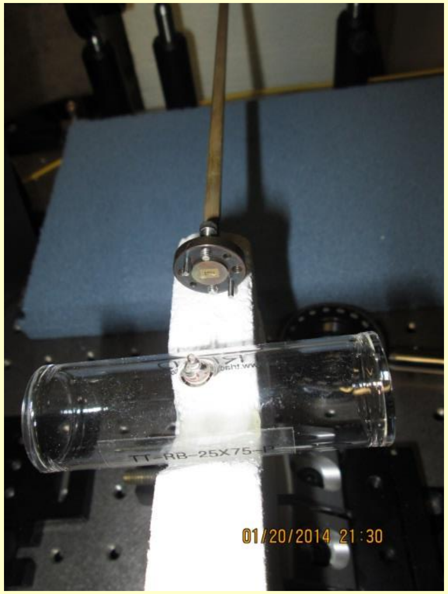


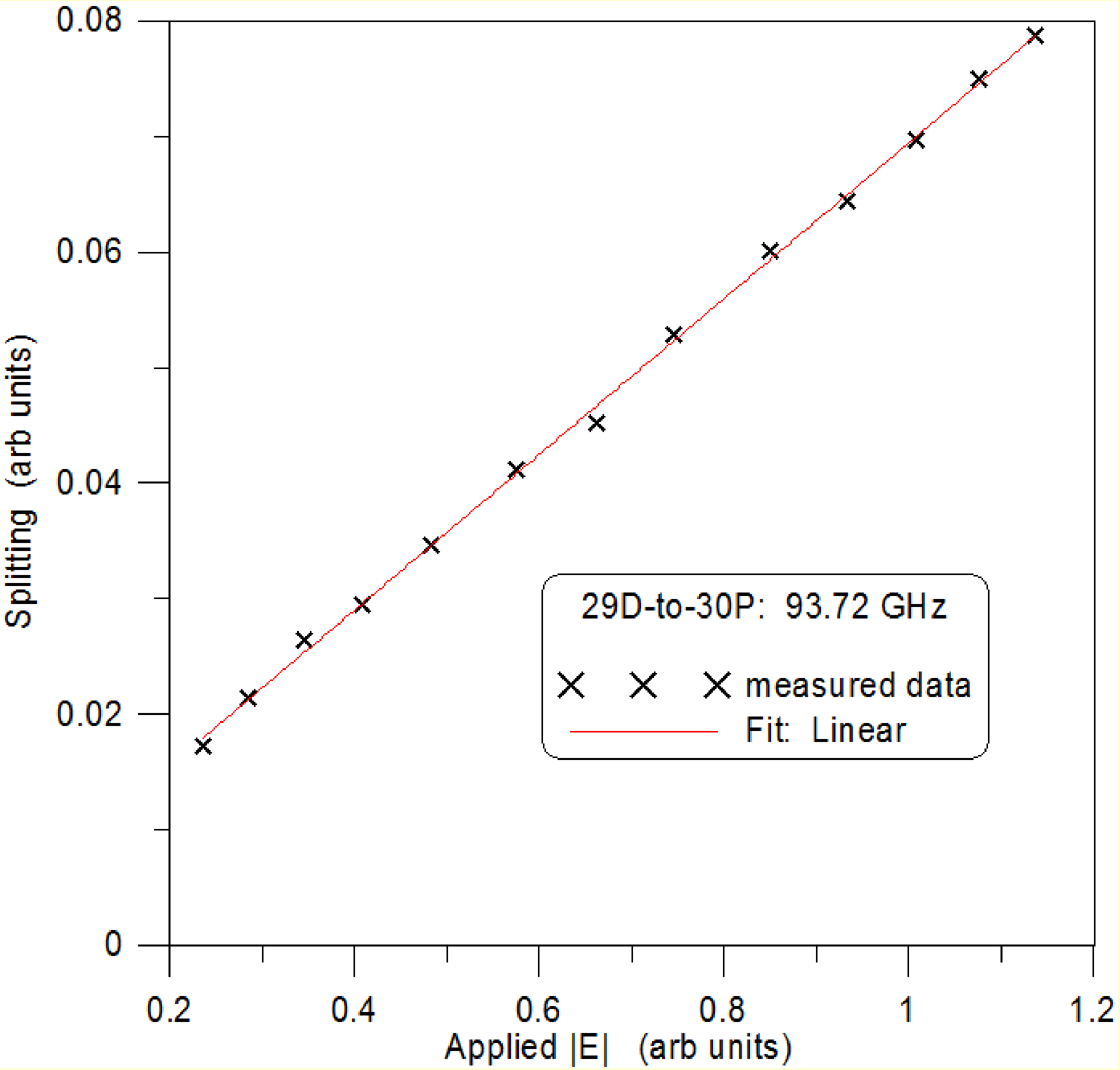




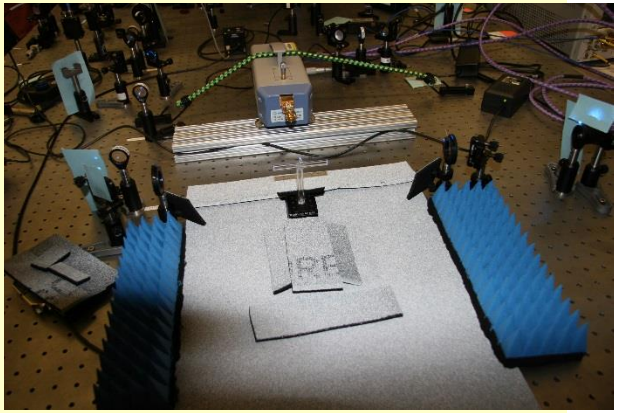
E-field Measurements at 93 GHz



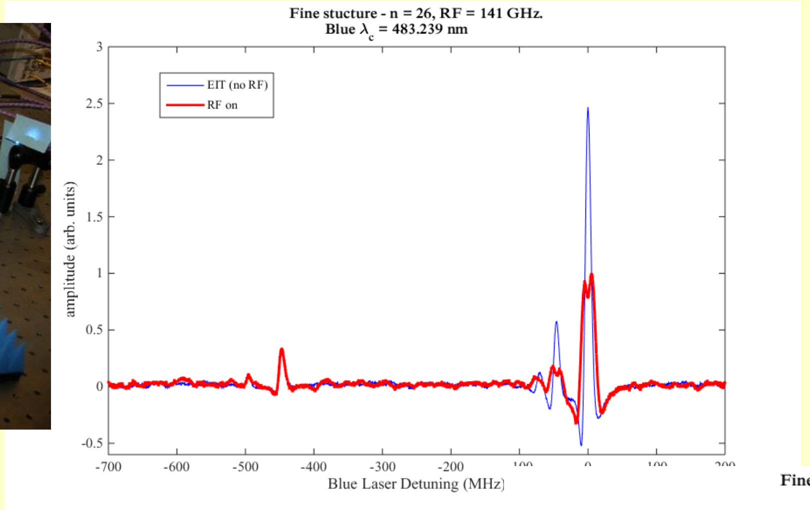




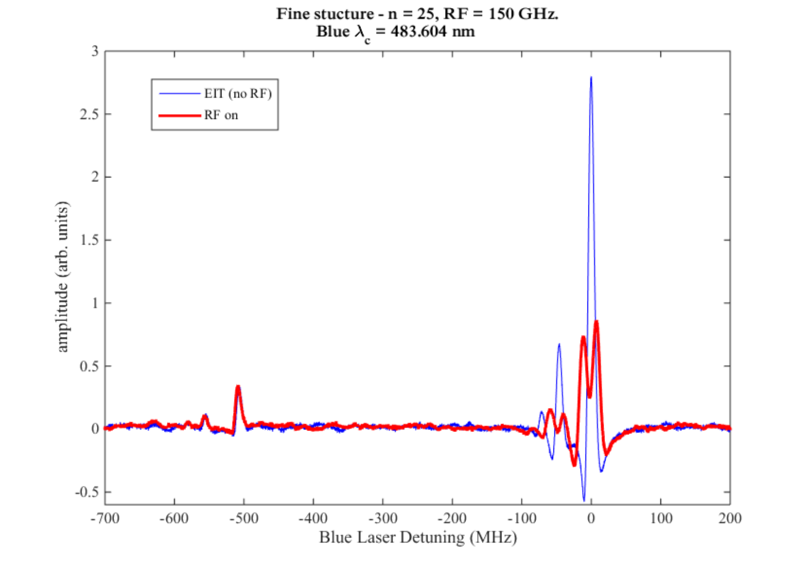
Going To Higher Frequencies



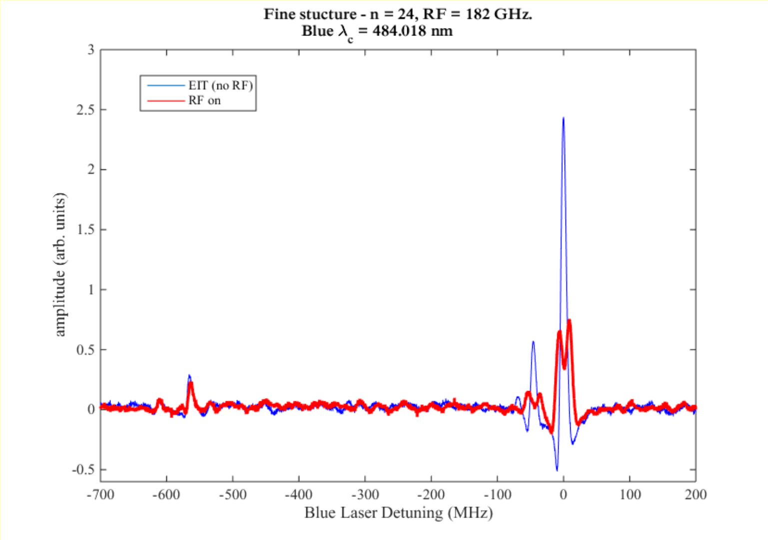
141 GHz



150 GHz

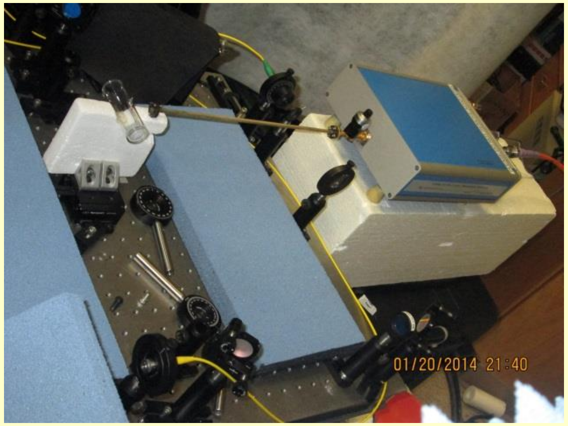


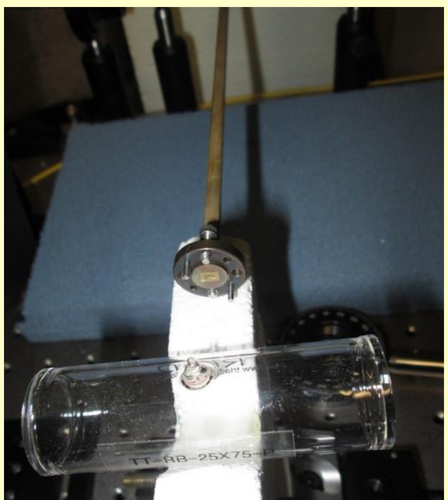
182 GHz

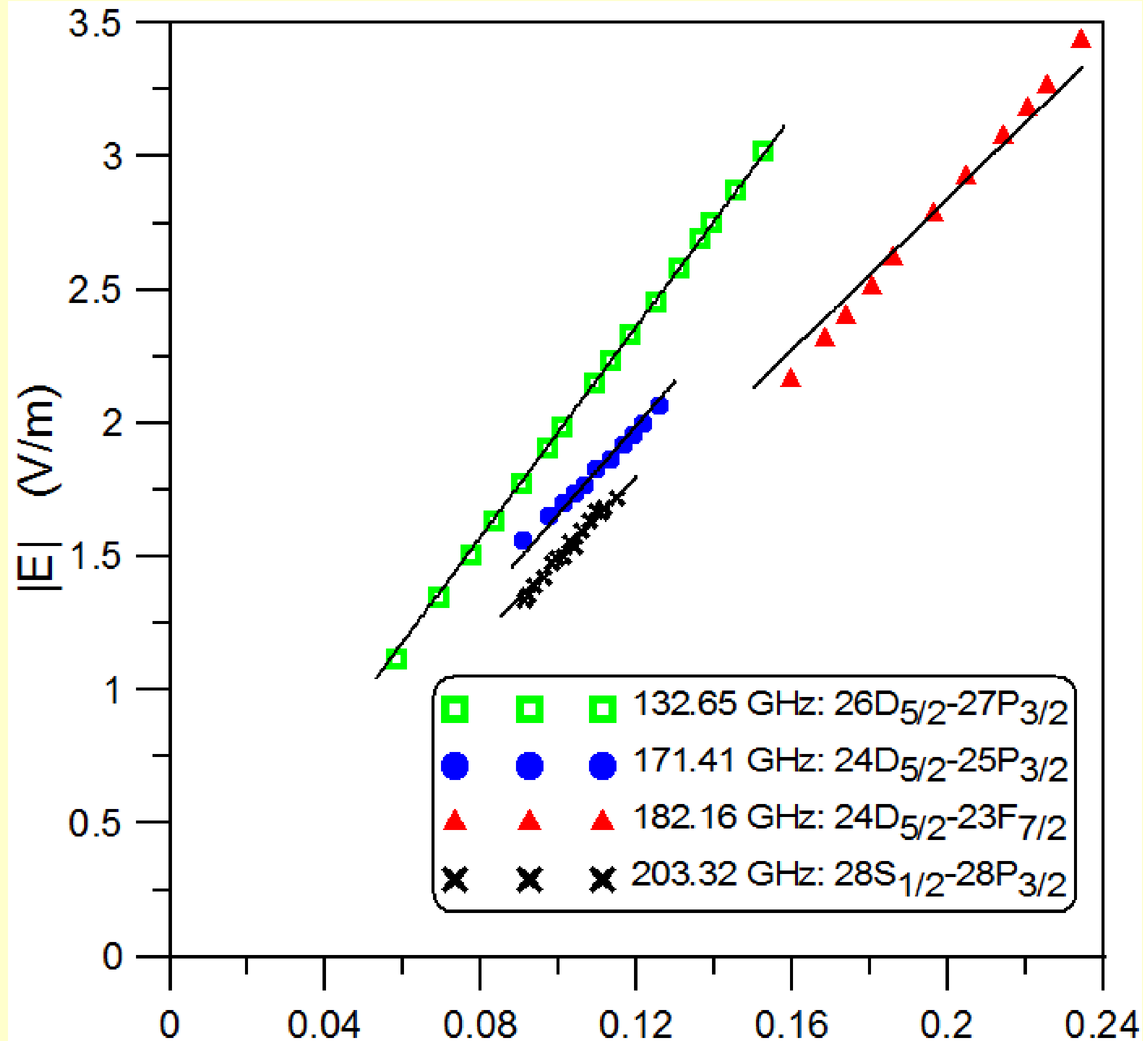


and up to 208 GHz

E-field Measurements at sub-THz and mm-waves: >200 GHz

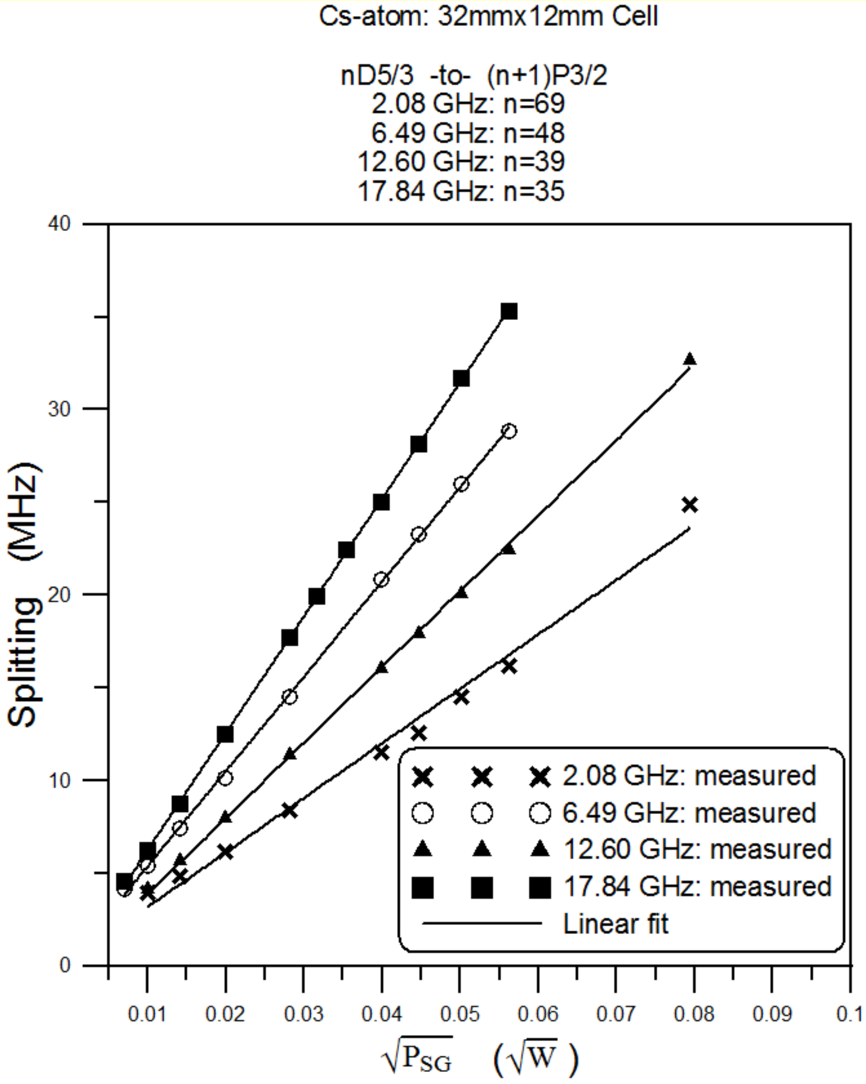




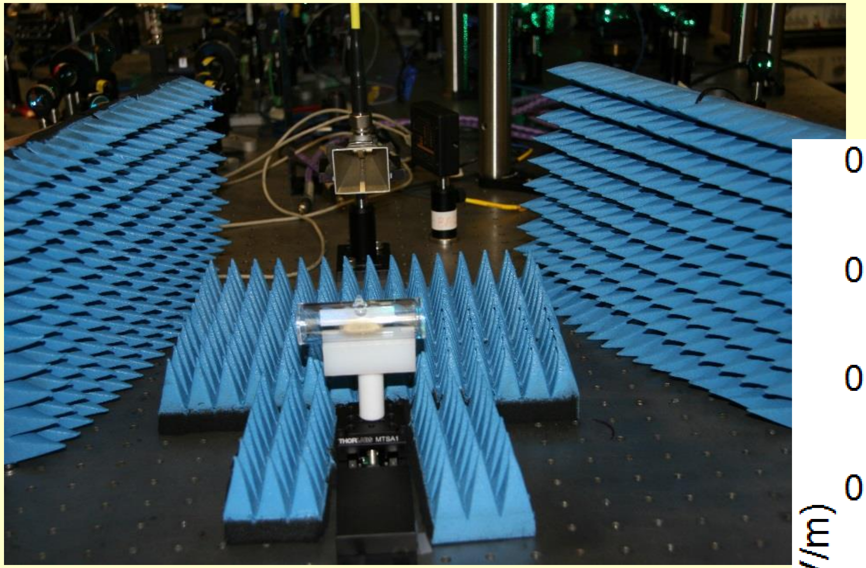


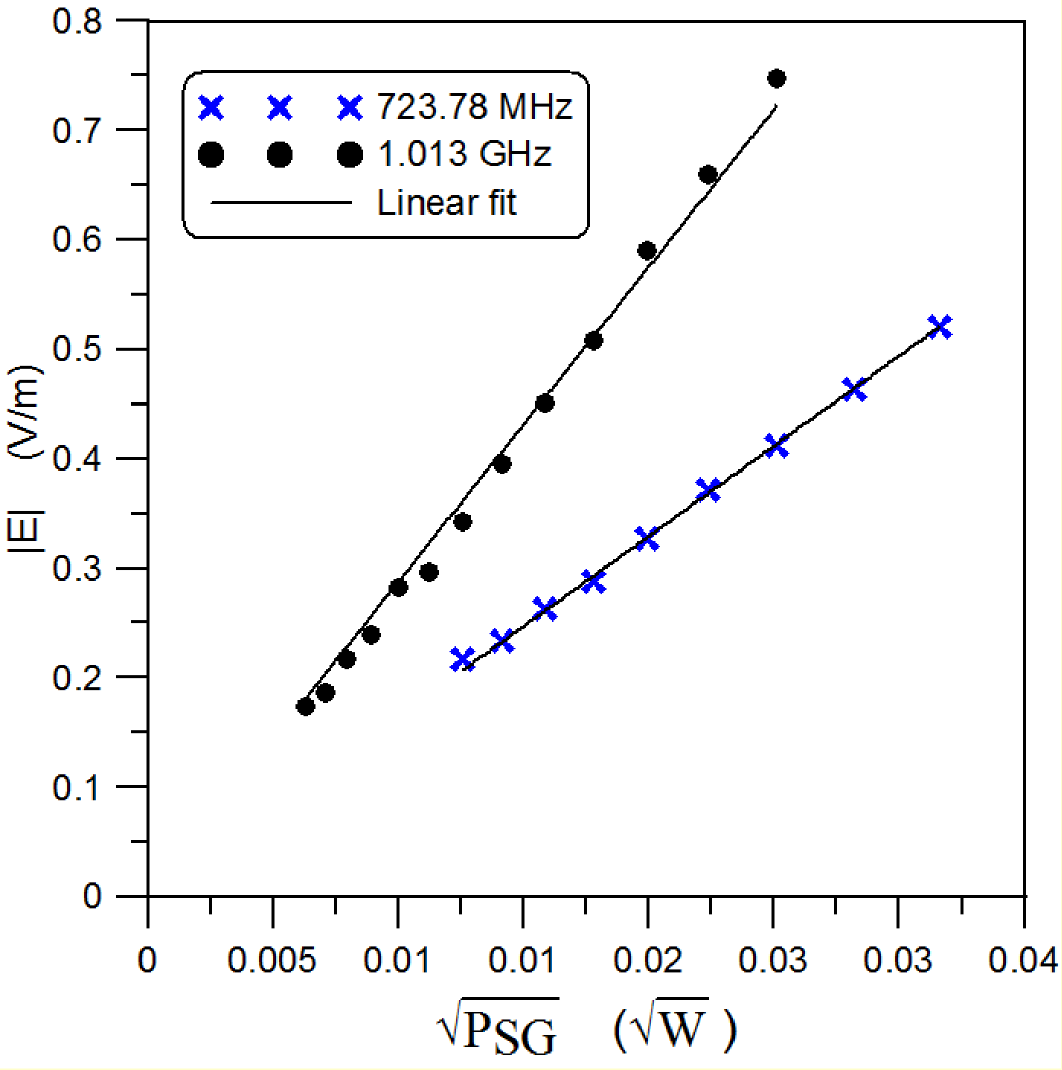
These results for >100 GHz are important from a calibration viewpoint.

Broadband Measurement is Cs



E-field Measurements Below 1 GHz





Round-Robin Test to Assess the Accuracy

For a new measurement method to be accepted by NMIs, the accuracy of the approach must be assessed. A method commonly used by NMIs to assess and quantify the accuracy of a new proposed measurement technique is to perform a so-called “round-robin” test, which is an inter-laboratory test performed independently.

In such a test, the artifact and/or device being measured is sent to various NMIs, and the measurements at these NMIs, performed on the same artifact, are then compared. That is, the same artifact is tested at different laboratories.

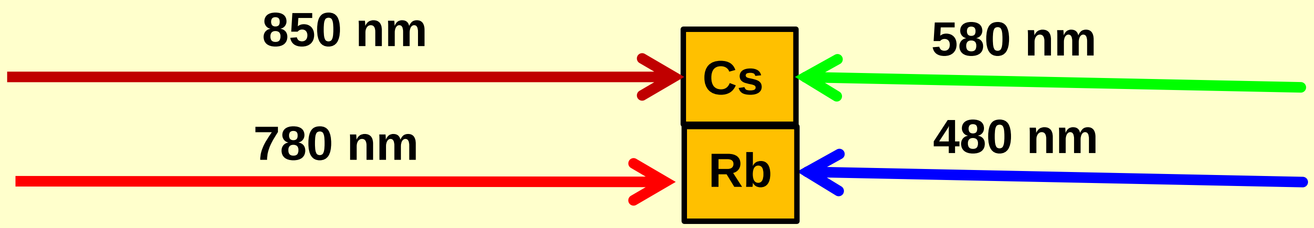
It can be problematic to setup and generate the identical RF E-field at different NMIs.

