Enhancement of Rydberg atom interactions using dc and ac Stark shifts

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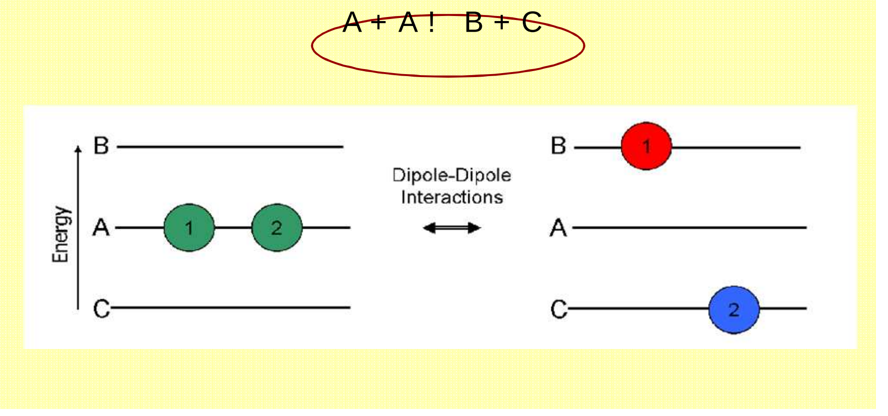
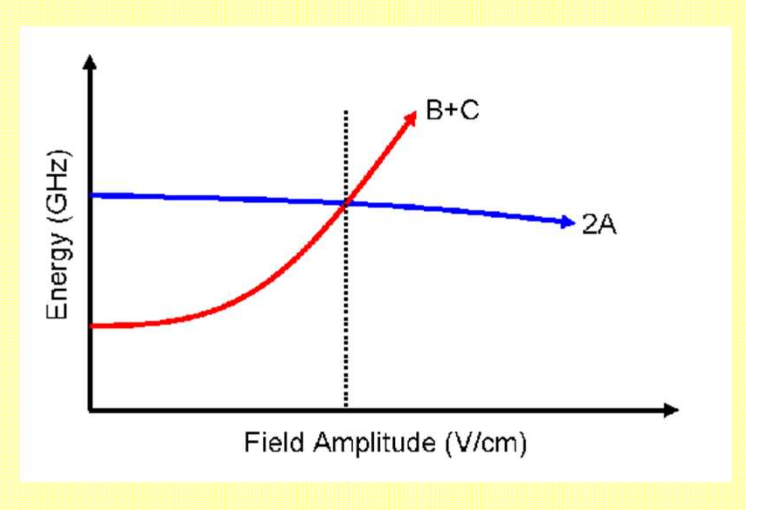
Objective

- Enhancement of interatomic interactions by electric field induced resonant energy transfer (RET)





Motivations

- Determining unknown atomic energy levels by dc field induced RET spectra
- Using ac field induced RET for energy level determination where dc field can not be used
- RET can be utilized in the implementation of dipole blockade

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Summary of the materials to be discussed

- Rydberg atoms
- Experimental methodology
  - Magneto-Optical Trap (MOT), Selective Field Ionization (SFI)
  - Laser frequency stabilization
- Dipole-Dipole interactions, RET
- **dc** electric-field-induced RET
  - Estimation of g series quantum defect
- Observation of **ac** electric-field-induced RET

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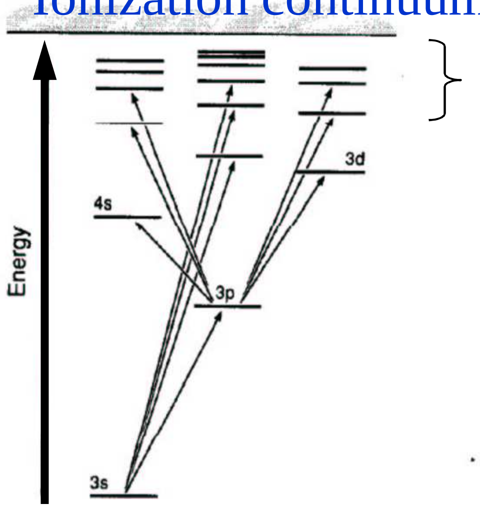
Rydberg atoms

- loosely bound electron circling ionic core.



Rydberg constant (13.5 eV)

ionization potential

$$E_{n,\ell} = \mathrm{IP} - \frac{R}{(n - \delta_\ell)^2}$$

quantum defect

$\delta_s = 1.3, \quad \delta_p = 0.85$ for Na

- these states have long lifetimes (eg. 17p of Na: 50 µs).
- properties scale with *n* and can be exaggerated.