However, if we can perform simultaneous electromagnetically-induced transparency (EIT) with two different atomic species (i.e., two different atoms) in the same vapor cell with coincident (overlapping) optical fields exposed to the identical E-field, we can in effect perform an in house round-robin test of the atom-based E-field technique: providing two immediate independent measurements.

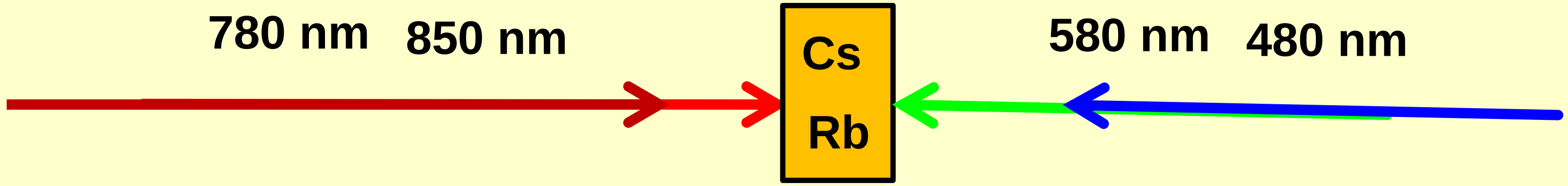
Dual Atom Experiments

Rb and Cs experiments running side-by-side such that we can use two different atoms to measure the same field. Such an experiment will help in quantifying various aspects of this type of technique.

Approach one: two cells

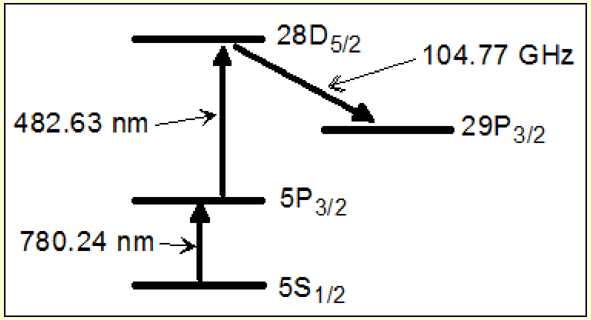


Approach two: one cell with both Cs and Rb atoms



In effect, it is like performing the same measurement in two different laboratories.

Dual Atom Experiments: What RF Frequency????



	Cs state and Frequency	Rb state and Frequency	Δf
1	$47D_{5/2}$-$48P_{3/2}$: 6.951 GHz	$69D_{5/2}$-$68F_{7/2}$: 6.957 GHz	0.09%
2	$45D_{5/2}$-$46P_{3/2}$: 7.981 GHz	$66D_{5/2}$-$65F_{7/2}$: 7.968 GHz	0.16%
3	$43D_{5/2}$-$44P_{3/2}$: 9.225 GHz	$61D_{5/2}$-$62P_{3/2}$: 9.226 GHz	0.01%
4	$40D_{5/2}$-$41P_{3/2}$: 11.626 GHz	$68S_{1/2}$-$68P_{3/2}$: 11.666 GHz	0.33%
5	$66S_{1/2}$-$66P_{3/2}$: 13.407 GHz	$54D_{5/2}$-$55P_{3/2}$: 13.434 GHz	0.20%
7	$63S_{1/2}$-$63P_{3/2}$: 15.551 GHz	$53D_{5/2}$-$52F_{7/2}$: 15.592 GHz	0.26%

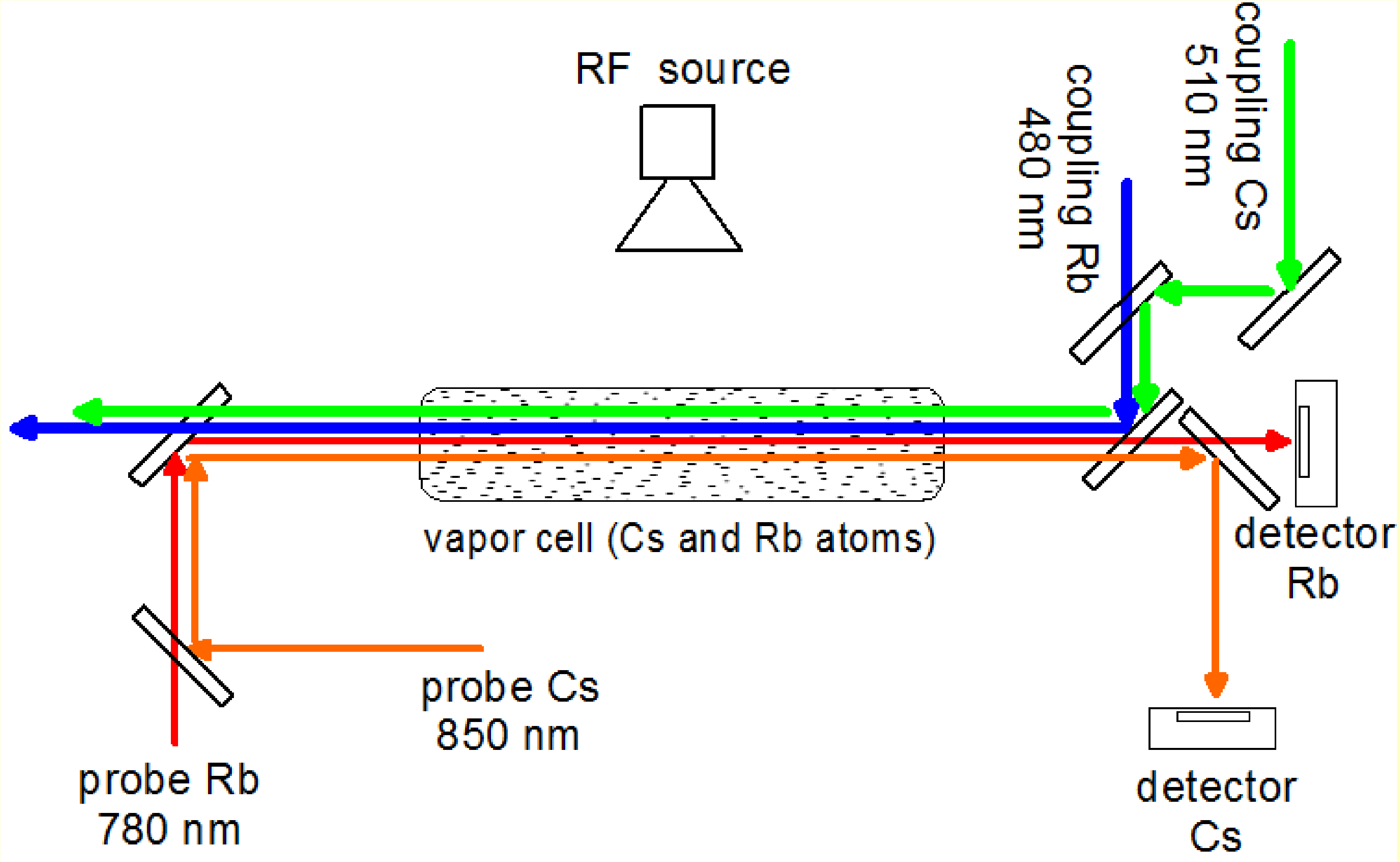
Dual Atom Experiments

First rule in government purchasing:

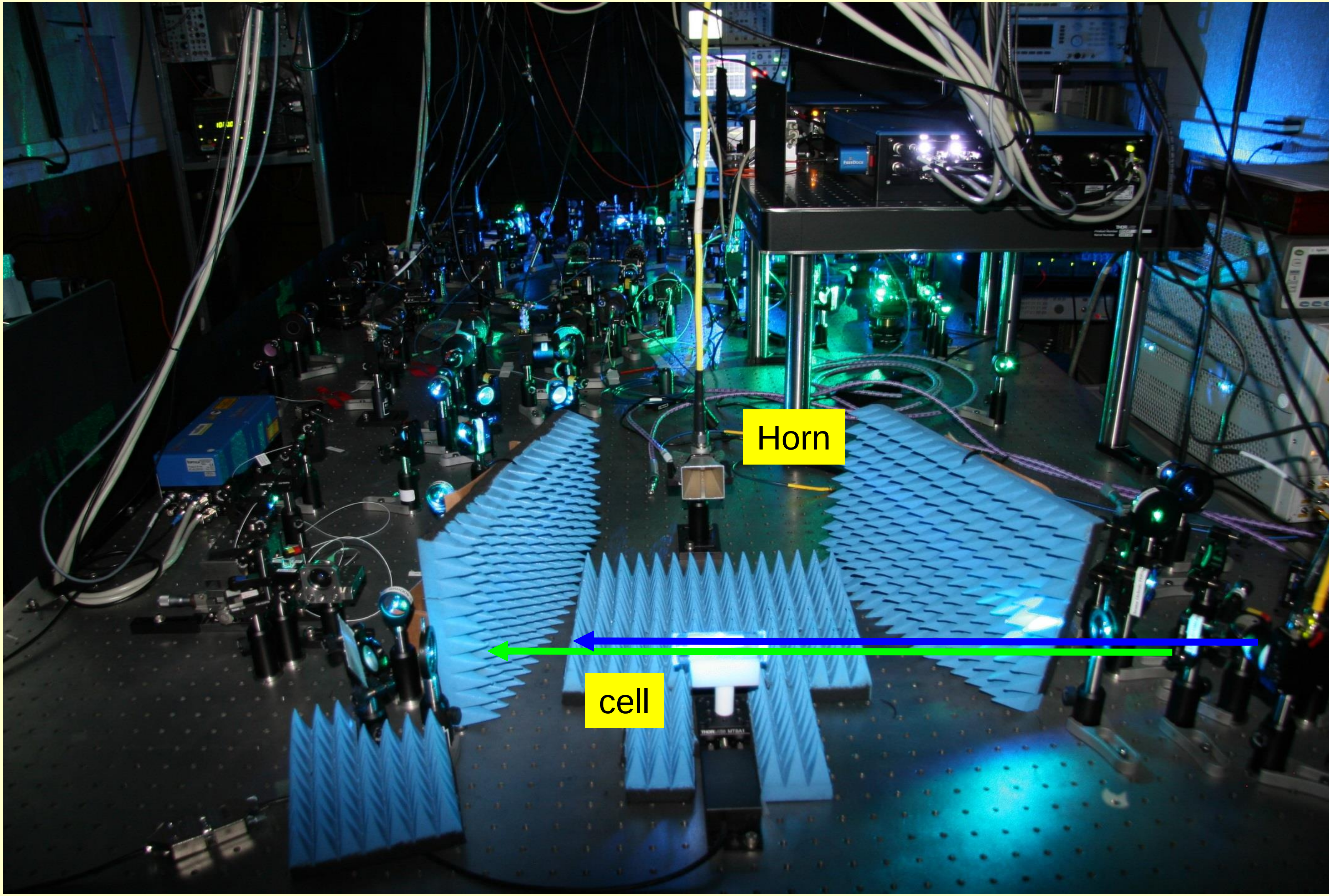
"Why buy one system when you can buy two at **twice** the cost?"
(From the Movie Contact)

In our case: two separate Rydberg atoms laser systems

Dual Atom Experiments



Dual Atom Experiments



Dual Atom Experiments at 9.2-ish GHz

Cs: $43D_{5/2}$-$44P_{3/2}$

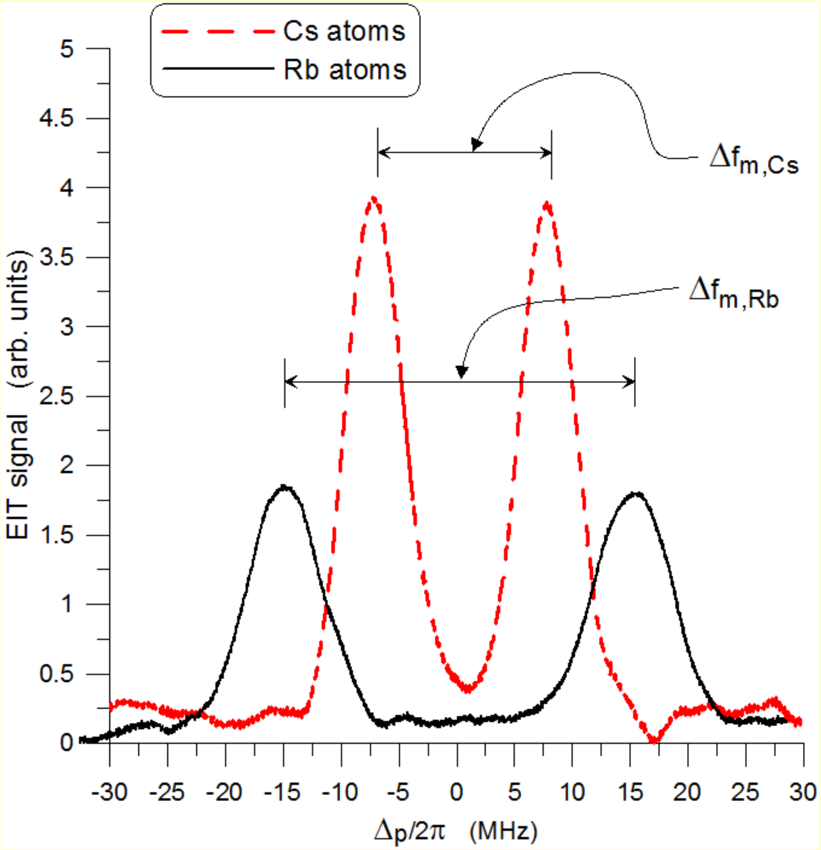
$\wp_{Cs} = 2440.629$

Rb: $61D_{5/2}$-$62P_{3/2}$

$\wp_{Rb} = 4829.407$

$$\Delta f = \wp \frac{|E|}{2\pi \hbar}$$

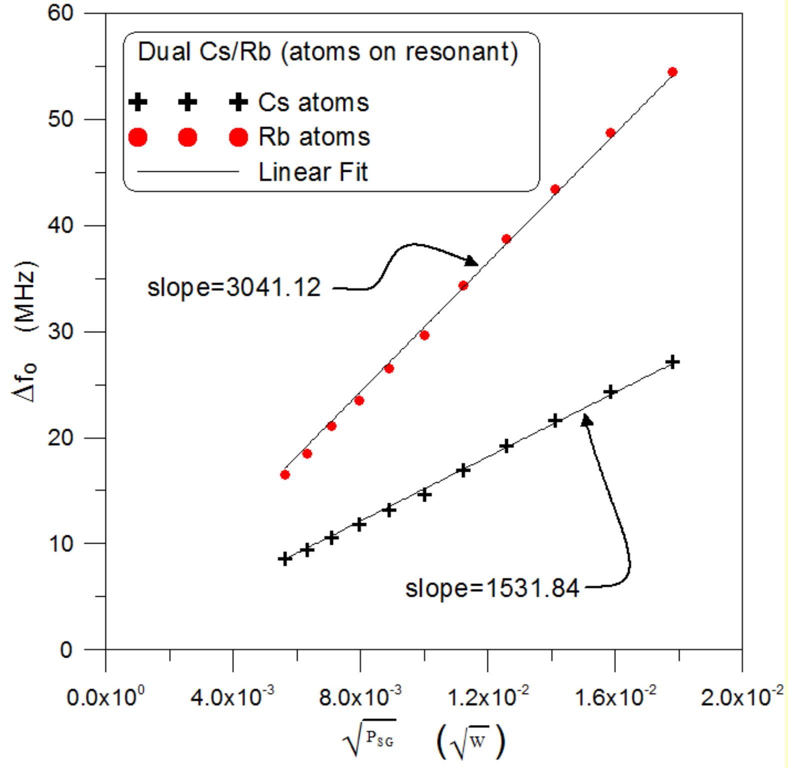
difference splitting for each atom for the same E-field



Dual Atom Experiments at 9.2-ish GHz

Cs: 43$D_{5/2}$-44$P_{3/2}$: 9.218 GHz

Rb: 61$D_{5/2}$-62$P_{3/2}$: 9.226 GHz



$$Senitivity\ Ratio(R) = \Delta slope = \frac{\wp_{Cs}}{\wp_{Rb}} : ratio\ of\ dipole\ moments$$

Theory

$$R = \frac{\wp_{Cs}}{\wp_{Rb}} = \frac{2440.61}{4829.41} = 0.505$$

Experiment

$$\Delta slope = \frac{1531.84}{3041.12} = 0.504$$

Δ % =0.1 %: confirm that the calculations of the two dipole moments for the two different atomic species are correct.

Dual Atom Experiments at 9.2-ish GHz

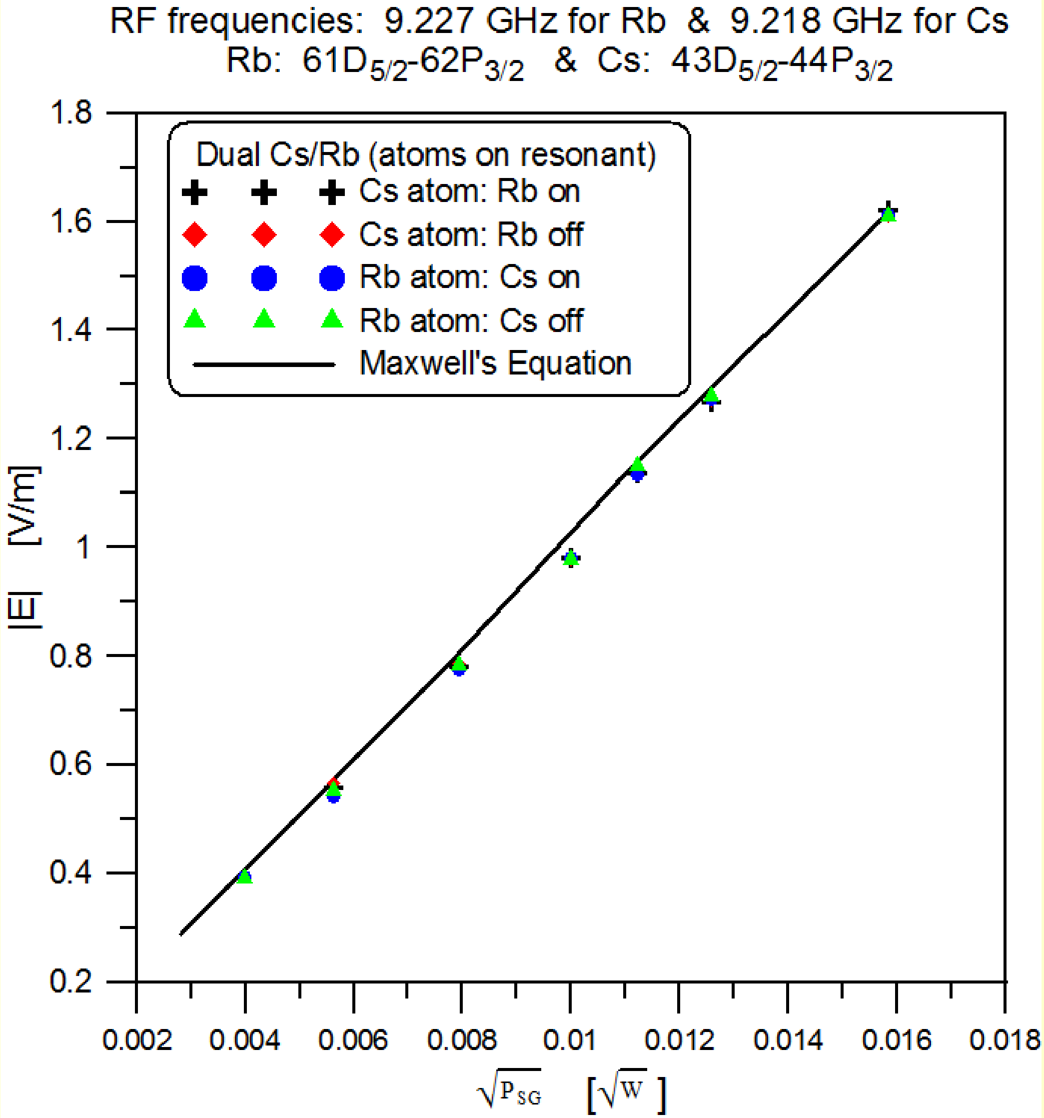
Cs: $43D_{5/2}$-$44P_{3/2}$: 9.218 GHz

Rb: $61D_{5/2}$-$62P_{3/2}$: 9.226 GHz

$$|E| = 2\pi \frac{\hbar}{\wp} \Delta f$$

$\wp_{Rb}$ = 4829.407 ea_o

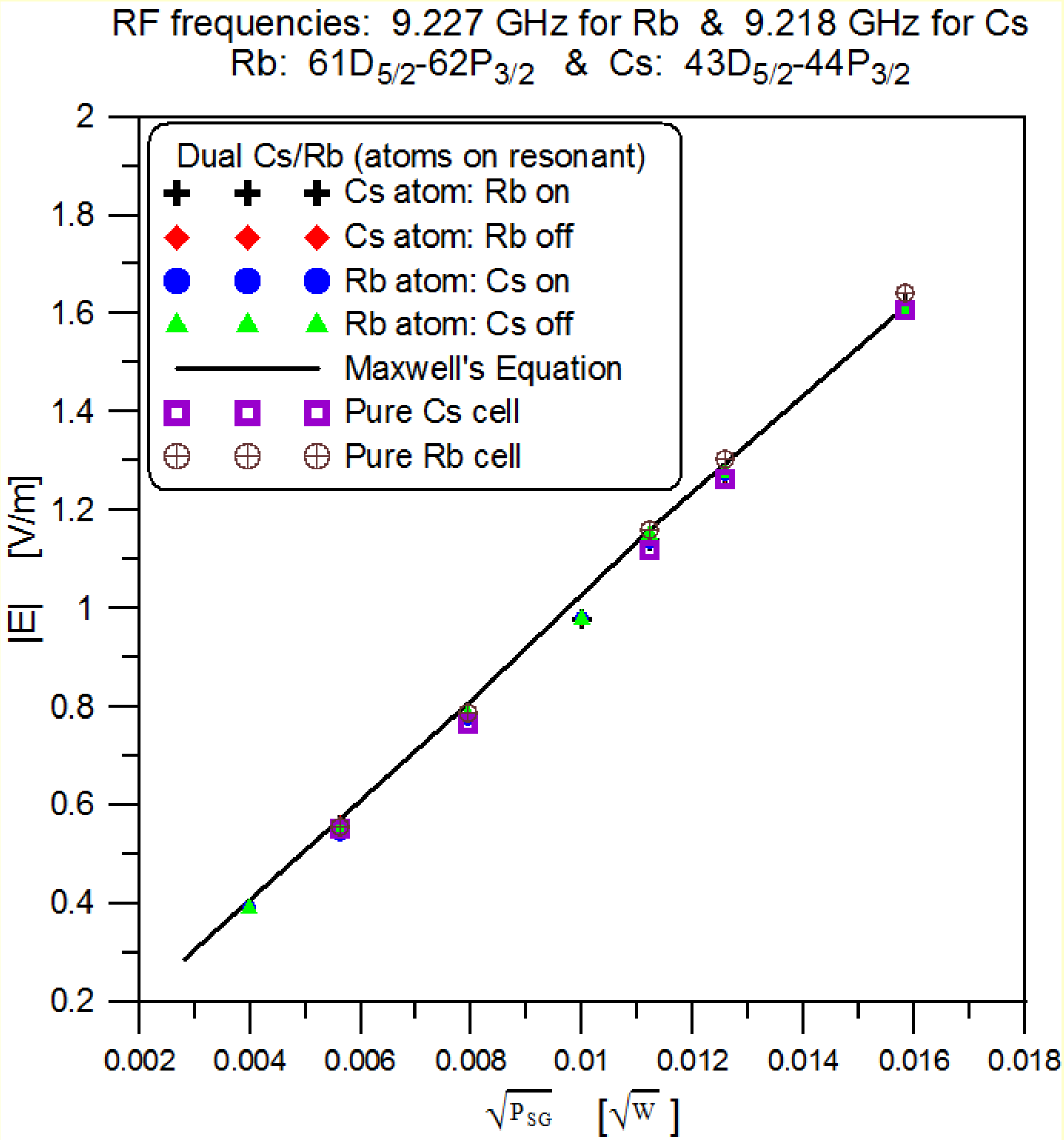
$\wp_{Cs}$ = 2440.629 ea_o



Comparisons to Pure Cell Experiments

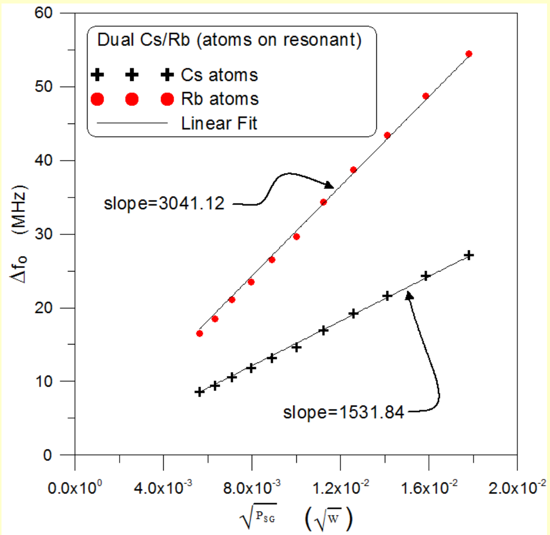
Cs: $43D_{5/2}$-$44P_{3/2}$: **9.218 GHz**