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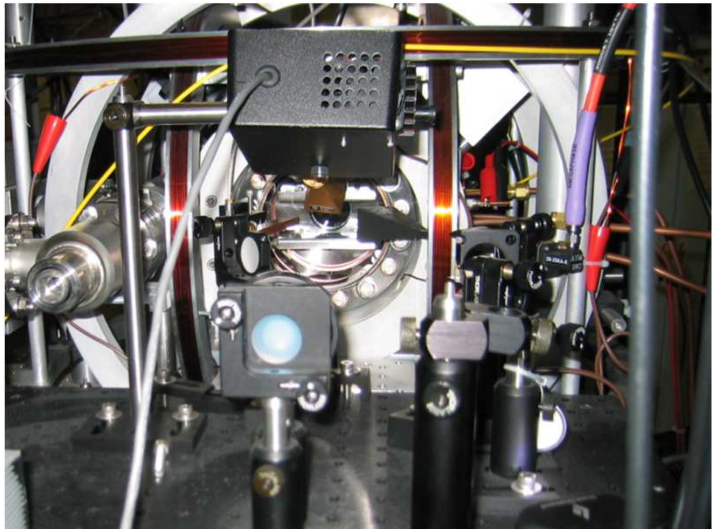
Experimental Methodology

- Form cold Rb atoms in a MOT for studies between *stationary* atom
  - 1 mm^3, 300 μK , Rydberg atoms: 10^7 cm^{-3}
- Rydberg atom excitation using 480nm frequency doubled Ti:sapphire laser



- Measurement and compensation of stray E and B fields using mwave transitions between Rydberg states
- Do experiment …
- Verify excitation using SFI technique
- 10 Hz repetition rate

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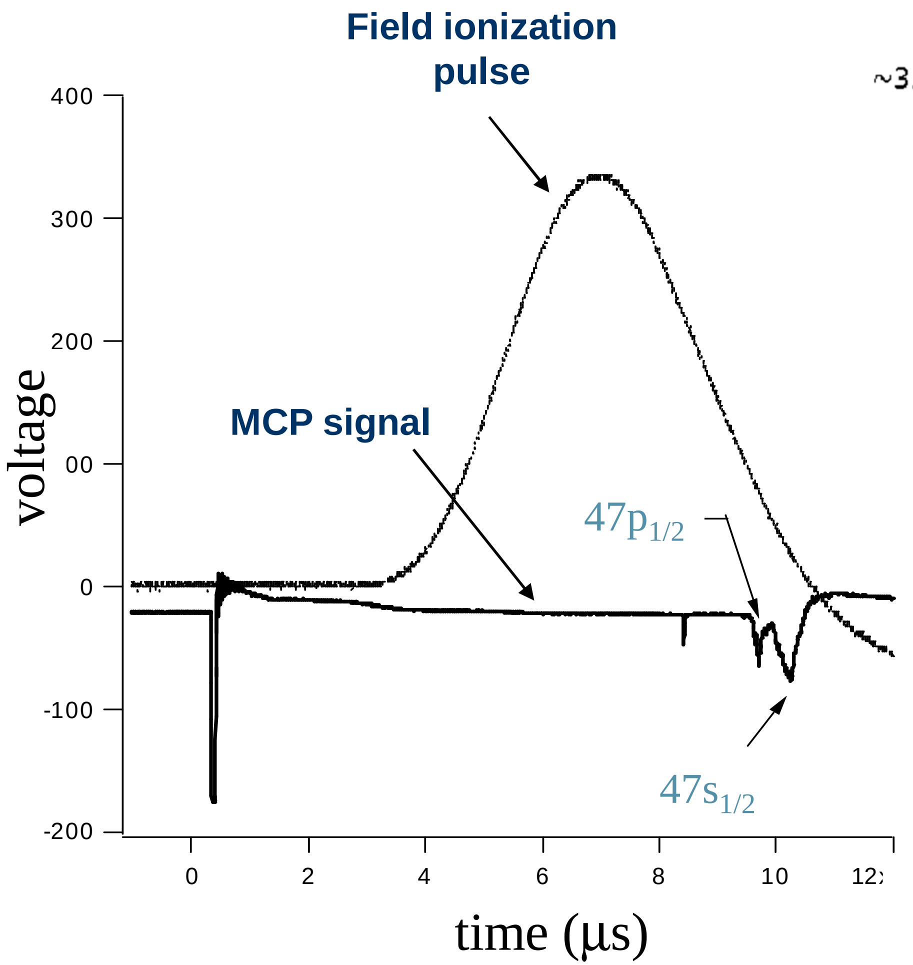
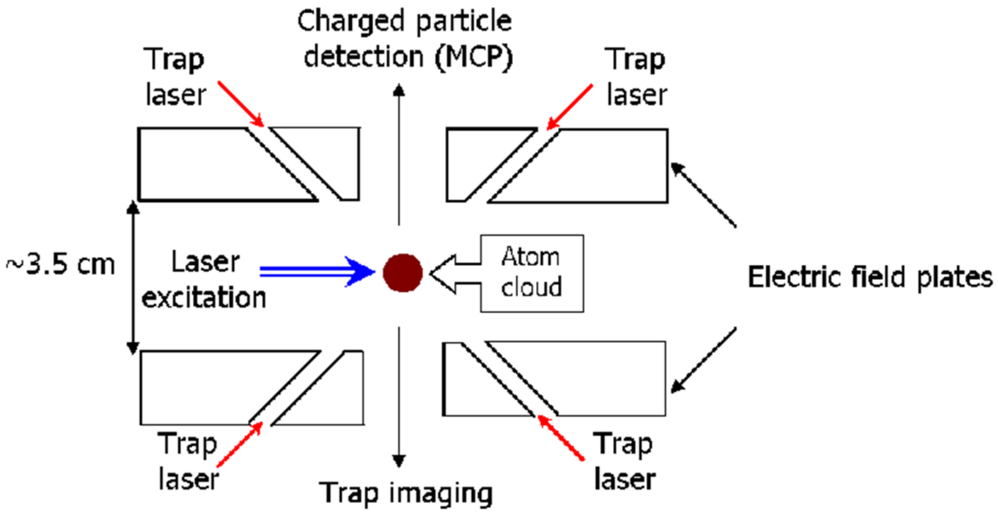
Selective Field Ionization (SFI) detection of Rydberg atoms