Rb: $61D_{5/2}$-$62P_{3/2}$: **9.226 GHz**



Dual Atom Experiments at 9.2-ish GHz

9.22 GHz



Theory

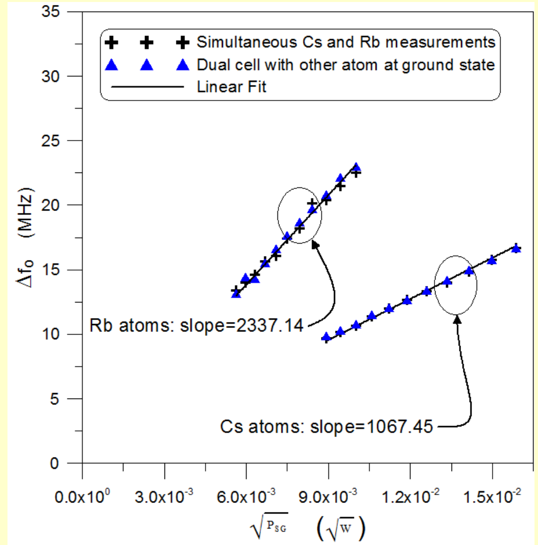
$$R = \frac{\wp_{Cs}}{\wp_{Rb}} = \frac{2440.61}{4829.41} = 0.505$$

Experiment

$$\Delta slope = \frac{1531.84}{3041.12} = 0.504$$

Δ % =0.1 %

11.66 GHz



Theory

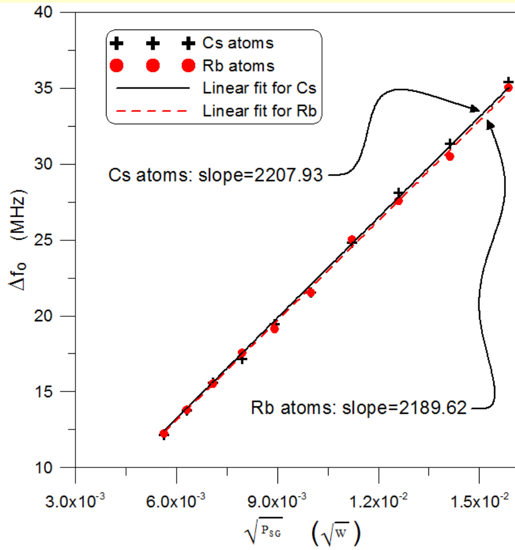
$$R = \frac{\wp_{Cs}}{\wp_{Rb}} = \frac{2092.565}{4781.494} = 0.505$$

Experiment

$$\Delta slope = \frac{1067.45}{2337.14} = 0.457$$

Δ % =0.4%

13.44 GHz



Theory

$$R = \frac{\wp_{Cs}}{\wp_{Rb}} = \frac{4360.132}{4352.837} = 1.002$$

Experiment

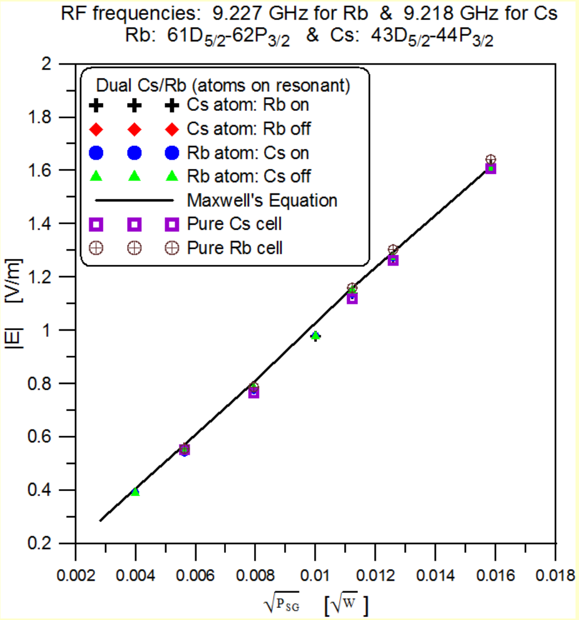
$$\Delta slope = \frac{2207.93}{2189.62} = 1.008$$

Δ % =0.6 %

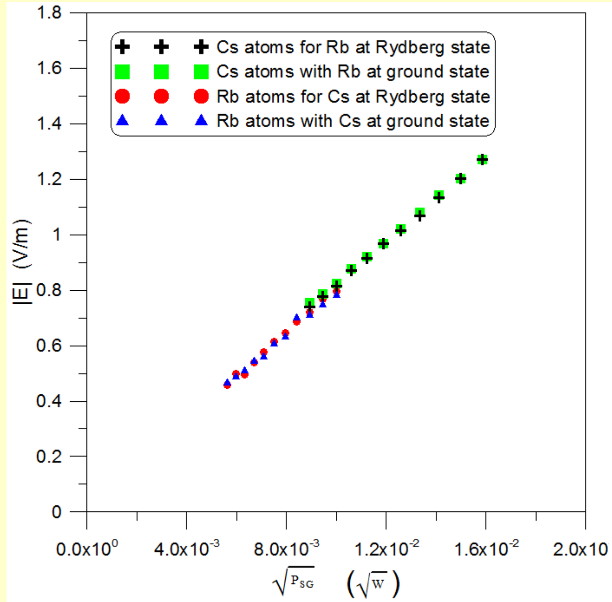
confirming that the calculations of the two dipole moments!

Comparisons for 9.22 GHz, 11.66 GHz, and 13.44 GHz

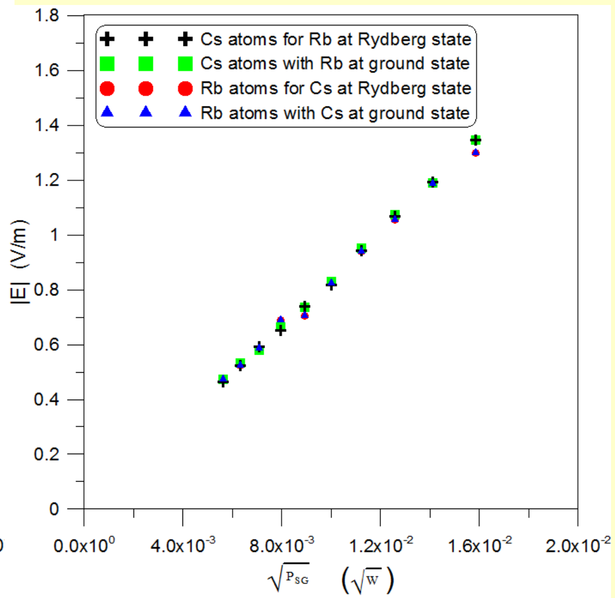
9 GHz



11 GHz



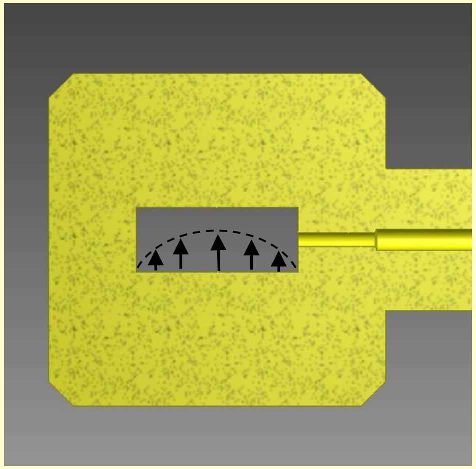
13 GHz



1. This illustrates that the two different atomic species can be used simultaneously to independent measure the same E-field strength, resulting in two independent measurements of the E-field.

2. Indicates that there is no significant interaction between the two different atomic species in the same vapor cell excited to high Rydberg states.

Power Measurements Using Rydberg Atoms



TE_{10} mode in rectangular waveguide

only allowed mode at measurement frequency

$$\vec{E} = E_0 \sin\frac{\pi x}{a}\left\{e^{-j\beta z} + \Gamma e^{j\beta z}\right\}\hat{y}$$

½ sinusoid in x, constant in y, partial standing wave in z

Initial Experiment

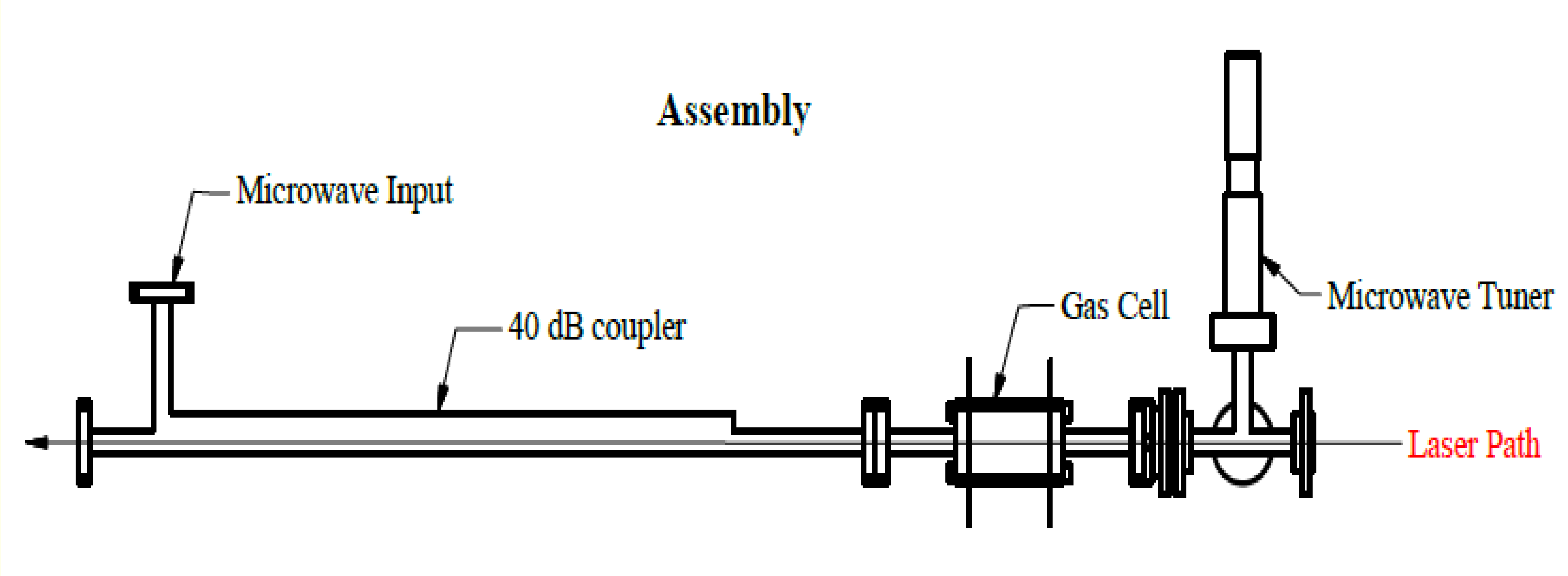
Remove standing wave with tuner

Transmitted Power

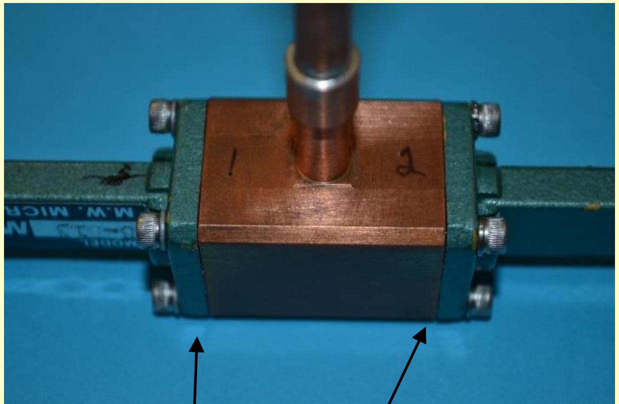
$$P_{trans} = E_0^2 \frac{ab}{4}\sqrt{\frac{\varepsilon_0}{\mu_0}}\sqrt{1-\left(\frac{c}{2af}\right)^2}$$

Depends on E, physical constants (ε_0, μ_0, c), and geometry (a,b)

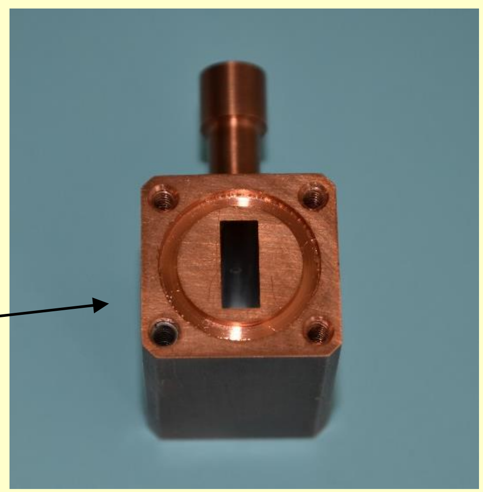
Power Measurement Apparatus

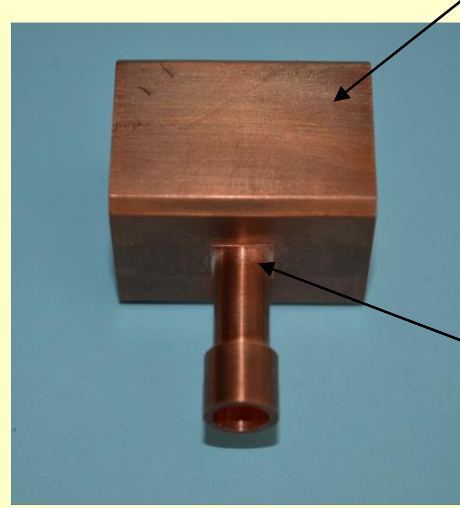


Old Copper Cell Design



Outgassing issues with copper



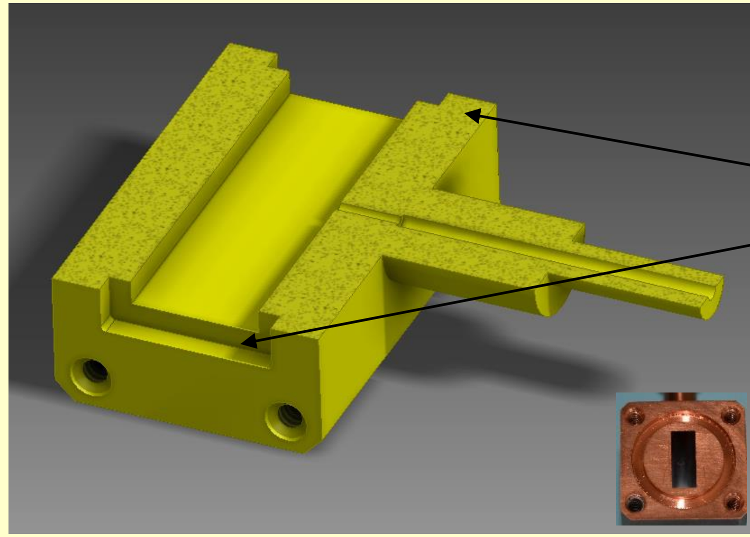


O-ring seal on mica windows

Press fit stem

New Copper Vapor Cell Design

- Need cell to hold a 10^{-9} torr vacuum
- Minimal E-field perturbation



- Replaced O-ring with indium seal
- Window recess

- Cleaning process to mitigate outgassing issues
- Thin glass windows <1mm

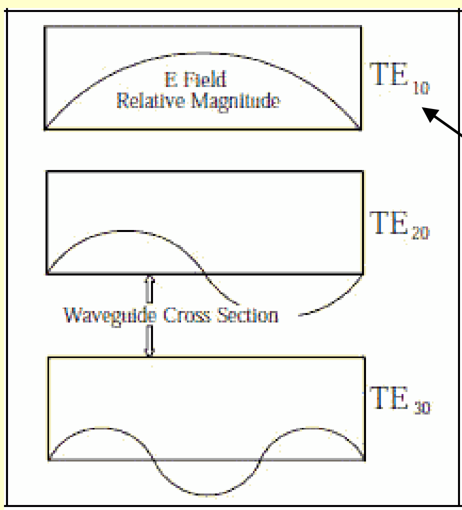
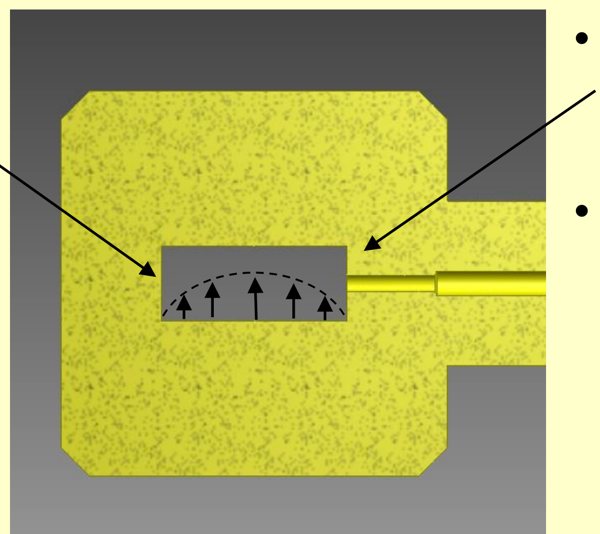
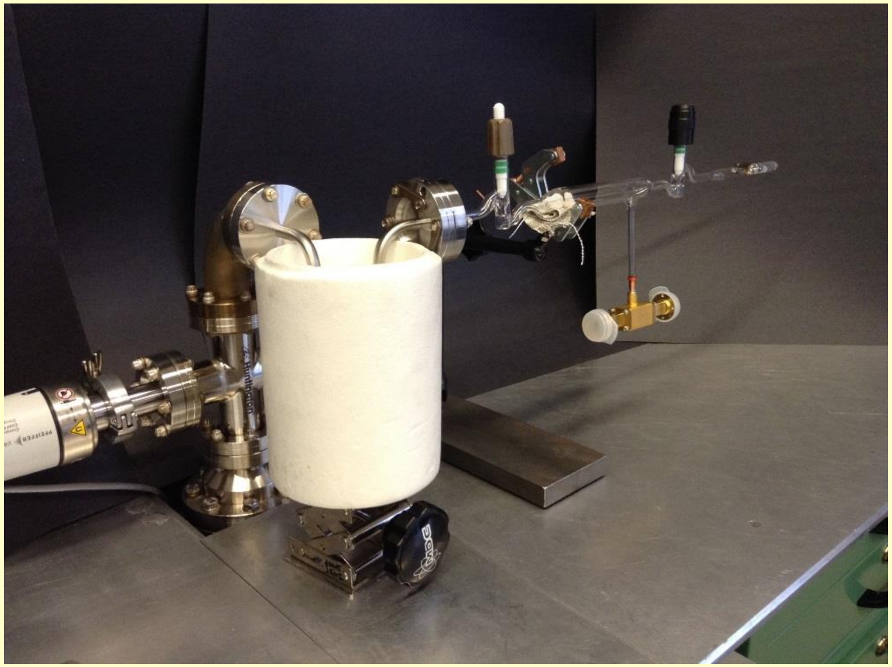


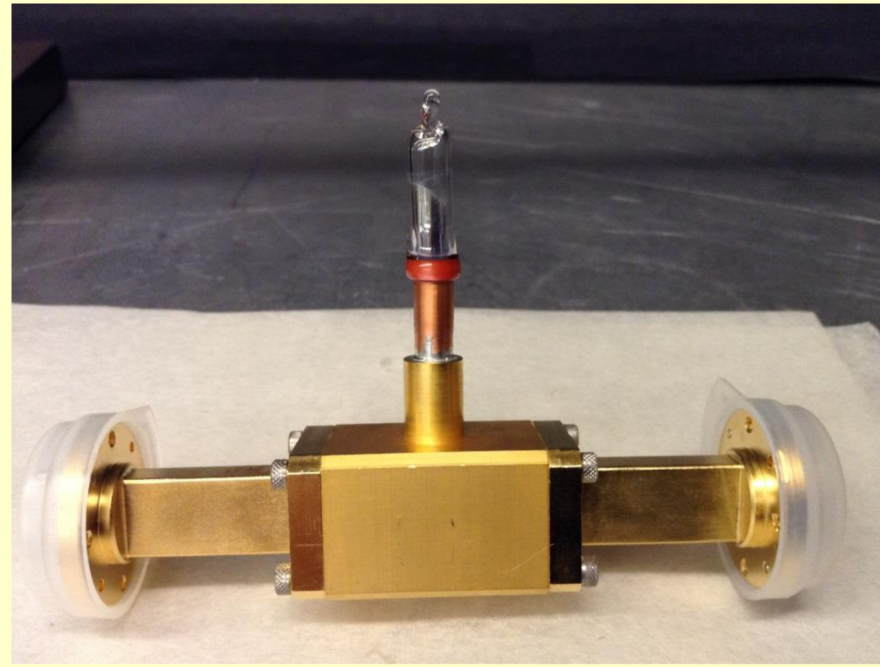
Figure 2. TE modes



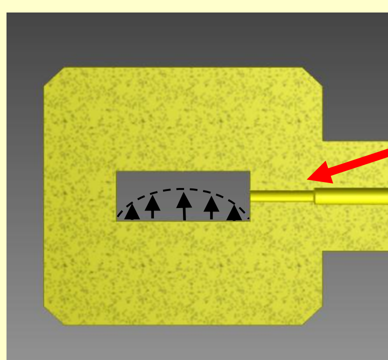
- Vapor inlet placement. E-field goes to zero at walls for in-band fields
- Inlet diameter <10th wavelength throughout WR42 band

New Copper Vapor Cell Design



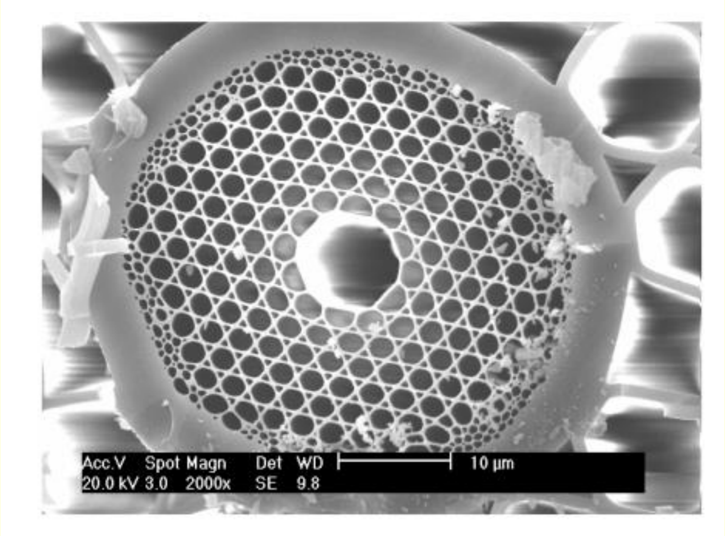


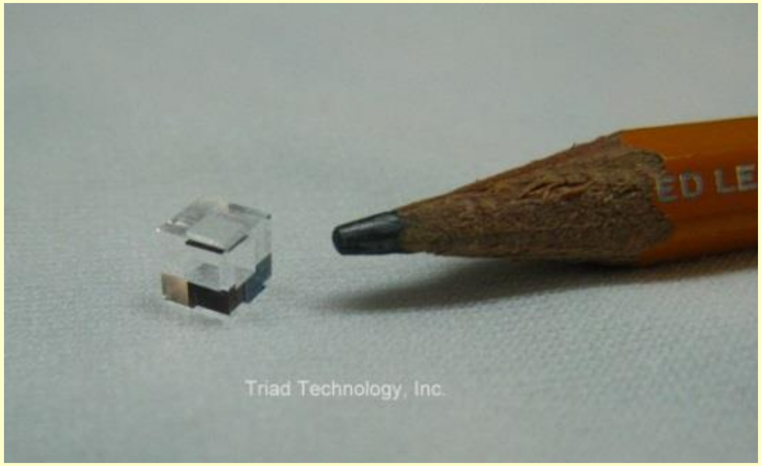
Still not working

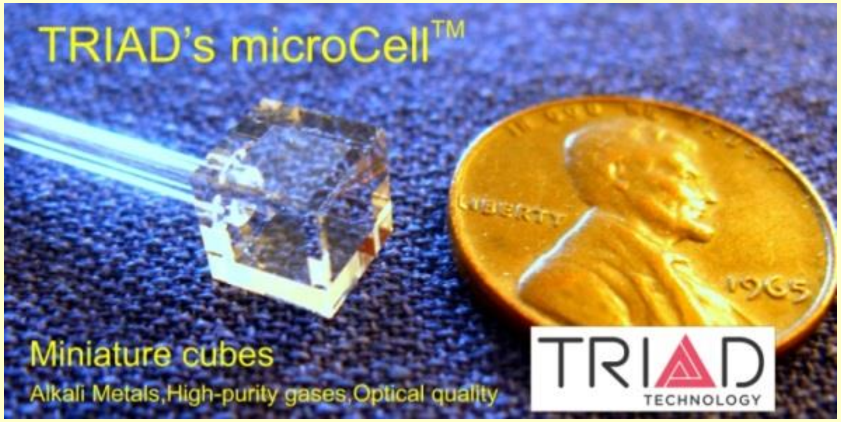


Possible problems are either the Rb is blocking the hole or glass windows are leaking.