- Use SFI to determine state distribution in the trap.

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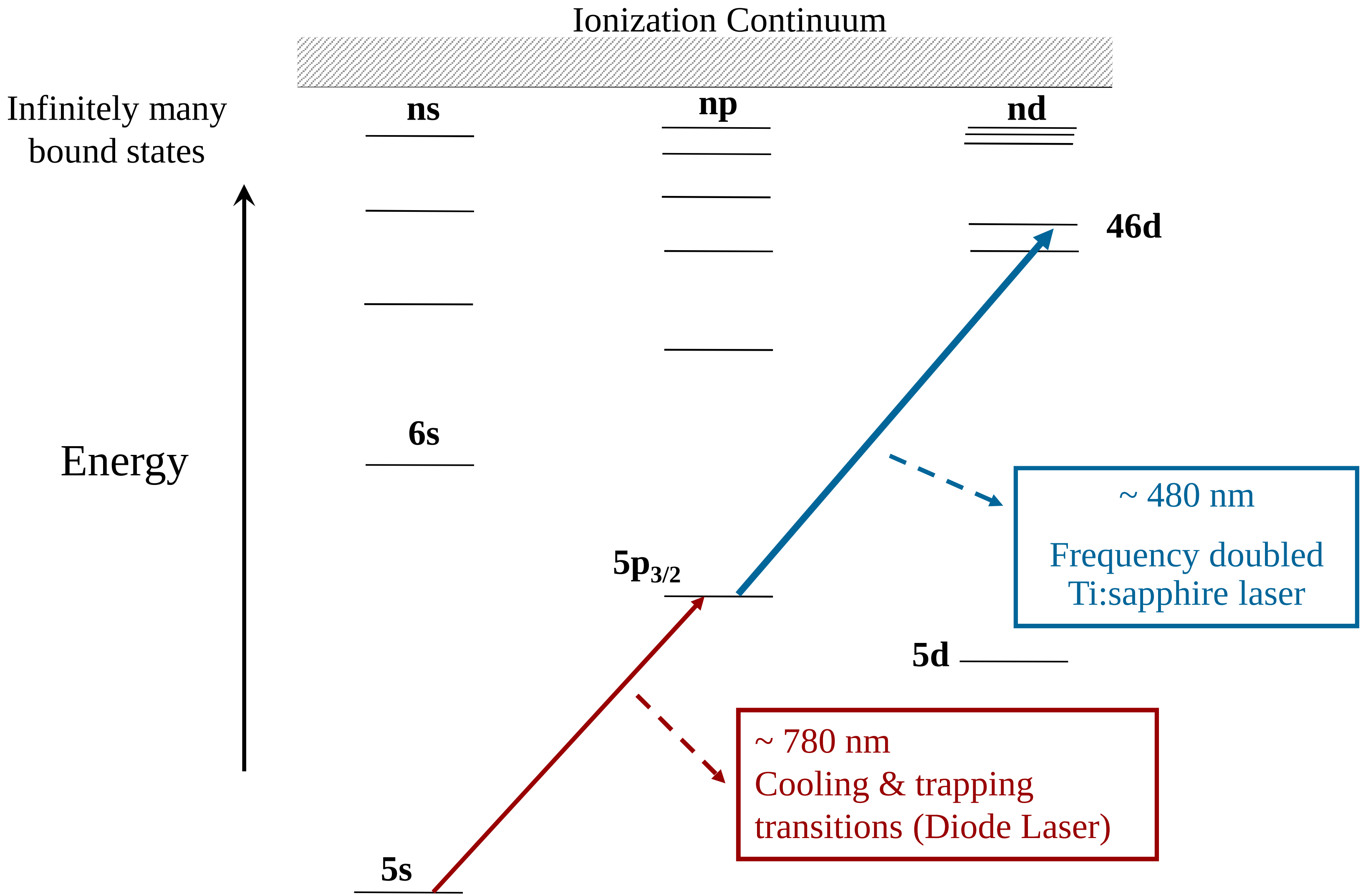
Rydberg Atom Excitation