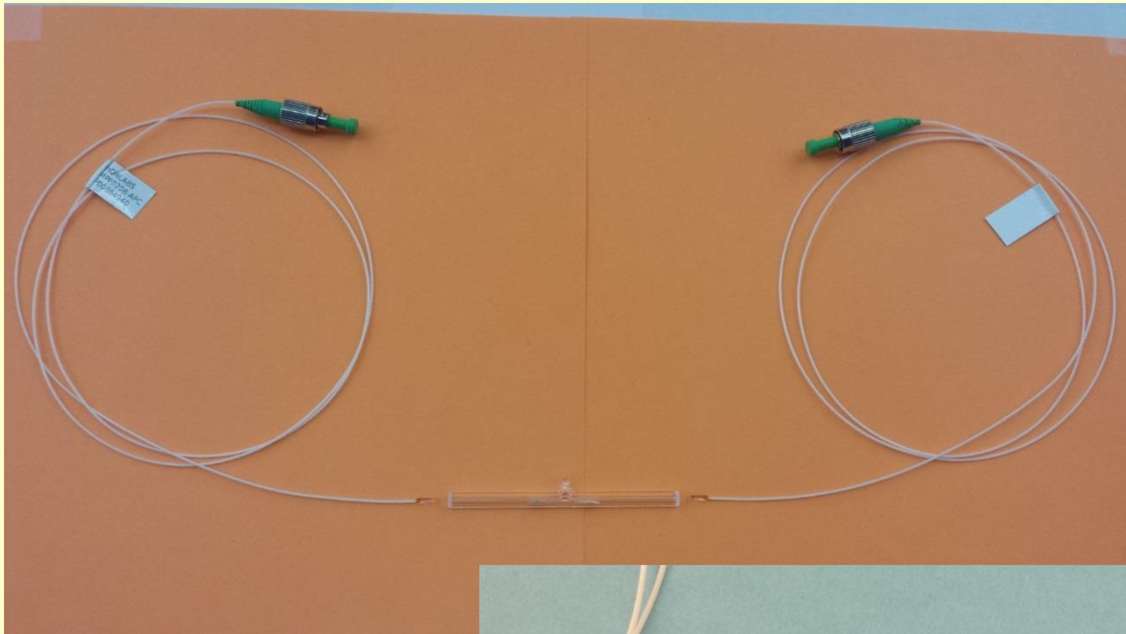
Small Compact Probe

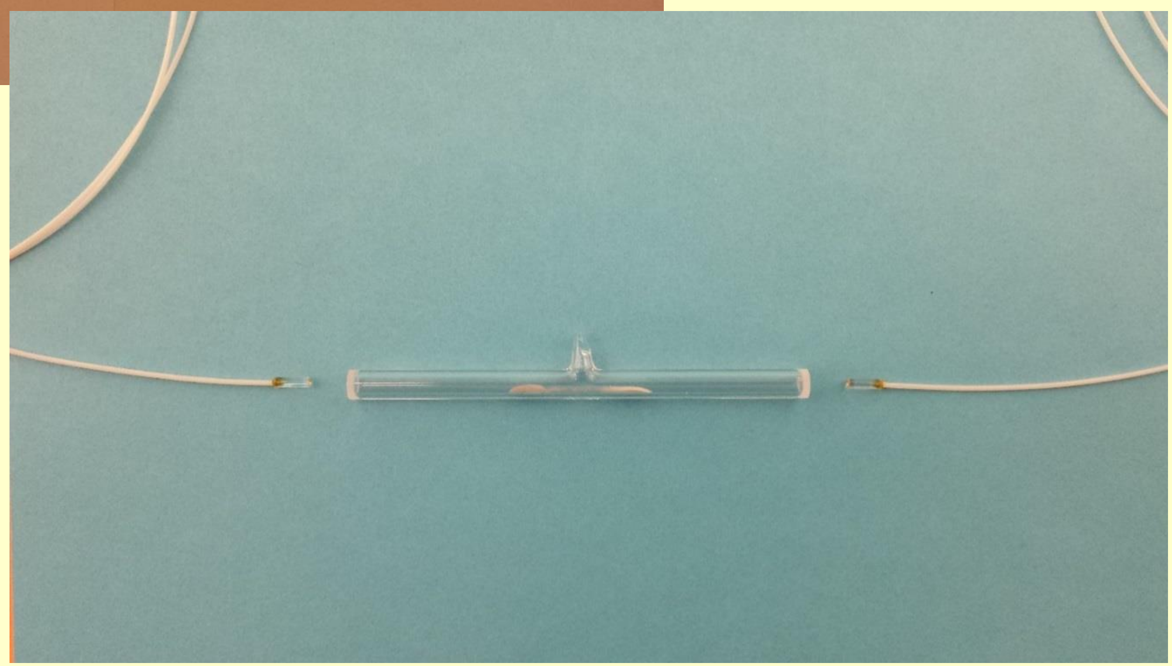




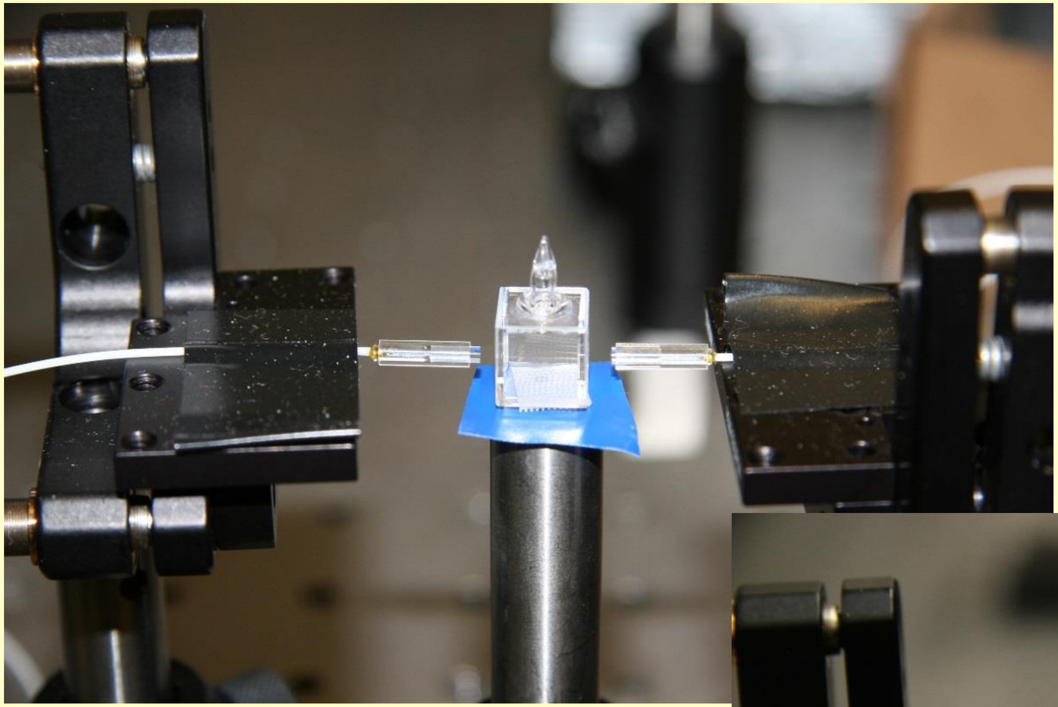


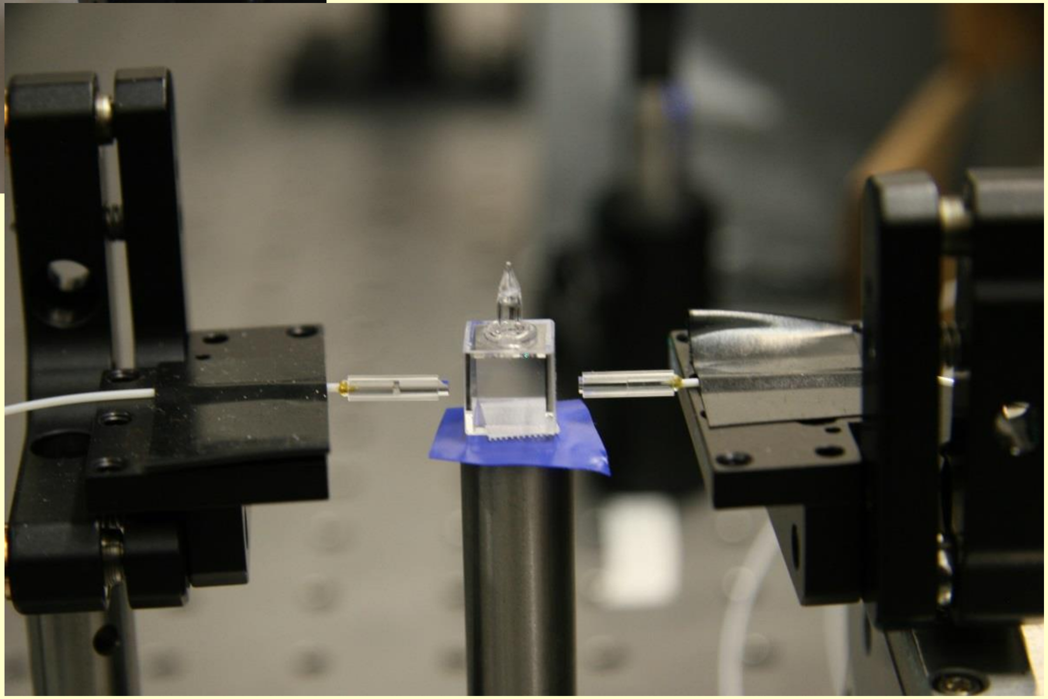
Moving Probe OFF Optics Table





New Design (10 mm cube)





Started Looking at Measurement Uncertainties

1) Quantum based uncertainties

$$Recall: \quad |E| = \frac{\hbar}{\wp}\ \Omega_{rf}$$

It is believed that we can determine the dipole moment to better than 0.1 %

2) RF based uncertainties

- RF resonances in the vapor cell

RF Resonances Inside Glass Vapor Cell

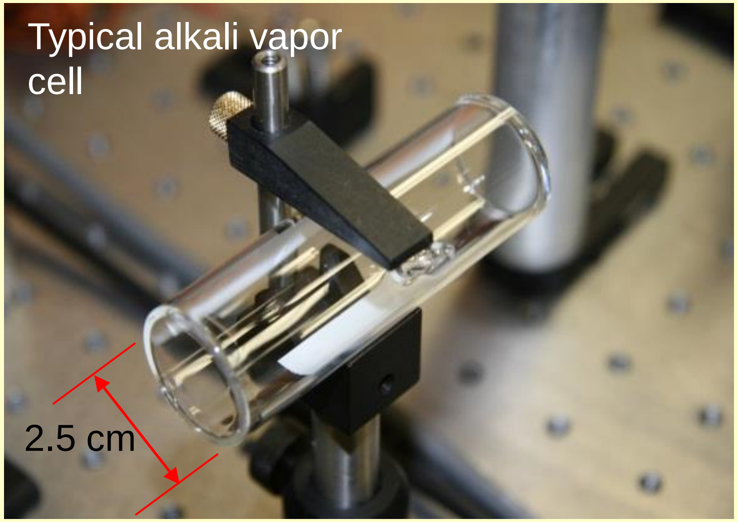
•***How does the presence of the vapor cell itself affect the traceability of such an atomic based electric field probe?***

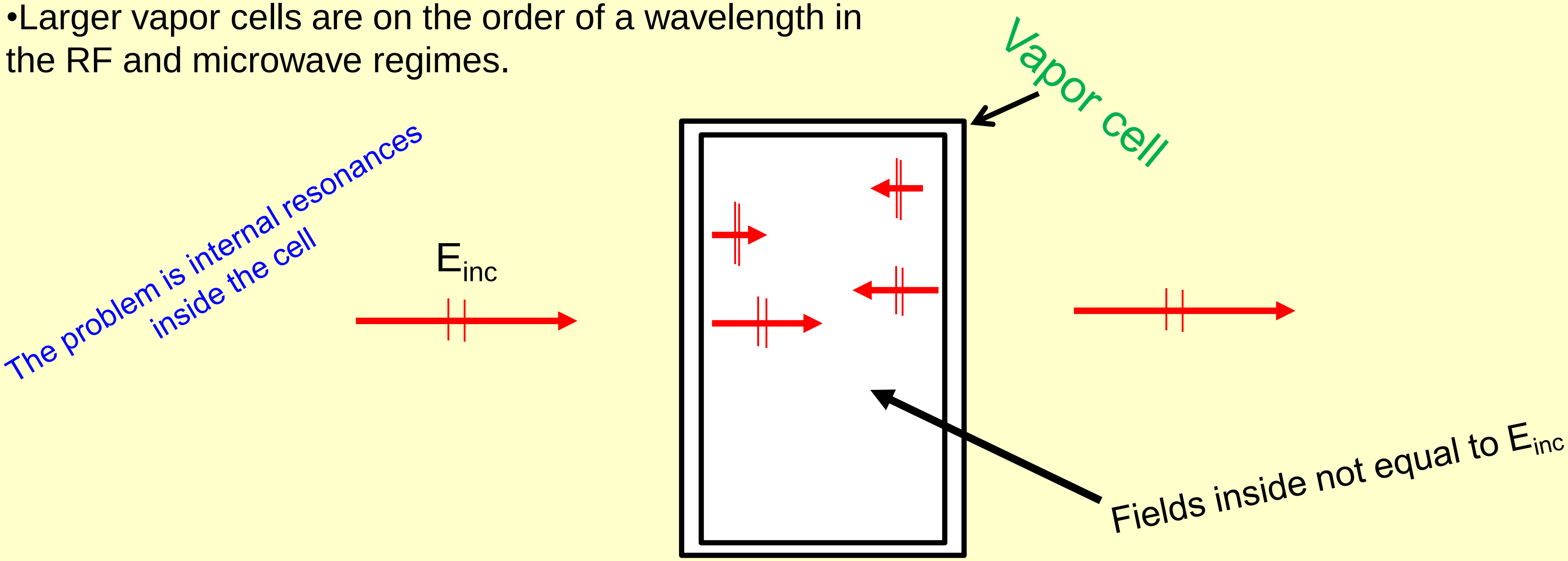
•***Do vapor RF cell resonances significantly distort the electric field we are trying to measure, thereby corrupting the measurement of the field?***

•***How can we overcome effects of the vapor cell from an electric perturbing perspective?***

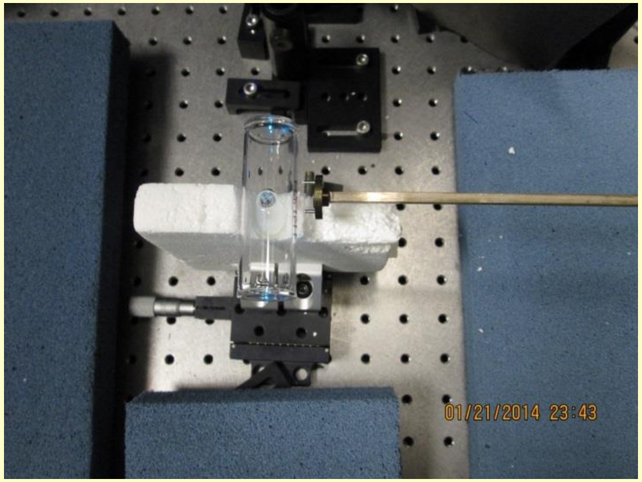
•RF field perturbations due to vapor cell apparatus.

•Larger vapor cells are on the order of a wavelength in the RF and microwave regimes.