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Optical Transfer Cavity Stabilization using Tunable Sidebands of RF Current-Modulated Injection-Locked Diode Lasers

Objective

- Stabilize lasers at frequencies where direct locking to a reference line is not possible

Motivation

- High resolution optical spectroscopy for laser cooled Rydberg atom excitation.

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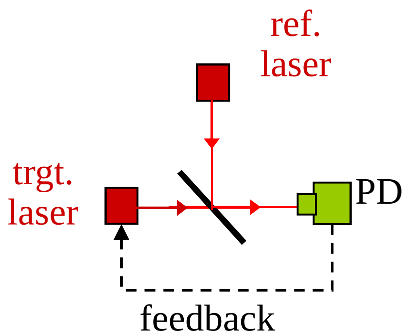
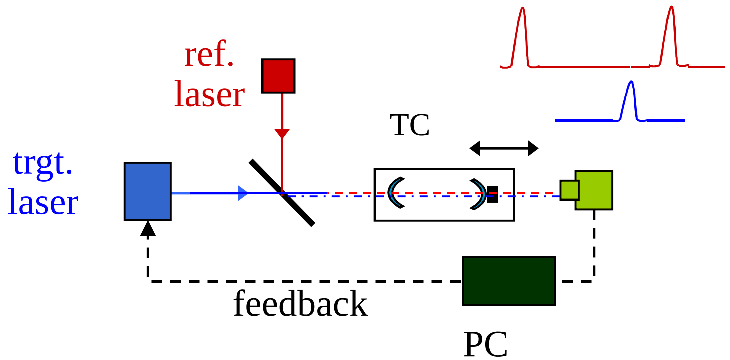
Review / Alternative approaches

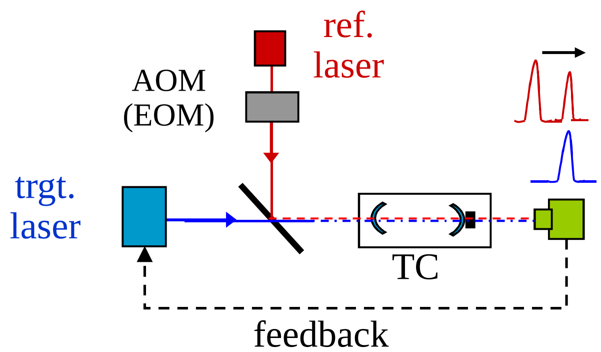
- Absolute frequency reference (Barger 1969)
  - Beat note locking
  - Practical up to a certain frequency difference



- Scanning transfer cavity (TC) (Lindsay 1991, Rossi 2002)
  - Scanning rate limits the maximum error correction
  - Sensitive to low frequency vibrations
  - Complexity of the fringe comparison



- Stabilized TC (Burghardt 1979, Plusquellic 1996)
  - Frequency shift using EOM or AOM



A general frequency stabilization technique

- Fabry--Perot TC stabilized using a tunable sideband

  from a current modulated injection locked diode laser.