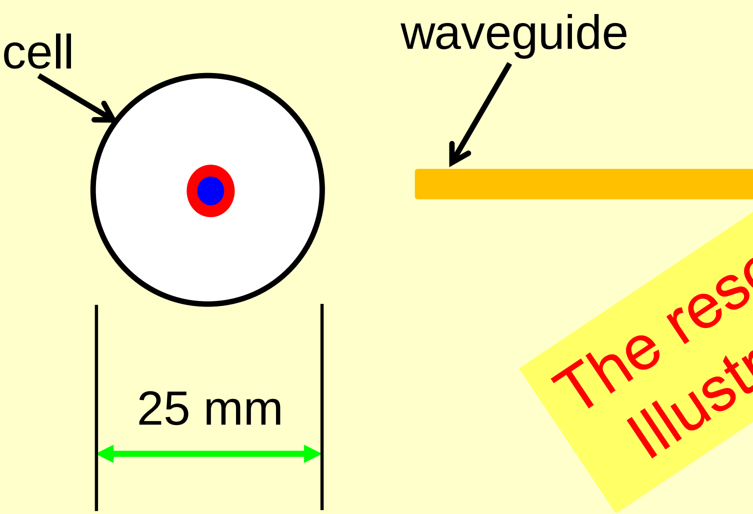


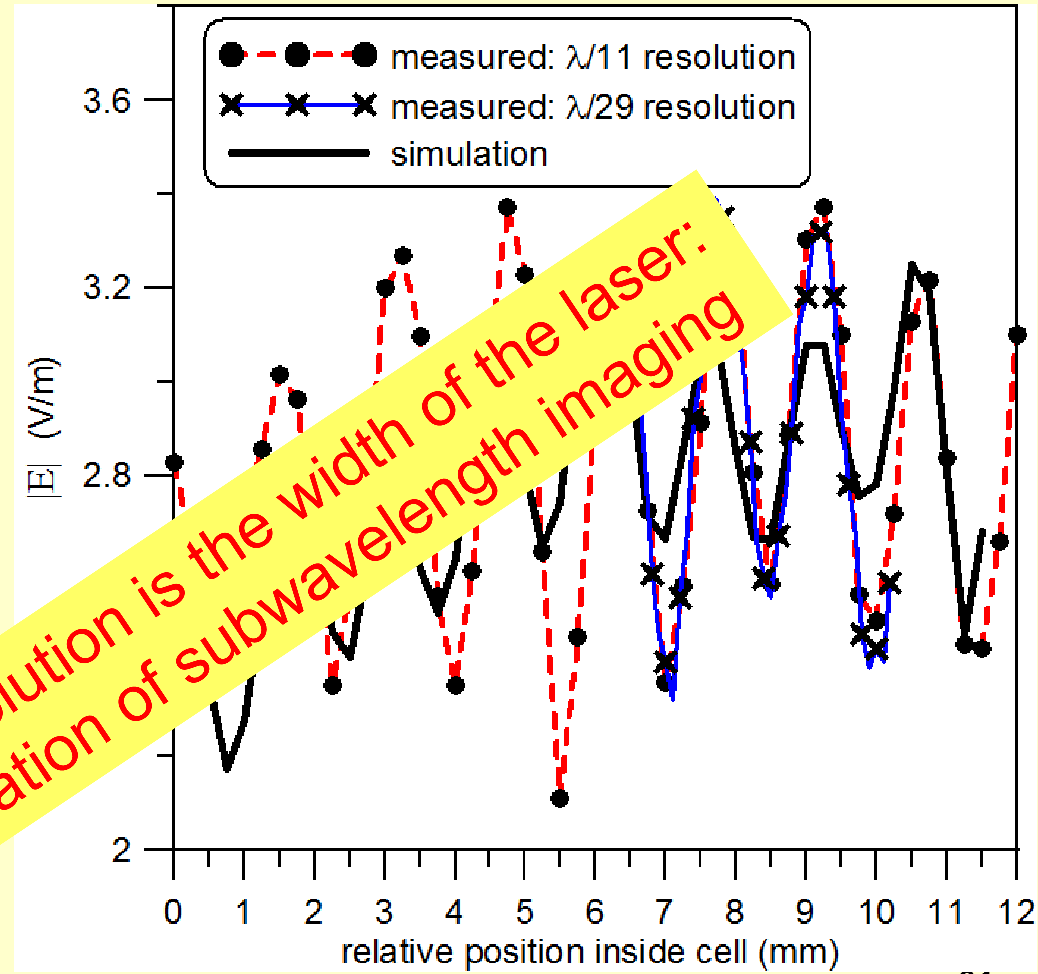


Field Mapping and Sub-wavelength Imaging



104.77 GHz : λ=2.88 mm

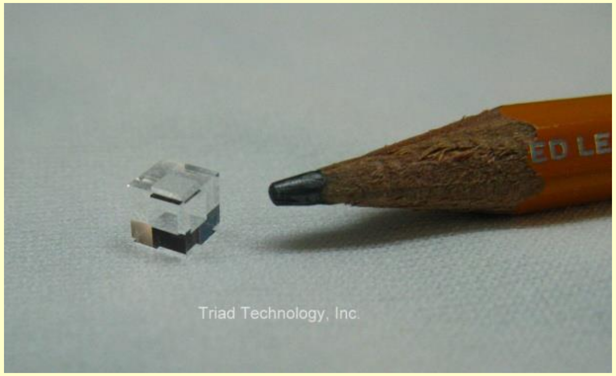




The resolution is the width of the laser:
Illustration of subwavelength imaging

Small Cell Measurements at Different Frequencies

Experiments at University of Oklahoma with 12 mm Cs

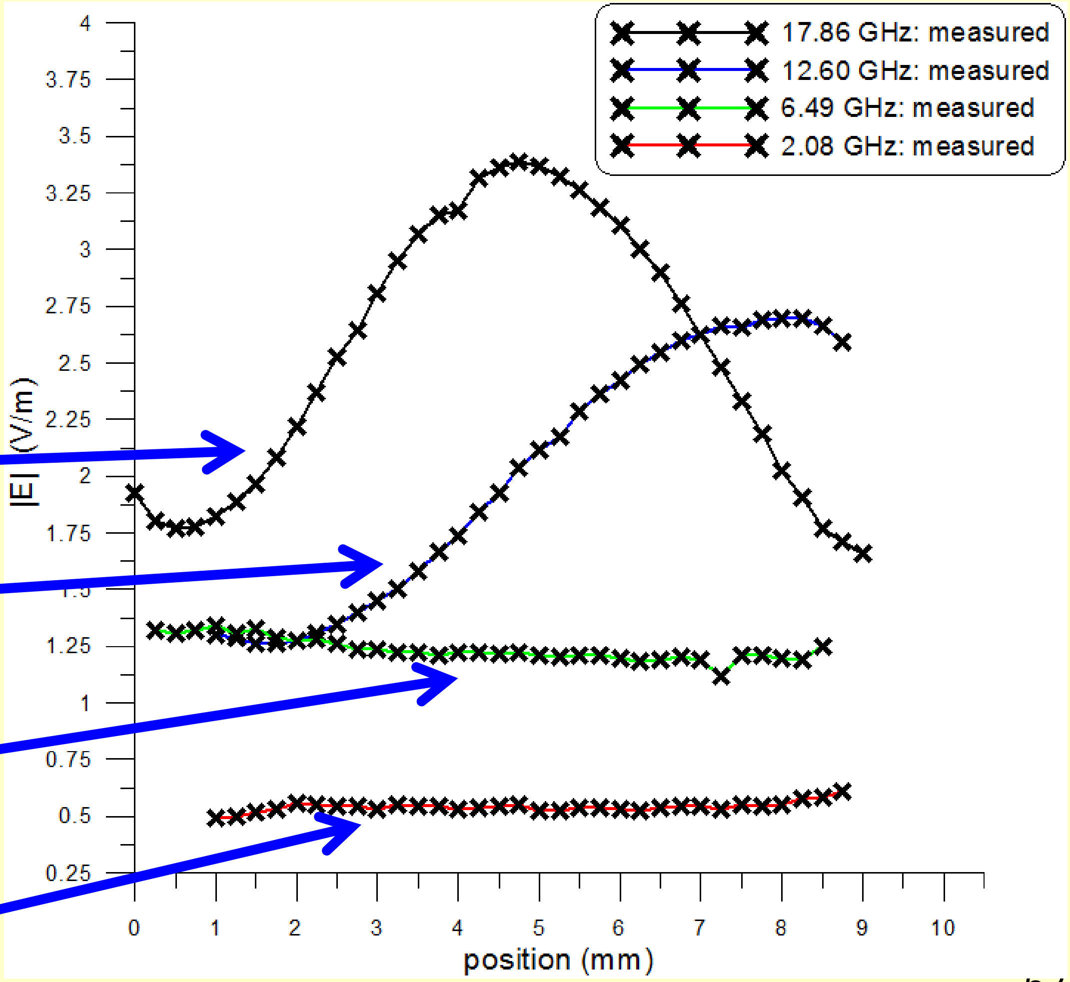


size/λ= 0.75

size/λ= 0.53

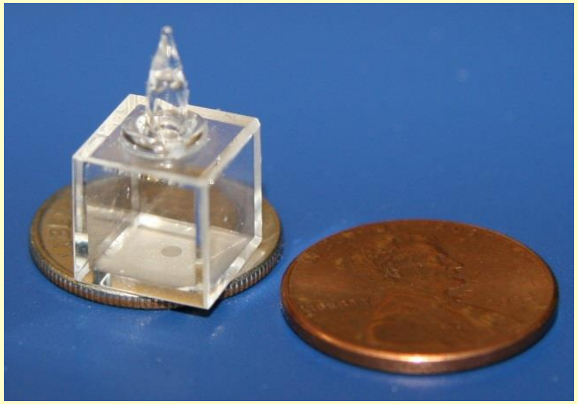
size/λ= 0.27

size/λ= 0.09

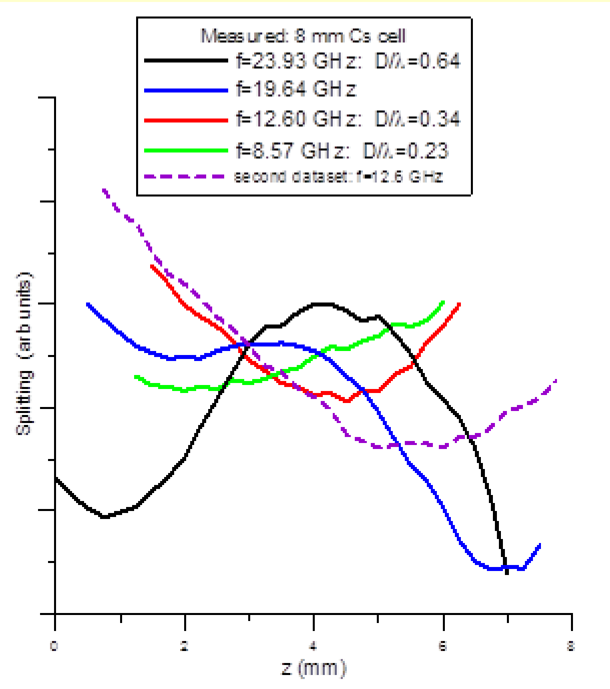


Small Cell Measurements at Different Frequencies

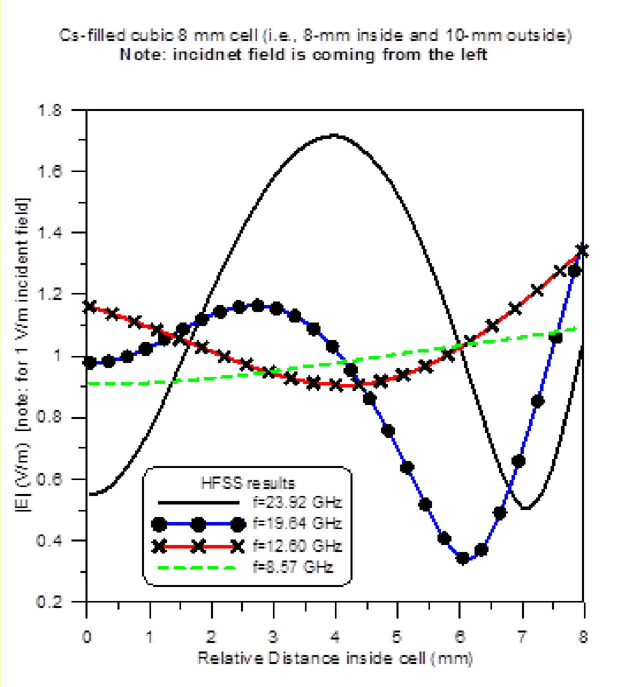
8 mm cubic Cs cell



Measured Data

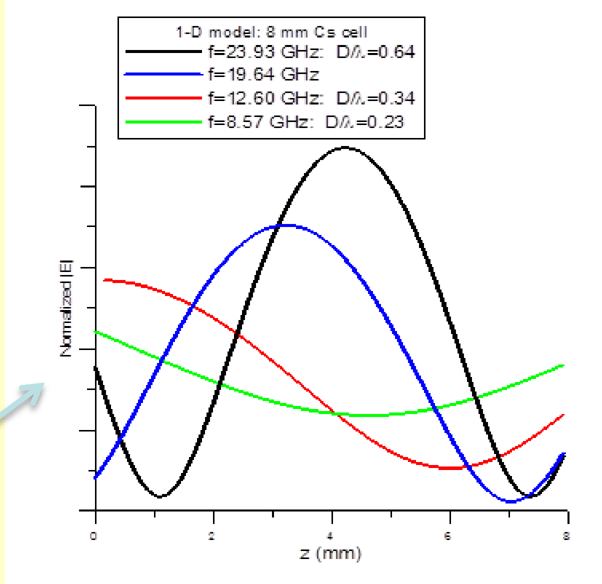


3D Numerical Simulation



1V/m incident plane wave

Analytical Results



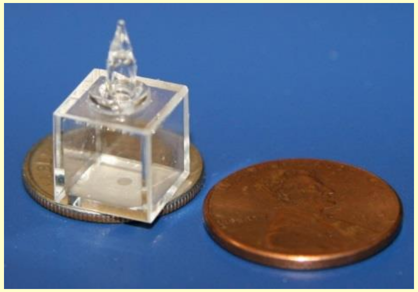
Dominant Effect-Fabry Perot resonances at RF

We see the field variation inside the cell can be reduces with small D/λ.

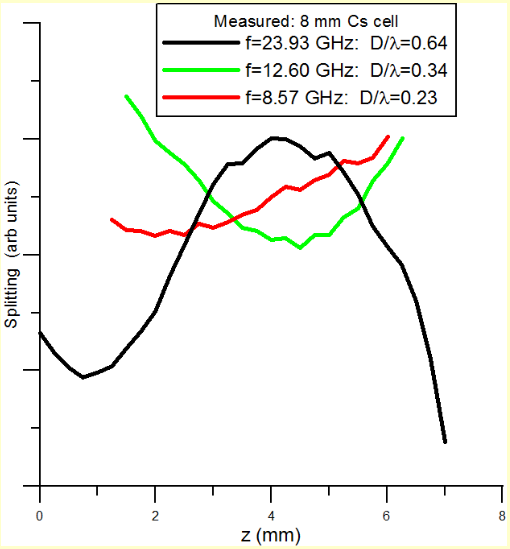
Small Cell Measurements at Different Frequencies

Experiments at University of Oklahoma.

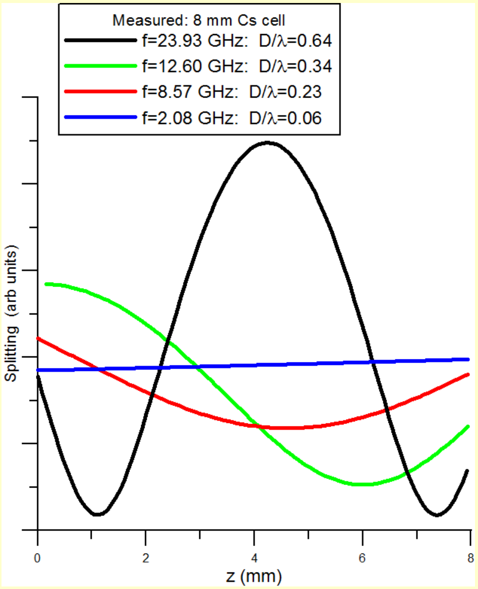
8 mm cubic Cs cubic cell



Measured Data



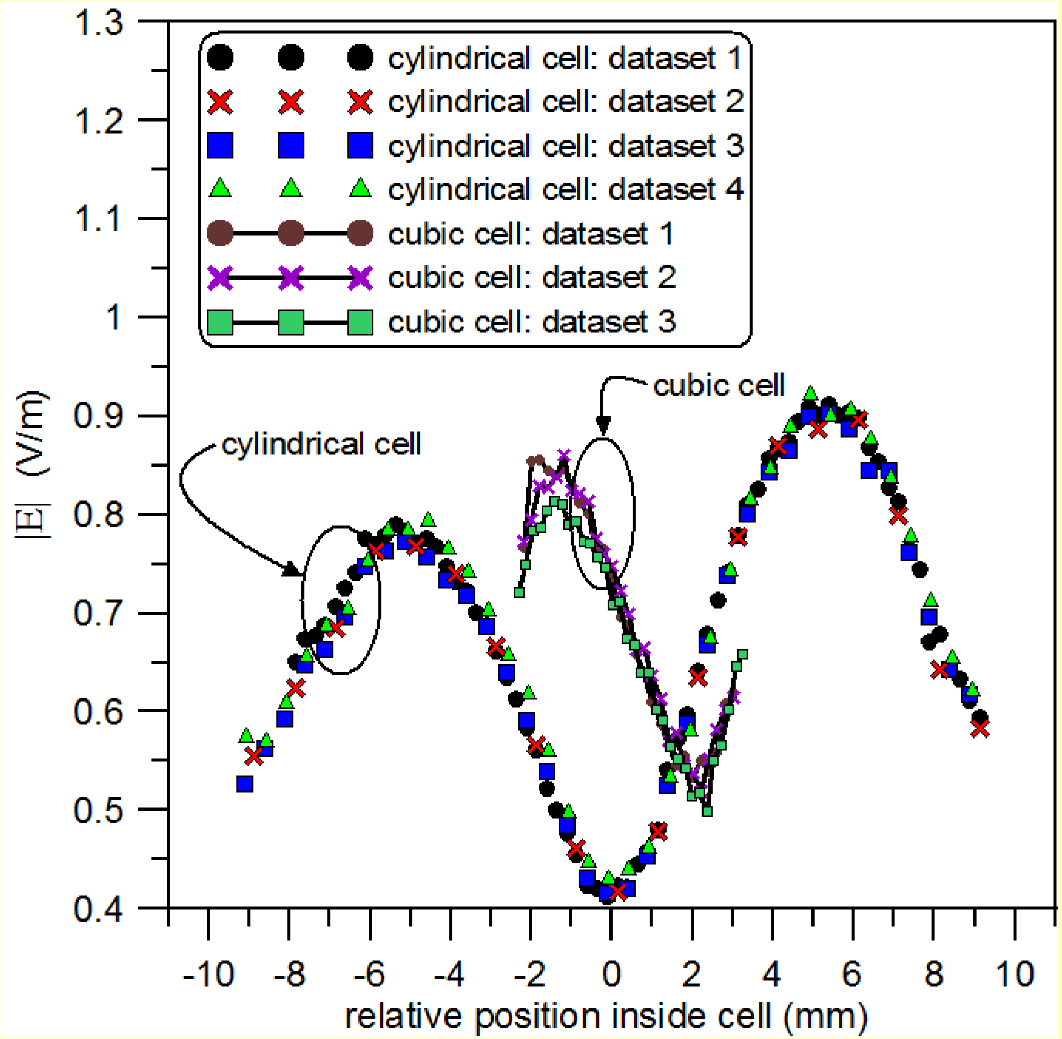
Analytical Results



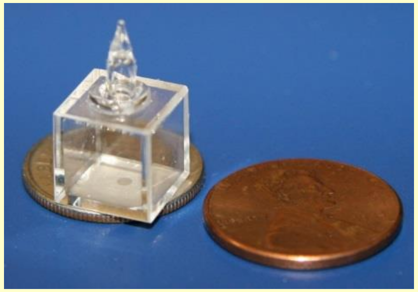
We see the field variation inside the cell can be reduced with small D/λ.

"Effect of Vapor Cell Geometry on Rydberg Atom-based Radio-frequency Electric Field Measurements", ***Physical Review Applied*****, 2015.**

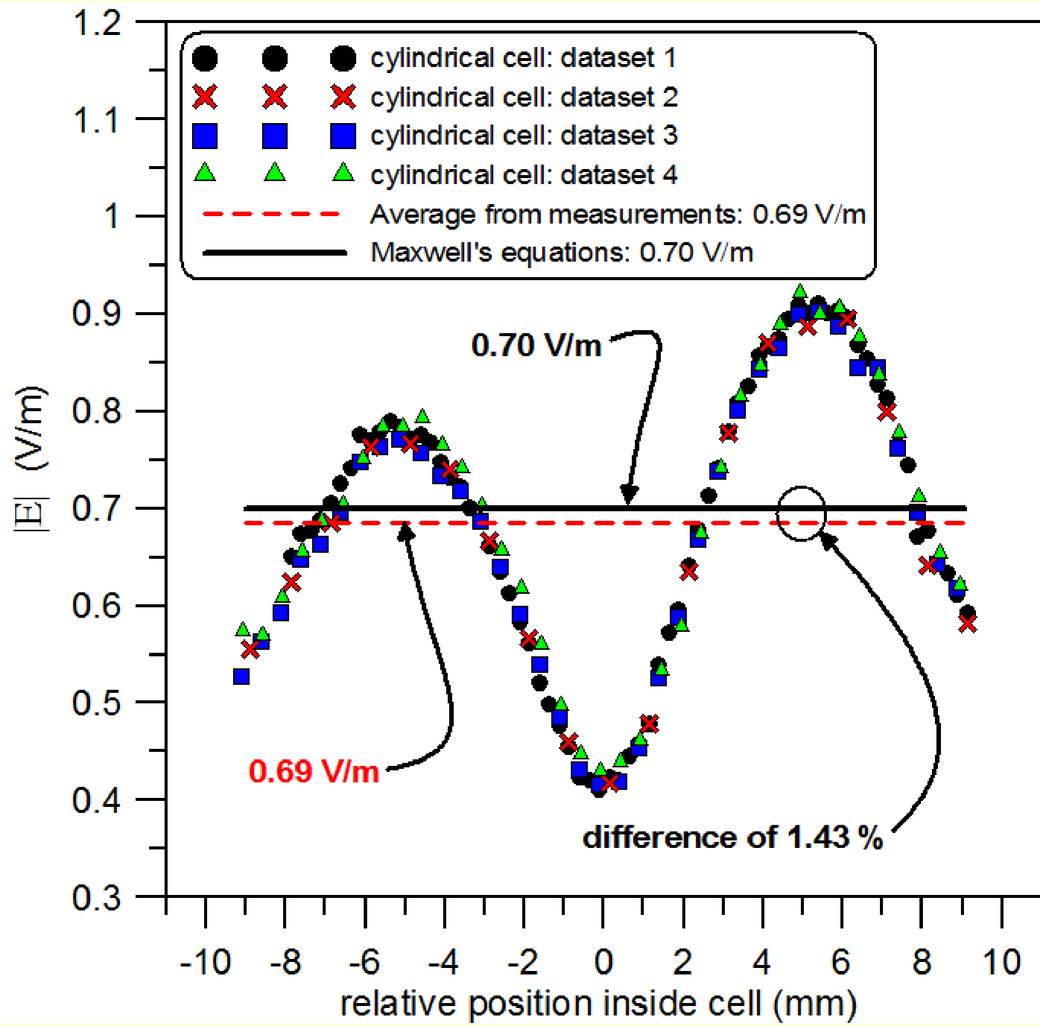
Repeatability



cubic cell



cylindrical cell



cylindrical cell

With this |E| measurement, we can estimate the on-axis gain of the antenna.

manufacturer data for gain: 44.67 (16.5 dB)

estimated gain from measured |E|: 43.07 (16.34 dB)

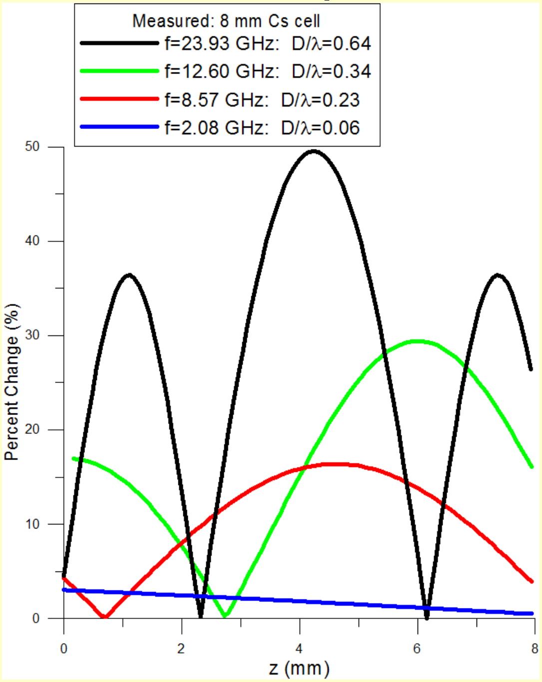
Measurement Uncertainties for Field Measurements

1) Anechoic Chamber and TEM Cell Techniques

0.5 dB or 6 % (in a field measurement)

2) Atom based approach

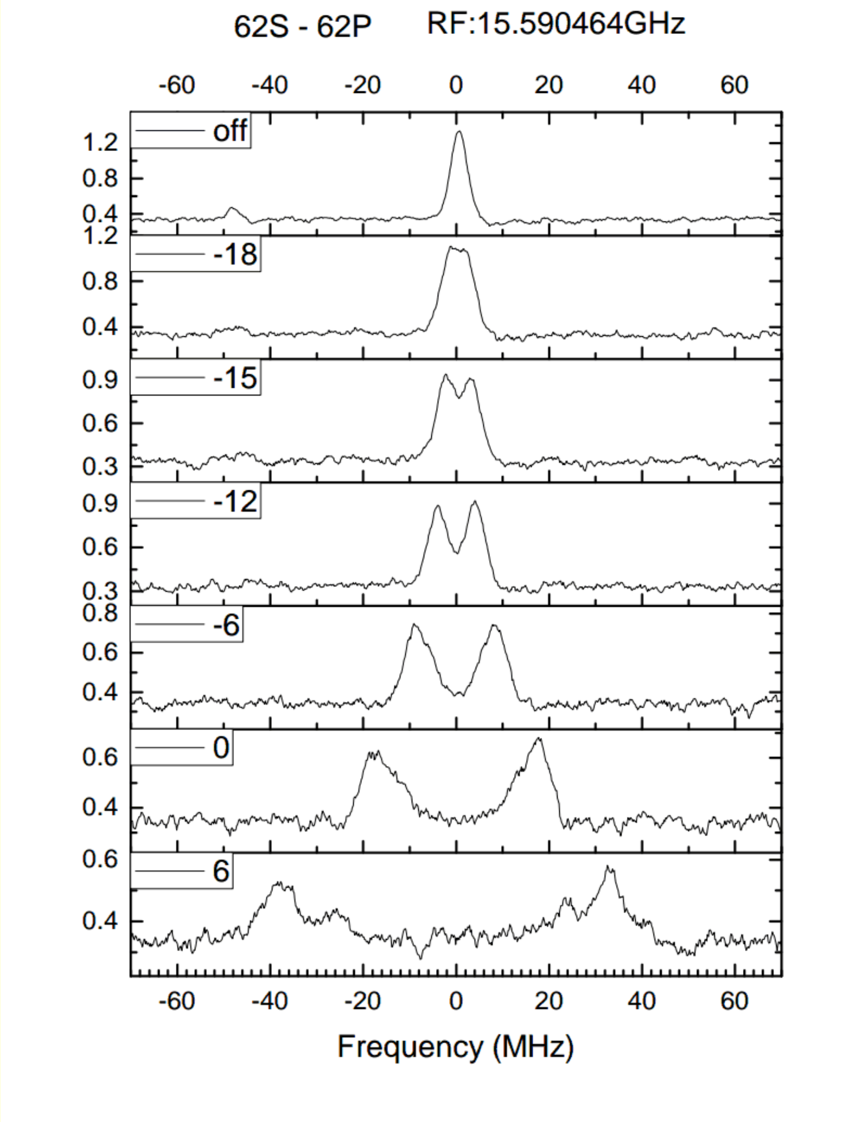
RF resonances in the vapor cell dominate uncertainties



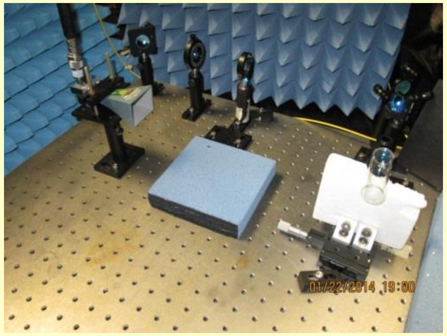
Less than 0.2 dB or 2.5 % (in a field measurement) for D/λ=.05

This can be reduced more for smaller cells!

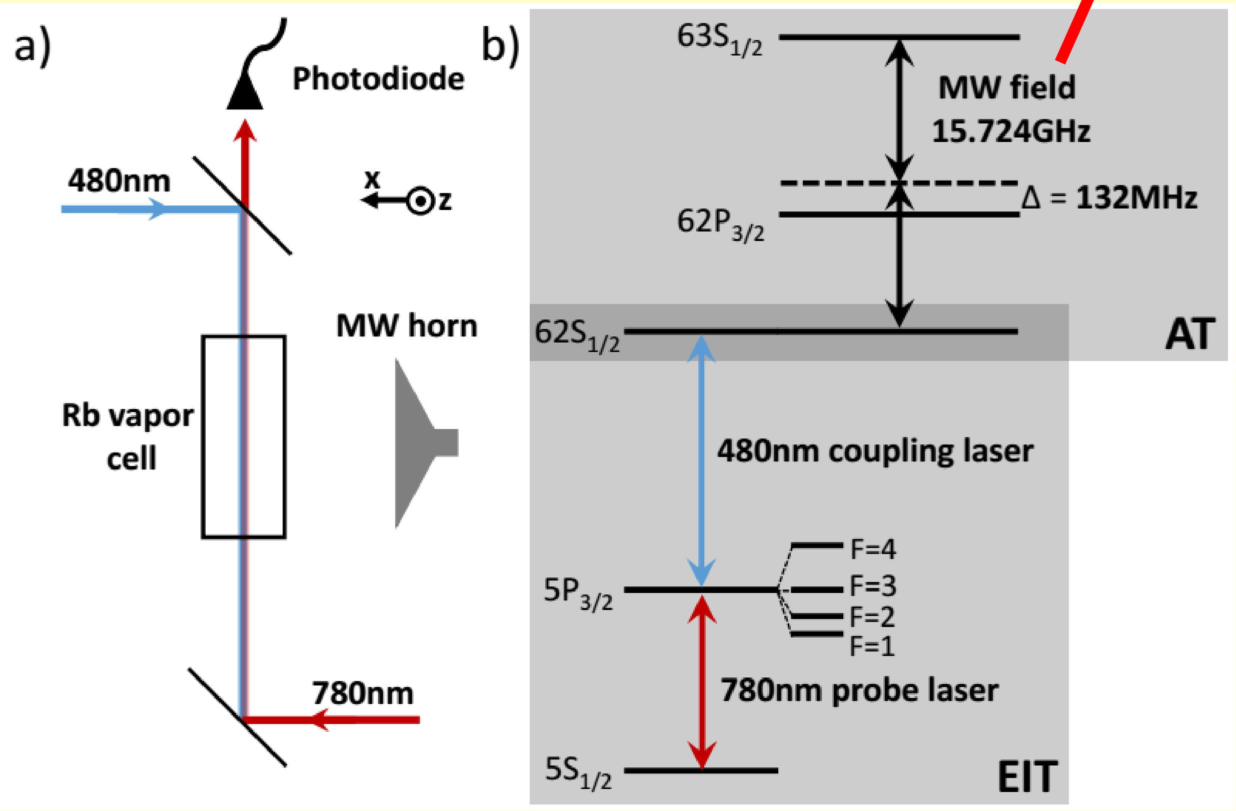
Problem with High E-Field Strength Measurement



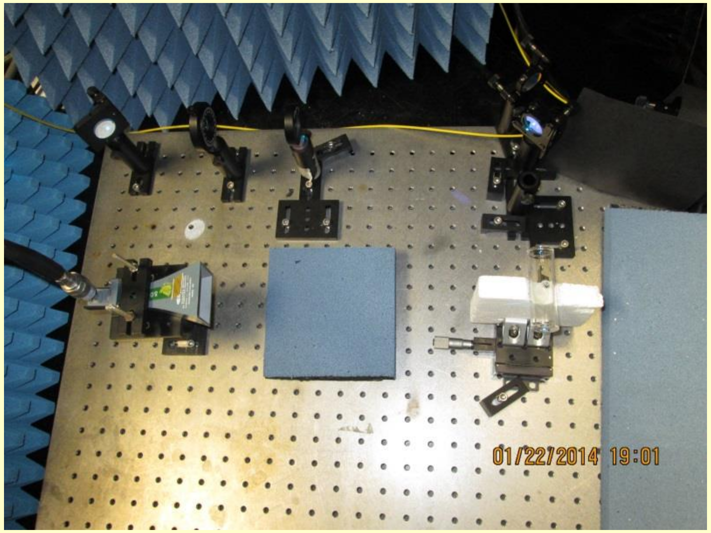
The two-photon transition: nS -to- (n+1)S

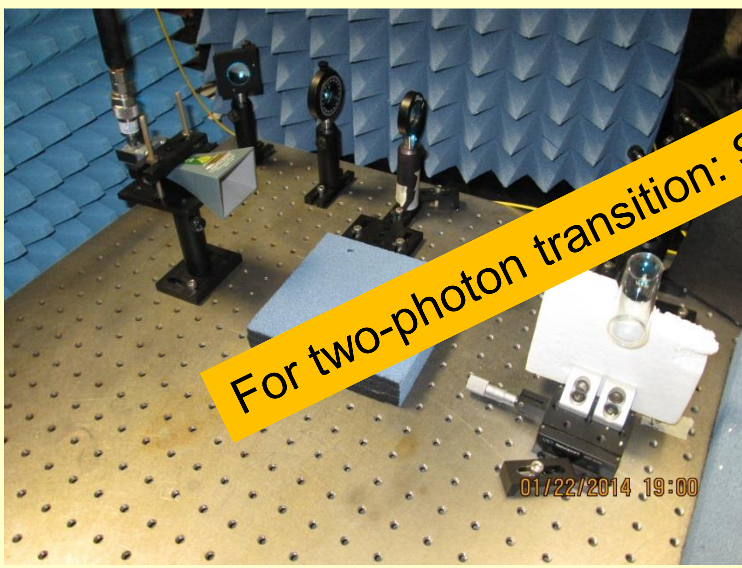


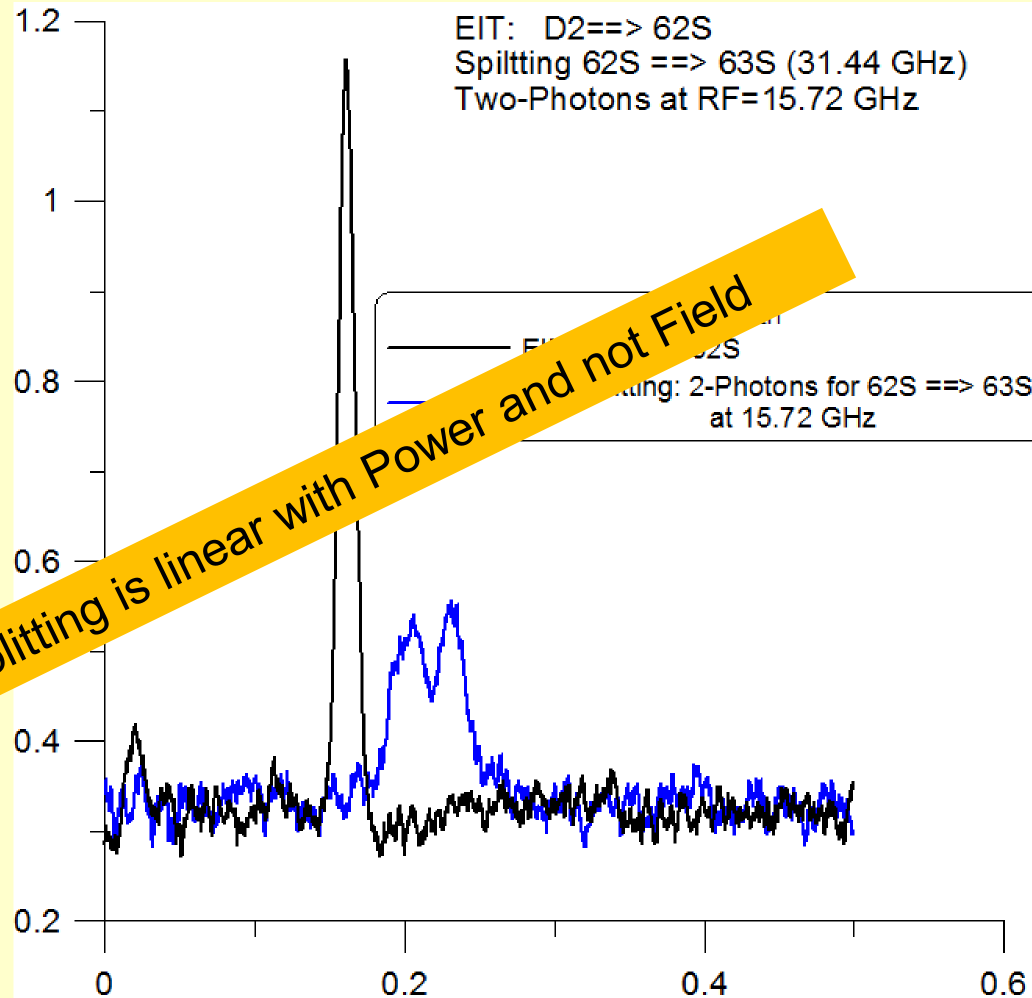
Power at one half the wavelength required
For 62S-to-63S transition



The two-photon transition: nS -to- (n+1)S

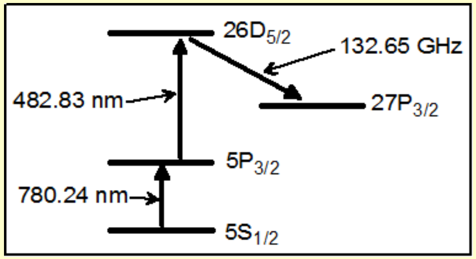


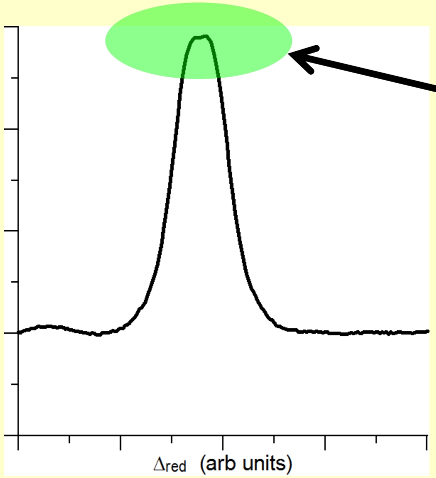




For two-photon transition: Splitting is linear with Power and not Field

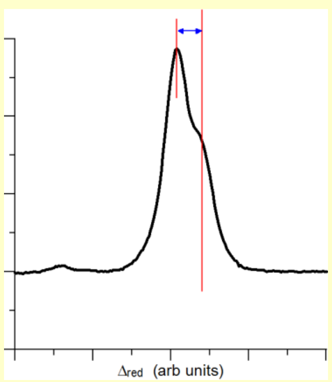
RF Detuning for Weak Field Detection

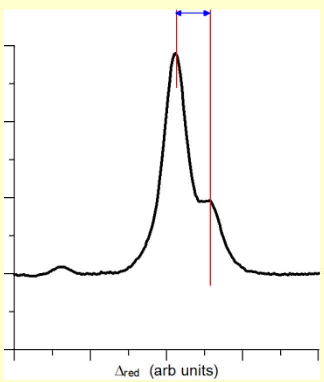


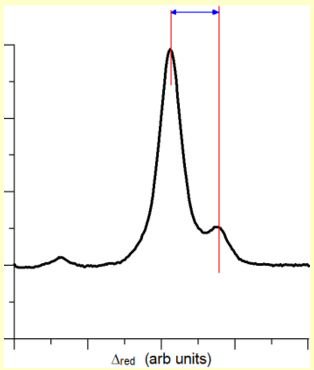


Difficult to determine splitting at low power

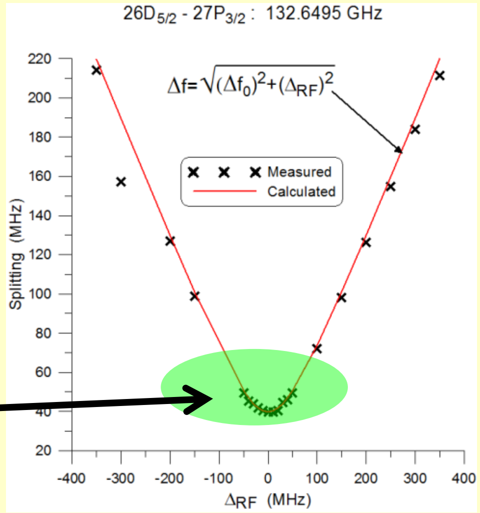
Increased splitting for increased RF detuning



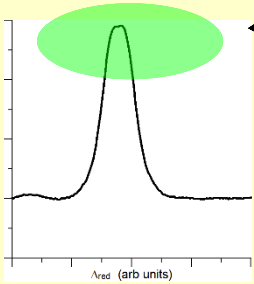




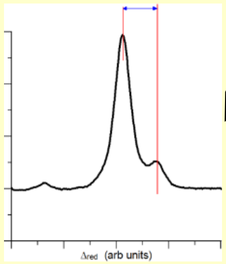
Curve-fit to determine Δf_0 and the applied field strength



Weak Field Detection at 183 GHz and 208 GHz

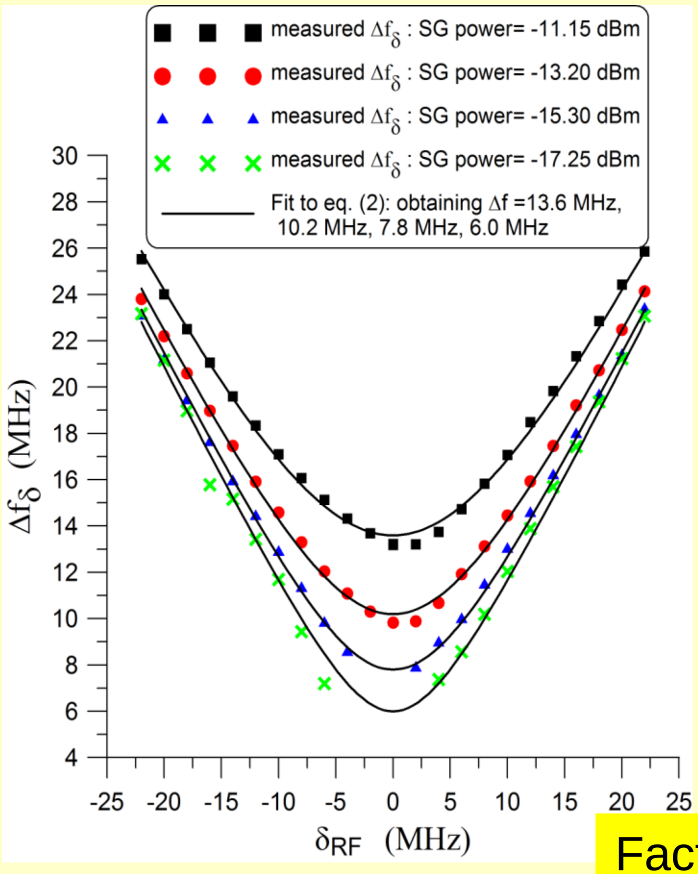


Difficult to determine splitting at low power

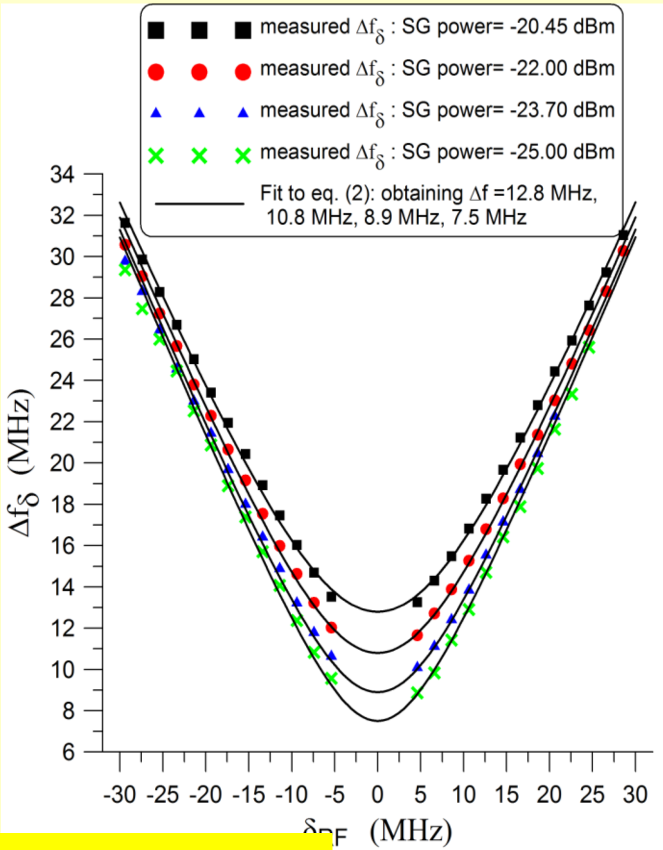


Measure this splitting at low power

183 GHz



208 GHz



Factor of 2 improvement in sensitivity

Applications

Obvious Applications

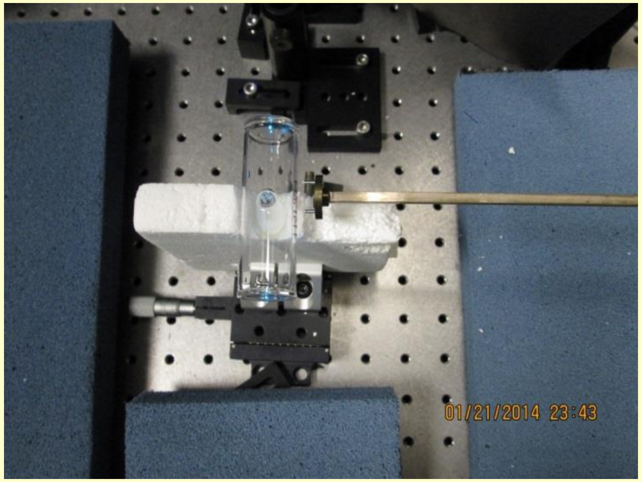
- Will allow direct SI units linked RF electric field (*E*-field) measurements
- Self calibrating due to atomic resonances
- Stand alone probe usable for test and measurement
  - -Calibration of existing probes
  - -Calibration of existing test facilities

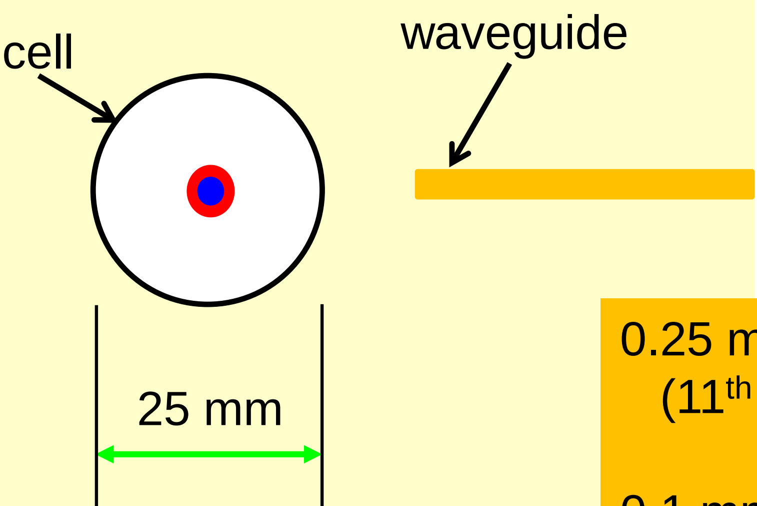
Other Applications

- **Broadband probe/sensor**
- Power calibrations
- Amplitude Reference (feedback control)
- Compact size probe
- Imaging/sensor technology
- It will find other applications where small spatial scale measurements are desired, including fabrication and design of small-scale devices
- THz traceable calibrations
- Small-array of sensors
- ??????

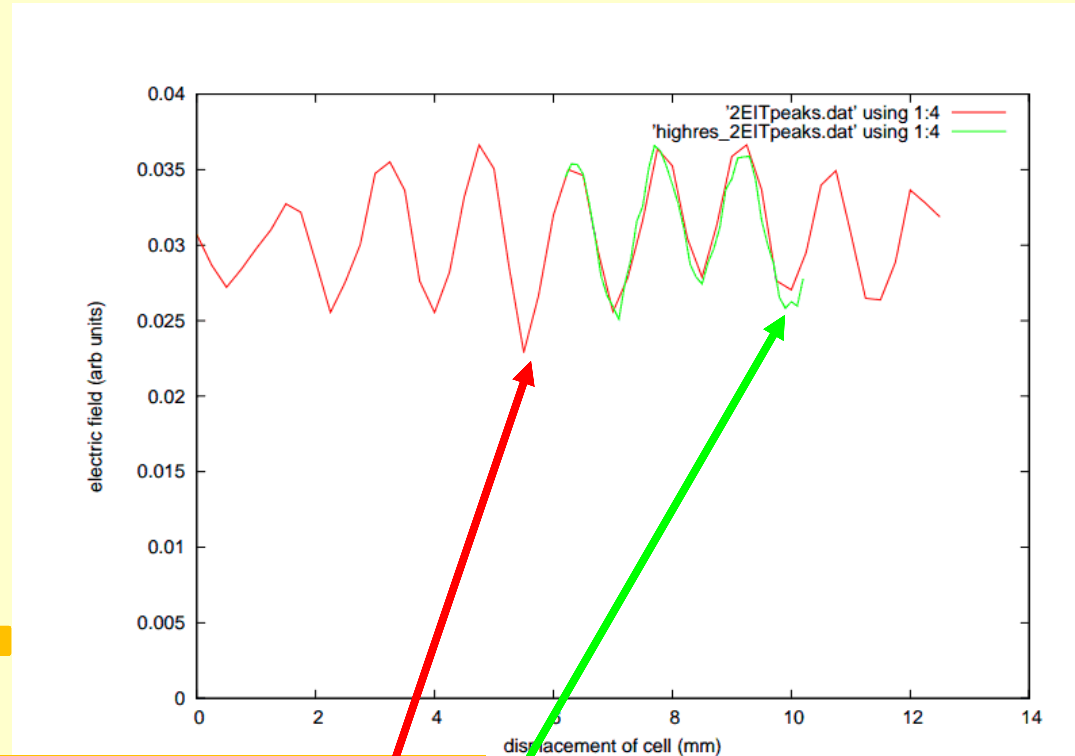
Sub-Wavelength Imaging with EIT

Field Mapping and Sub-wavelength Imaging





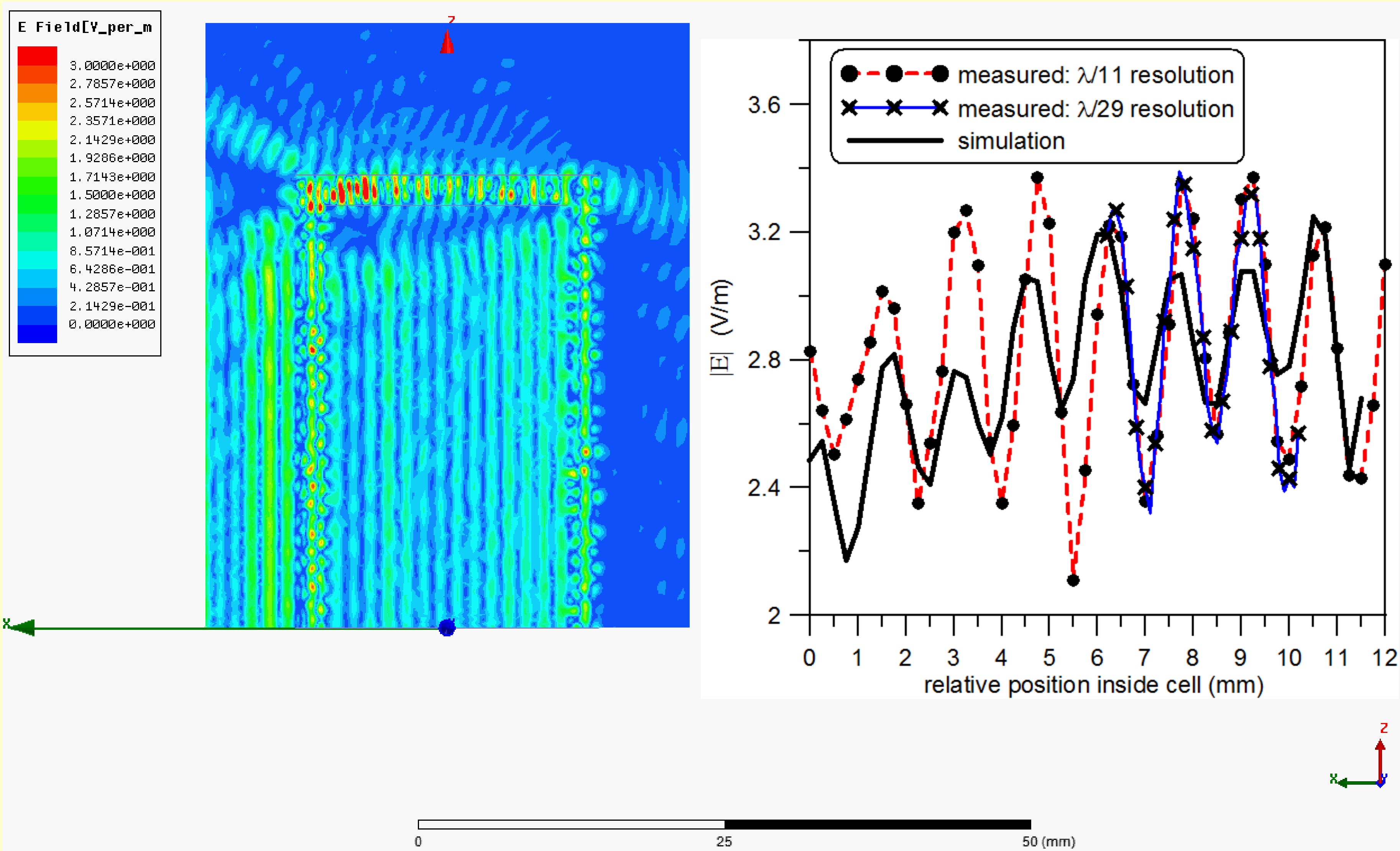
104.77 GHz : λ=2.88 mm



0.25 mm step size: red (11th of a wavelength)

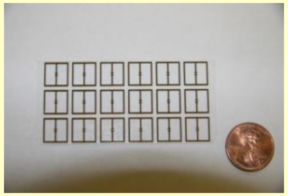
0.1 mm step size: green (29th of a wavelength)

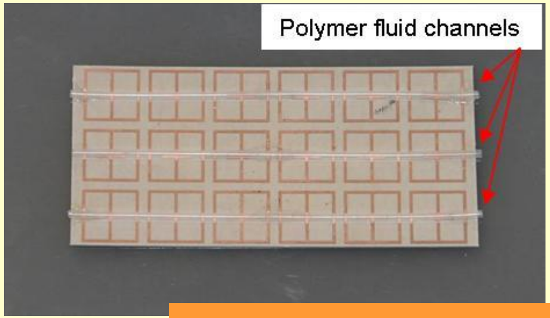
Numerical Comparison at 104.77 GHz

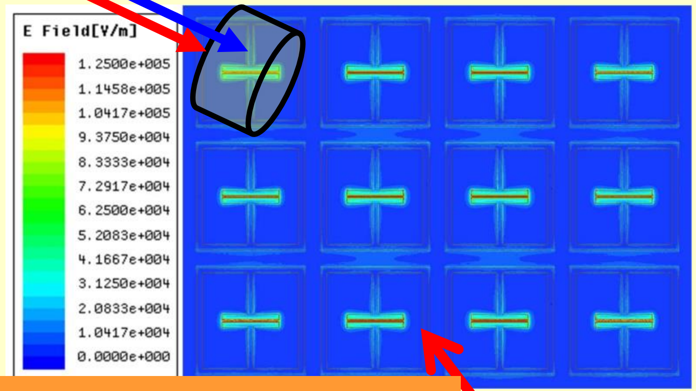


Metamaterial/Metasurface Devices

Microwave-Assisted Chemistry





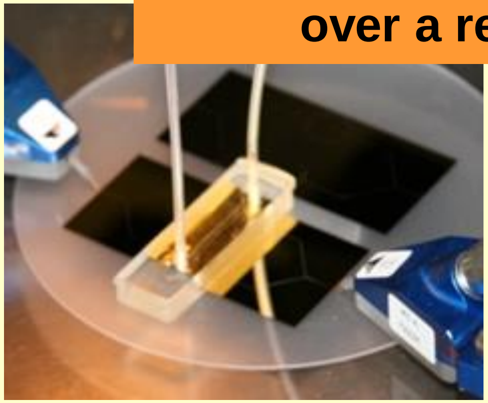


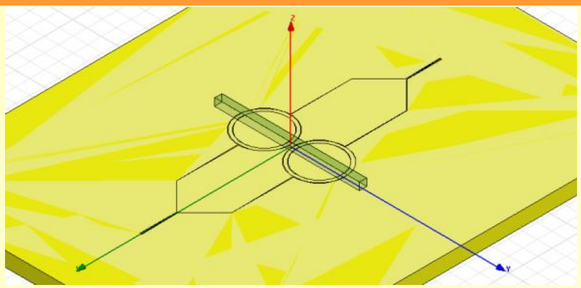
<u>Sub-wavelength</u> imaging at RF via the laser width

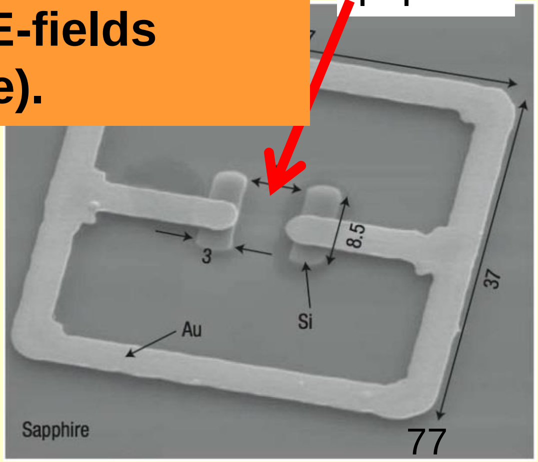
While with current probes we would integrate the E-fields over a region of space (due to the probe size).

|E|=??

Particl

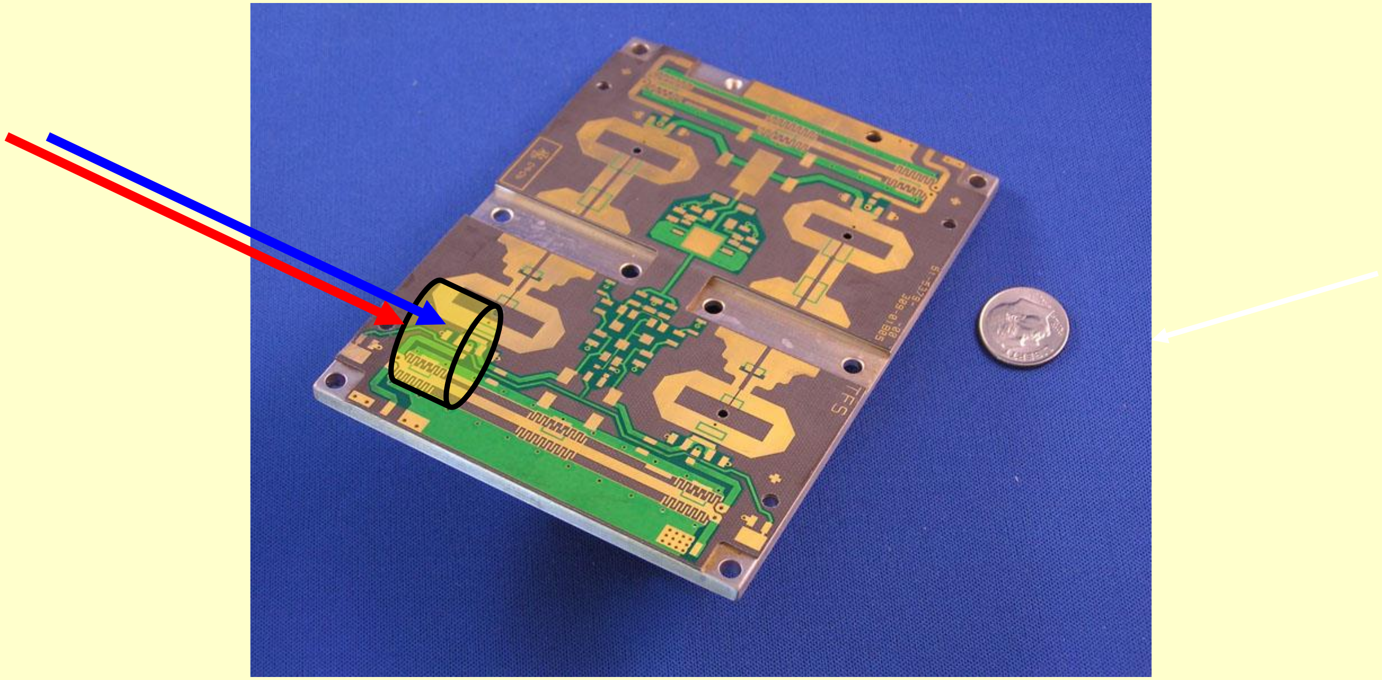




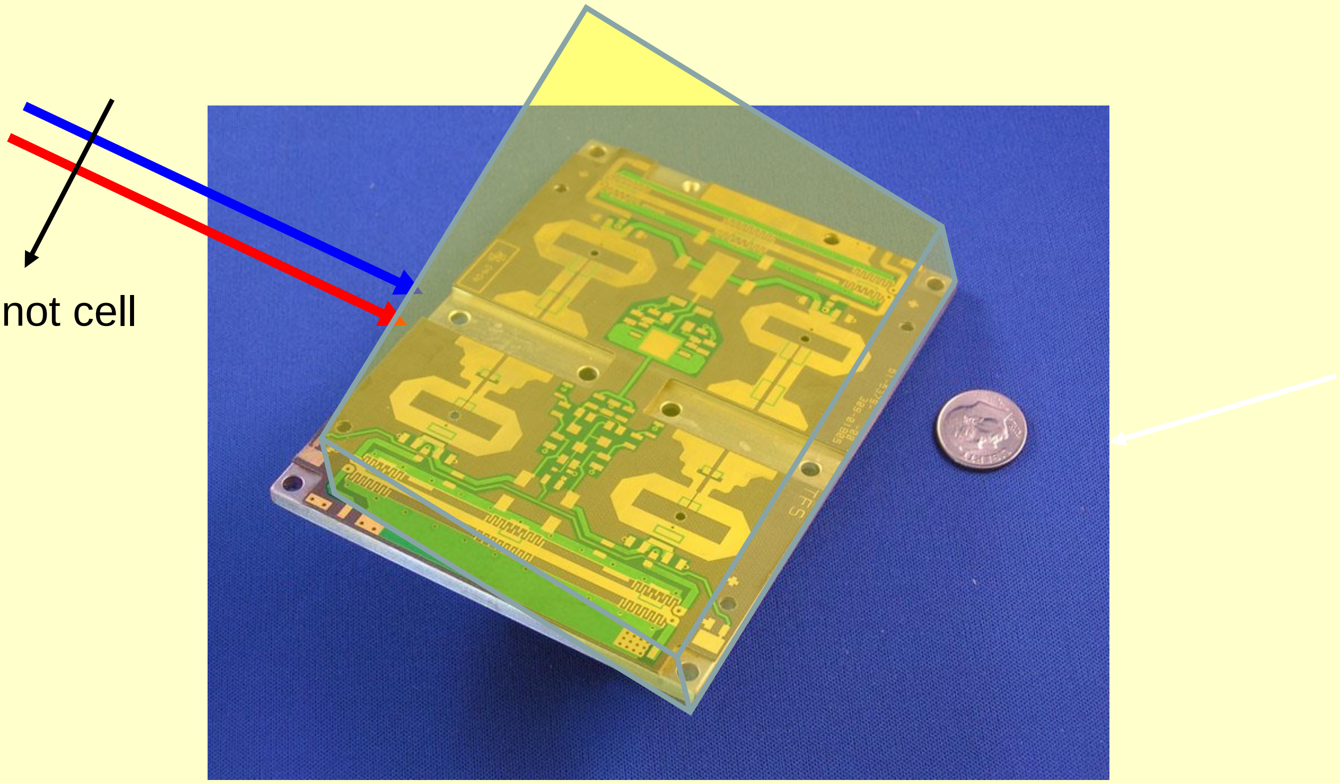


Sub-wavelength imaging at RF via the laser width

While with current probes we would integrate the E-fields over a region of space (due to the probe size).

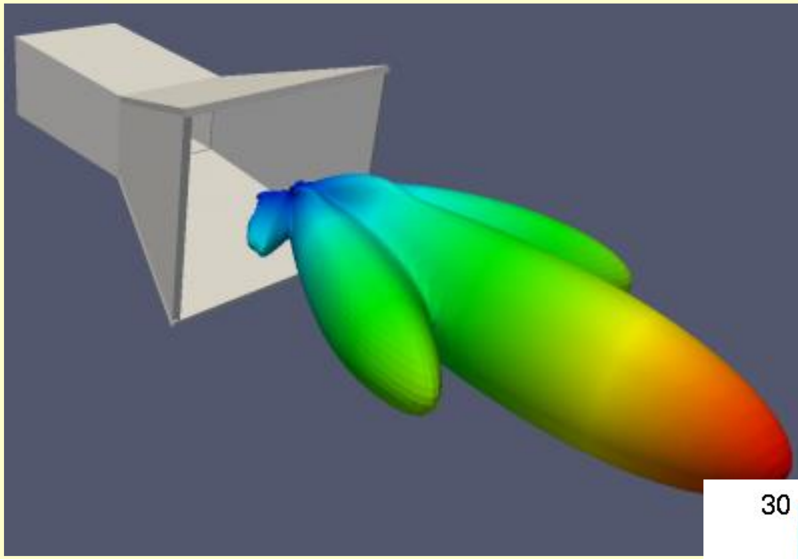


<u>Sub-wavelength</u> imaging at RF via the laser width

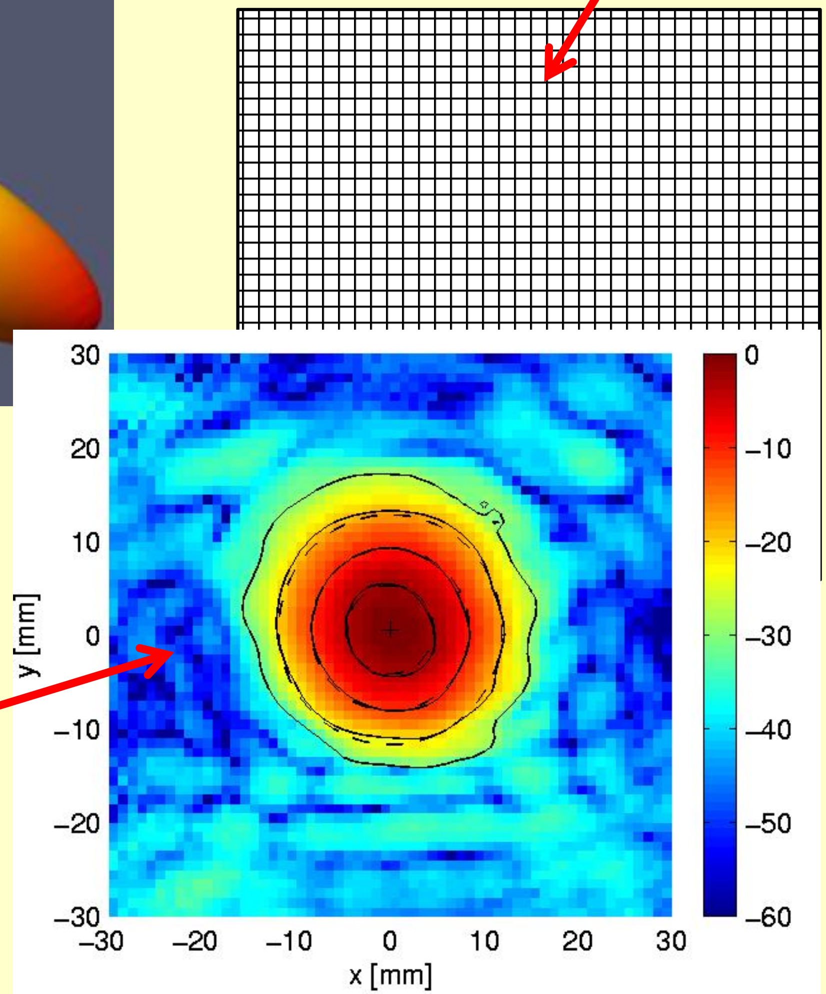


scam lasers not cell

RF Atom Vapor Cell (AVC) Camera

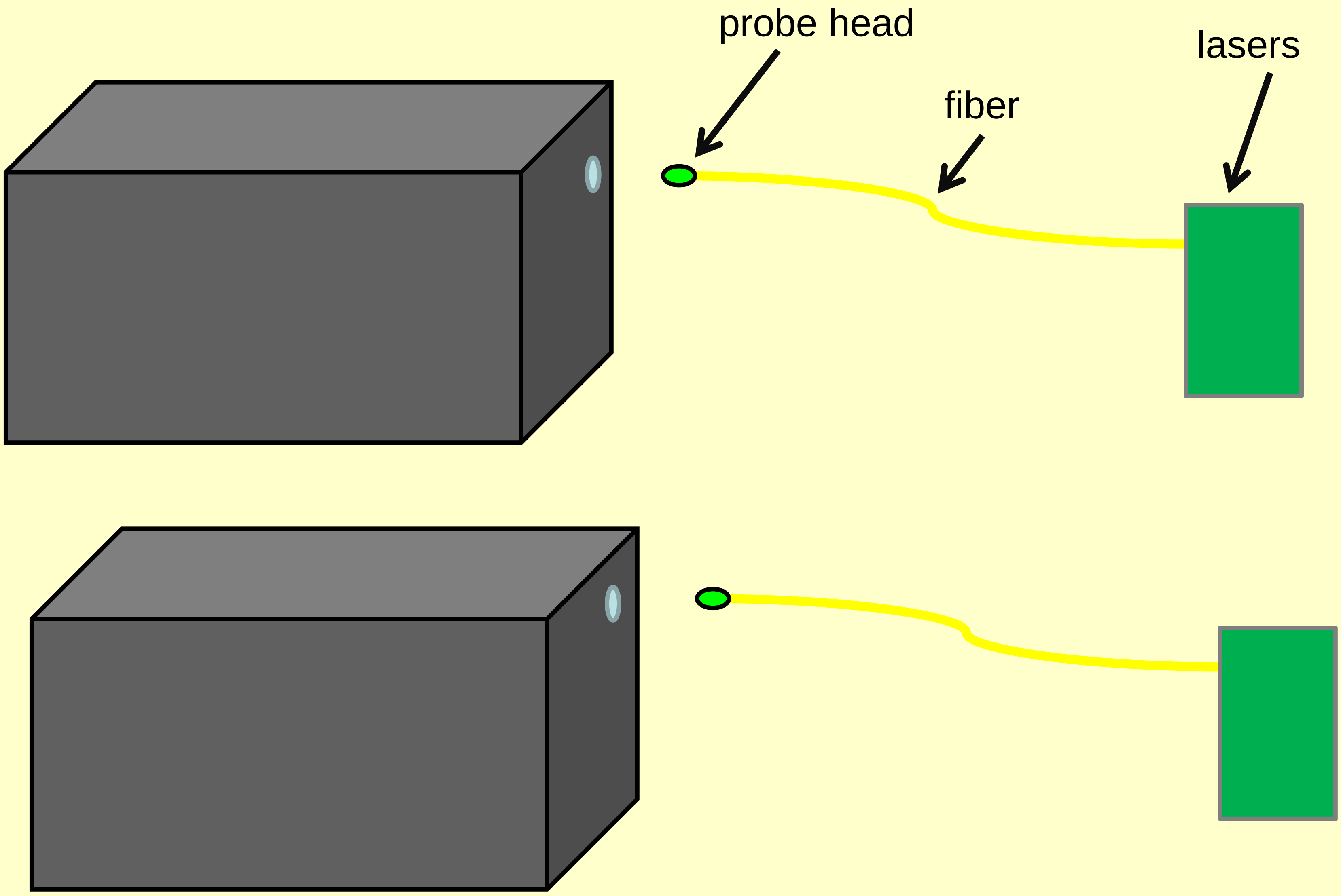


AVC array
Vapor cell pixel



RF Image
RF AVC Camera

Detecting Weak Signals in Confined Places



Competing Size Issues

Two aspects to consider:

- **Self-calibrating traceable probe (may not need to be small or compact)**
- **Compact probe (if needed, could be calibrated)**

Publications

1. **Holloway, et al. , "Sub-Wavelength Imaging and Field Mapping via electromagnetically induced transparency and Autler-Townes Splitting In Rydberg Atoms," *Applied Physics Letters*, 2014.**

2. **Holloway, et al., "Broadband Rydberg Atom-Based Electric-Field Probe/Sensor: From Self-Calibrated Measurements to Sub-Wavelength Imaging," *IEEE Trans. on Antenna and Propagation*, 2014.**

3. **Gordon, et al., "Millimeter-Wave Detection via Autler-Townes Splitting In Rubidium Rydberg Atoms", *Applied Physics Letters*, 2014.**

4. **Anderson, et al., "Two-photon transitions and strong-field effects in Rydberg atoms via EIT-AT," Applied Physics Review, 2014.**

5. **Holloway, et al., Atom-Based Field Metrology: From Self-Calibrated Measurements to Sub-Wavelength Imaging", *IEEE Trans. on Nano Technology*, INVITED paper, 2015.**

6. **Fun et al. "Effect of Vapor Cell Geometry on Rydberg Atom-based Radio-frequency Electric Field Measurements", *Physical Review Applied*, 2015.**

7. **Anderson et al., "Atom-based field measurements of high-power electromagnetic radiation", *Physical Review Applied*, 2015.**

8. **Holloway et al., "Atom-Based RF Electric Field Measurements: An Initial Investigation of the Measurement Uncertainties'', *EMC 2015: Joint IEEE International Symposium on Electromagnetic Compatibility and EMC Europe*, Dresden, Germany, 2015.**

9. **Holloway et al., "Atom-Based RF Field Probe: From Self-Calibrated Measurements to Sub-Wavelength Imaging", *IEEE NANO 2015: 15th International Conference on Nanotechnology*, Rome, Italy, 2015.**

10. **Holloway et al., "Broadband Rydberg Atom Based Self-Calibrating RF E-Field Probe", ROACH 2014- Seattle, WA.**

11. **Gorgon, et al., "Millimeter-Wave Detection via Autler-Townes Splitting In Rubidium Rydberg Atoms", ROACH 2014- Seattle, WA.**

12. **Holloway et al., "Rydberg Atom Based Self-Calibrating RF E-Field Prob for subwavelength imaging", APS/URSI 2014, Mephaus, TN**

13. **Miller et al. , "Microwave-induced two-photon Autler-Townes splitting in Rydberg EIT," 45th Annual Meeting of the APS Division of Atomic, Molecular and Optical Physics, Vol. 59, No. 8, June 2–6, 2014; Madison, Wisconsin.**

14. **Simons, et al., "Enhanced absorption and Autler-Townes splitting of electromagnetically induced transparency"', APS DAMOP, 2015.**

15. **Holloway et al, "The Uncertainties Associated with Rydberg Atom Based Electric Field Measurements," APS/URSI 2015, Canada.**

Summary

Fundamentally new approach for E-field measurements

•**Broadband probe/sensor: 1 GHz-to-500 GHz (possibly to 1 THz)**

•Will allow direct SI units linked RF electric field (*E*-field) measurements

•Self calibrating due to atomic resonances

•Would provide RF field measurements independent of current techniques

•Power measurements

•Calibrations above 110 GHz

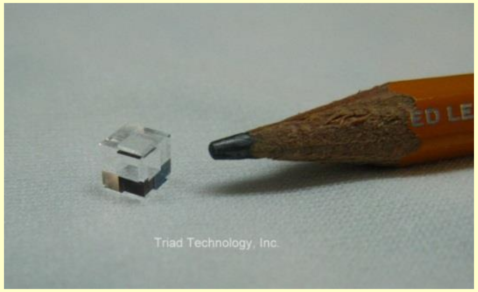
•Potentially very small and compact probe: optical fiber and chip-scale probe

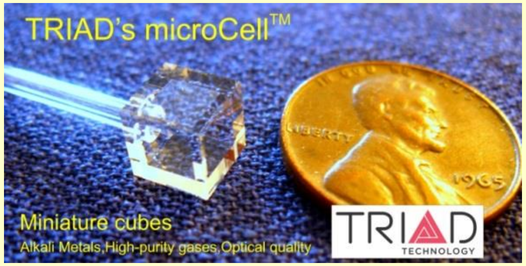
•Measure very weak E-fields over a large range of frequencies :
< 1 mV/m: *two orders of magnitude improvement*

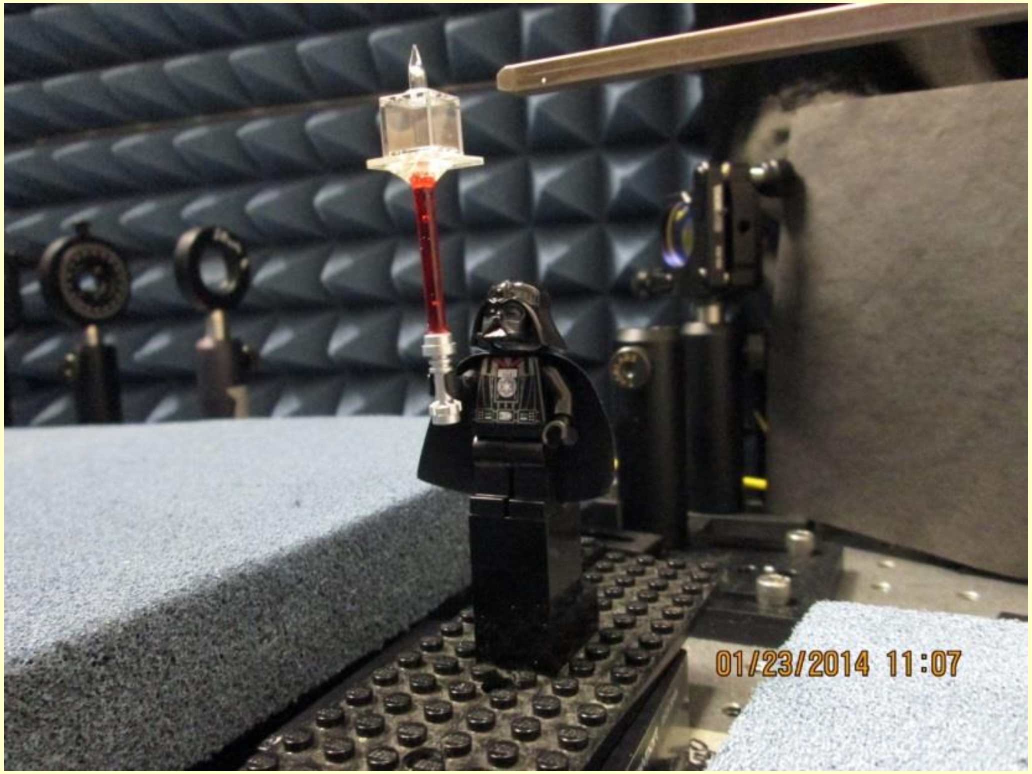
•The RF resonance in the vapor cell is the dominant uncertainty, which can be reduced by making the cell as small as possible.

The bottom line is that we would be developing a measurement technique that could be applied to various form factors and applications.

??? Questions???


Triad Technology, Inc.


TRIAD's microCell™
Miniature cubes
Alkali Metals,High-purity gases,Optical quality
TRIAD
TECHNOLOGY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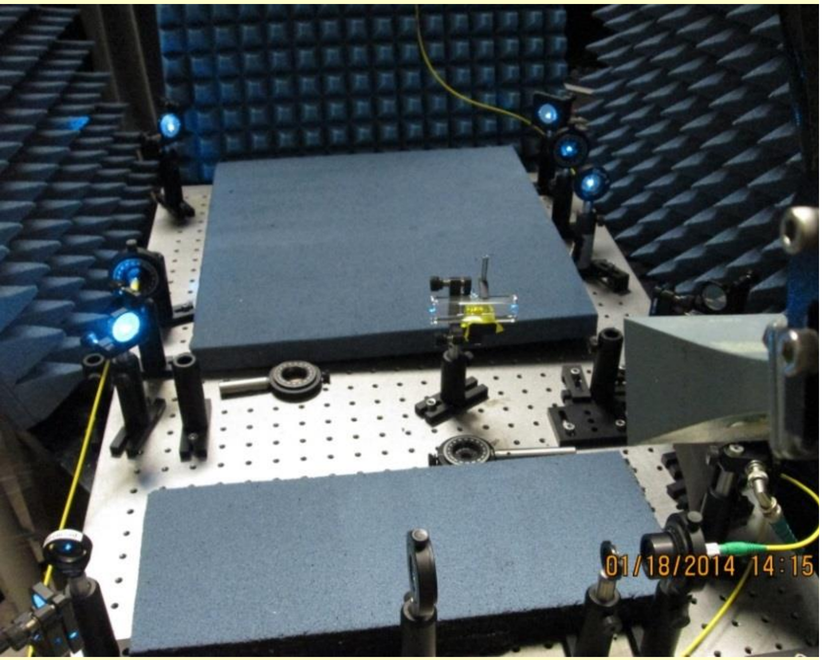
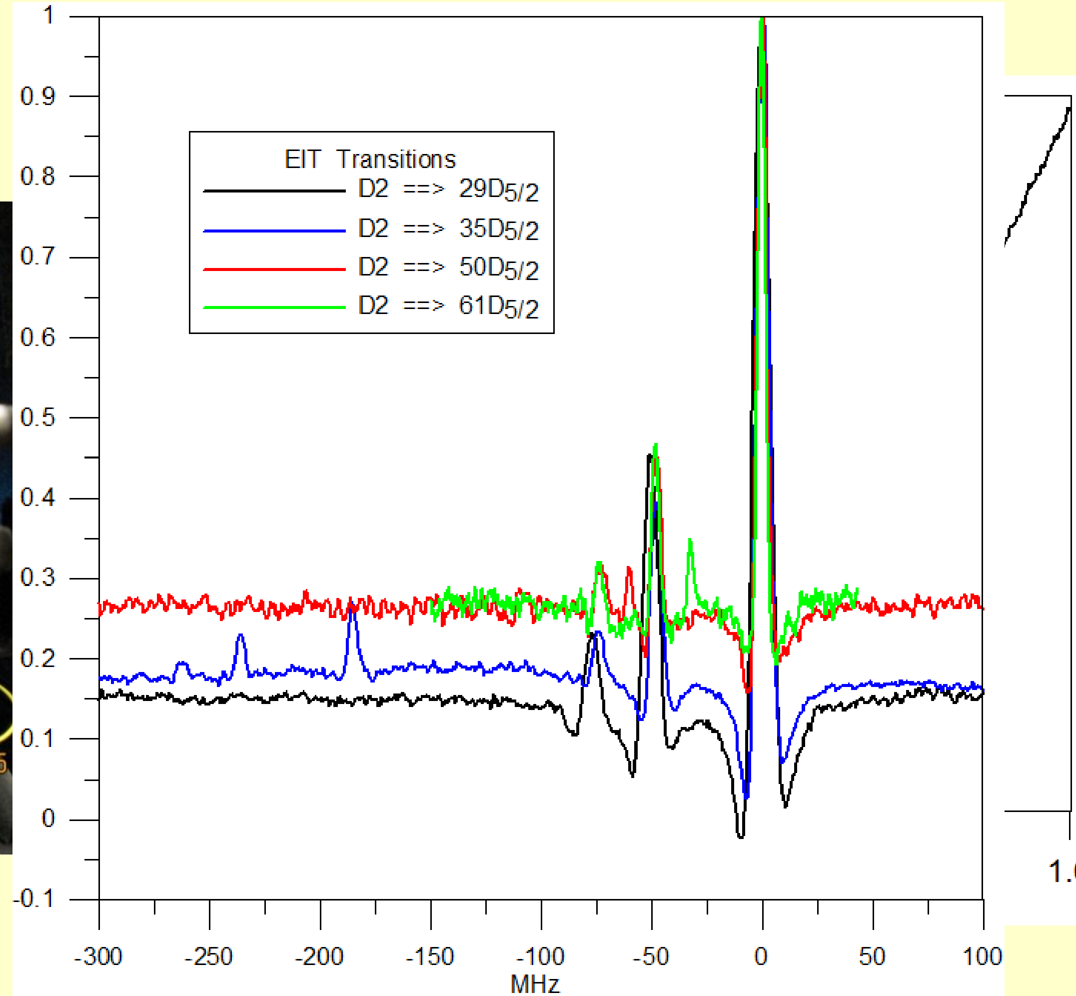
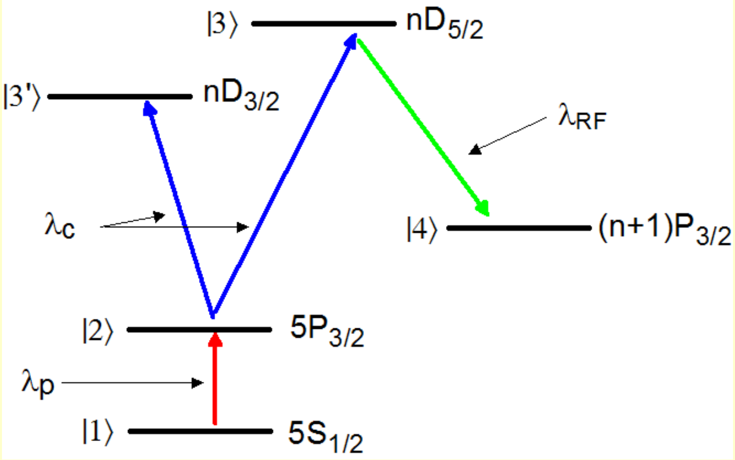
Demonstrate EIT for large number of D2 transitions: from 26D-to-68D





Theoretical Model for Multi-level EIT Signals: Including Fine- and Hyperfine-Structure

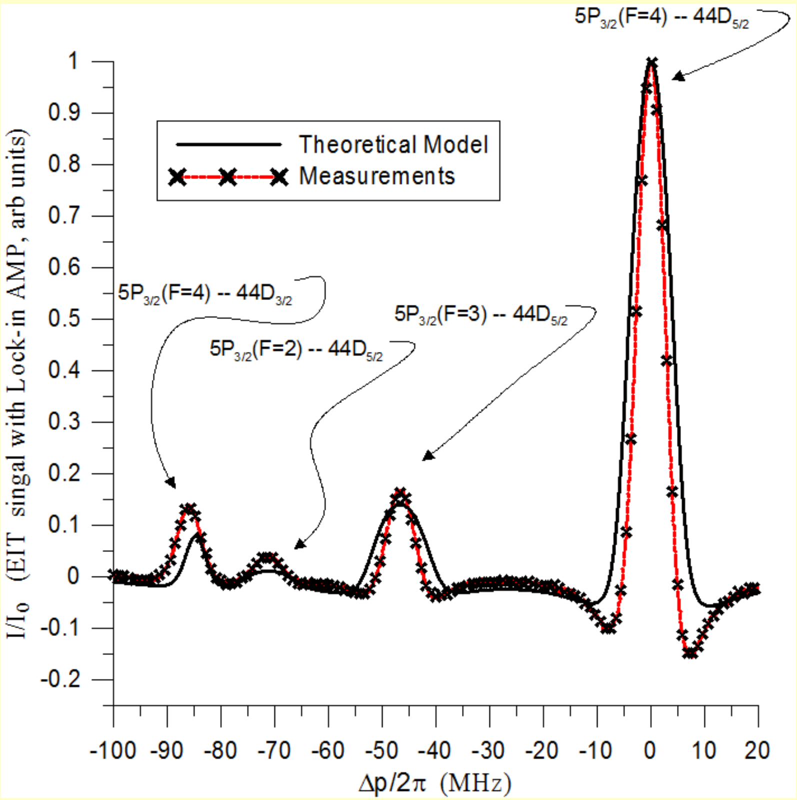
74 possible atomic states to consider



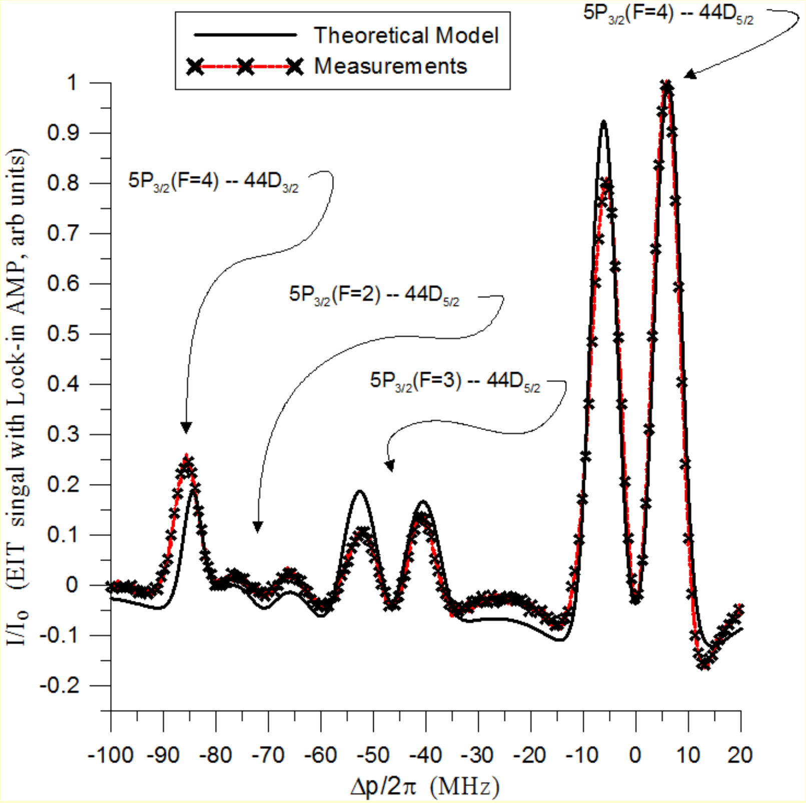
Theoretical Model for Multi-level EIT Signals: Including Fine- and Hyperfine-Structure

74 possible atomic states to consider

No RF



RF at 25.34 GHz



Dipole Moment

Since the dipole moment is directly related to the field we can measure, it is one of parameters that govern the uncertainty of the E-field measurement. We need accurate values of the dipole moment.

We have written a numerical code to first determine the wavefunction for a given set of states. These wavefunction were then numerical integrated to give the desired dipole moment.

We follow the technique of Numerov as discussed in Gallagher's book, in which the wavefunction is obtained from a finite-difference technique. We start with:

$E_{n,l,j} = \frac{-R_y}{(n-\delta_{l,j})^2}$ and $\left(\frac{\nabla^2}{2} + \frac{1}{r} + E_{n,l,j}\right)\psi = 0$ $\textit{where } \delta_{l,j} \textit{ is the empirically quantum defect}$

we need $\wp_{12} = e\langle\psi_1|\, r\,|\,\psi_2\rangle$ which we get from a numerical integration of the wavefunctions

After writing the program, we compared the dipole moment to various values in the literature for both H and Rb atoms.

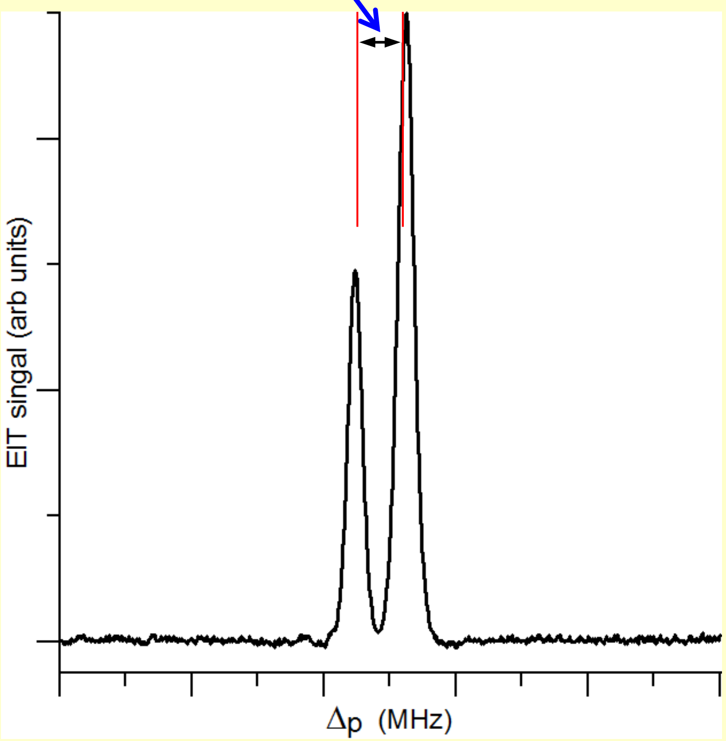
Dual Atom Experiments at 9.2-ish GHz

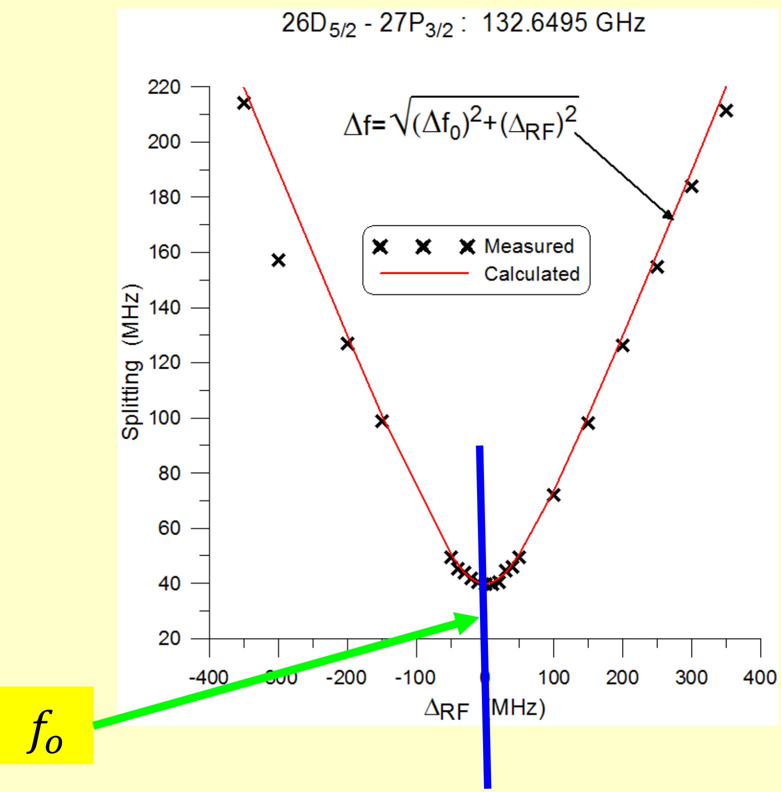
Theoretical Energies/Frequencies from the quantum defects

Cs: $43D_{5/2}$-$44P_{3/2}$: <u>9.225 GHz</u>   Rb: $61D_{5/2}$-$62P_{3/2}$: <u>9.226 GHz</u>

Experimental Energies/Frequencies from RF detuning

$$\Delta f = \sqrt{(\Delta f_o)^2 + (f_{RF} - f_o)^2}$$





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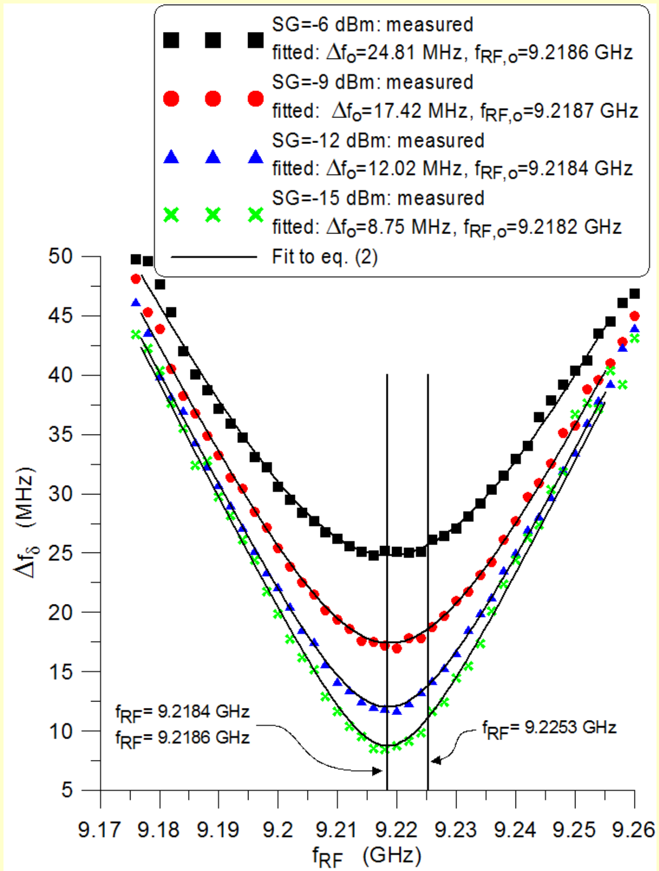
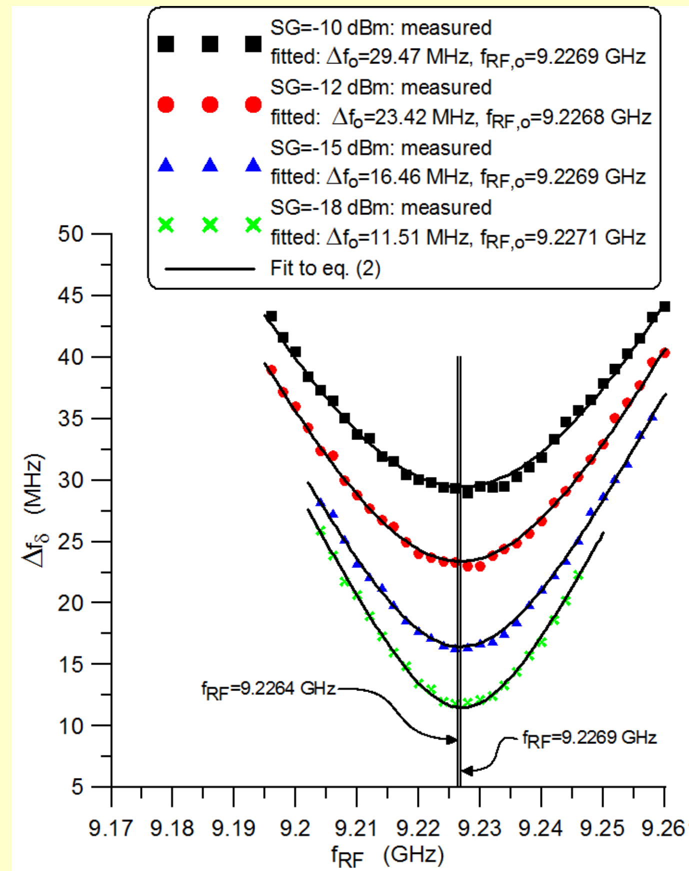


Cs: <u>9.218 GHz</u> : n=43



Rb: <u>9.226 GHz</u> : n=61

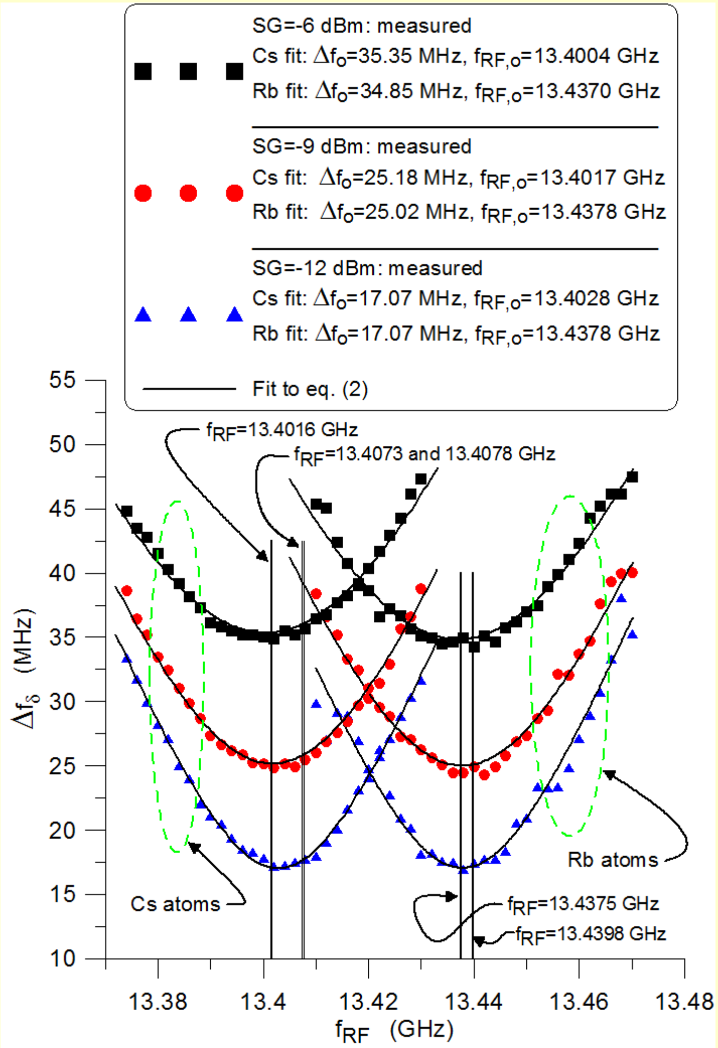
The quantum defects for Rb (*high n*) are very good, while there is some small errors for Cs (*low n*).

Dual Atom Experiments at 13-ish GHz

Theoretical Energies/Frequencies from the quantum defects

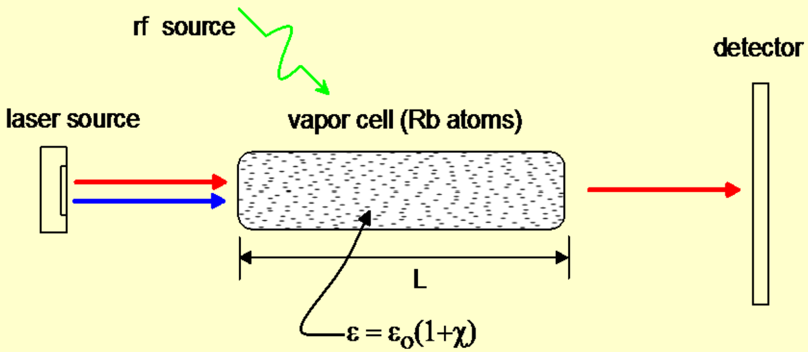
Cs: $66S_{1/2}$-$66P_{3/2}$: 13.4016 GHz   Rb: $65S_{1/2}$-$65P_{3/2}$: 13.4375 GHz

Experimental Energies/Frequencies from RF detuning

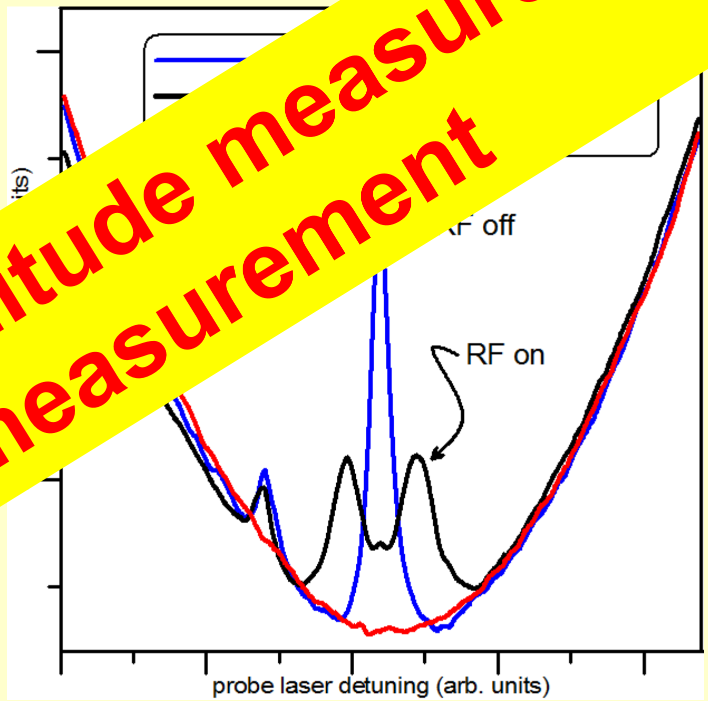


Both the quantum defects for Rb and Cs have errors.

EIT with an RF source



The blue laser gets us high eno
next transition can be m



We have reduced an amplitude measurement to a frequency measurement

Splitting in the EIT signal
(Autler-Townes Splitting)

$$\Omega_{rf} = |E|\frac{\wp}{\hbar}$$

or

$$|E| = \Omega_{rf}\frac{\hbar}{\wp}$$

Four-Level EIT: RF E-field Measurement

RF-trans

$\Omega_{rf} \approx 290$

$C \cdot m]$

$^{-10}$ $[m]$

^{19} $[C]$