  - Frequency shifts without using AOMs or EOMs.
  - Not limited to certain wavelengths
  - Tuning frequency with RF precision.

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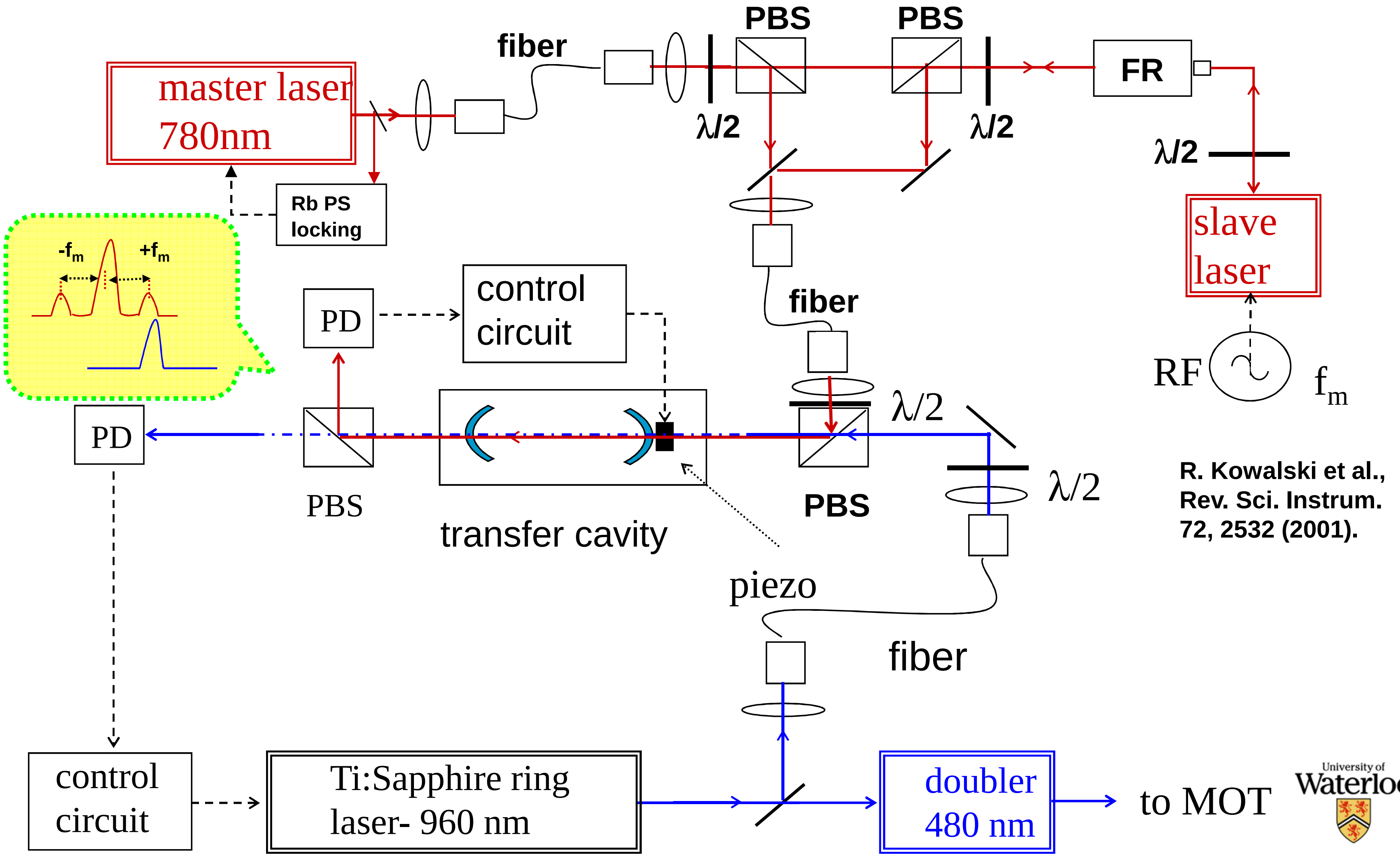
Experimental setup :



R. Kowalski et al.,
Rev. Sci. Instrum.
72, 2532 (2001).

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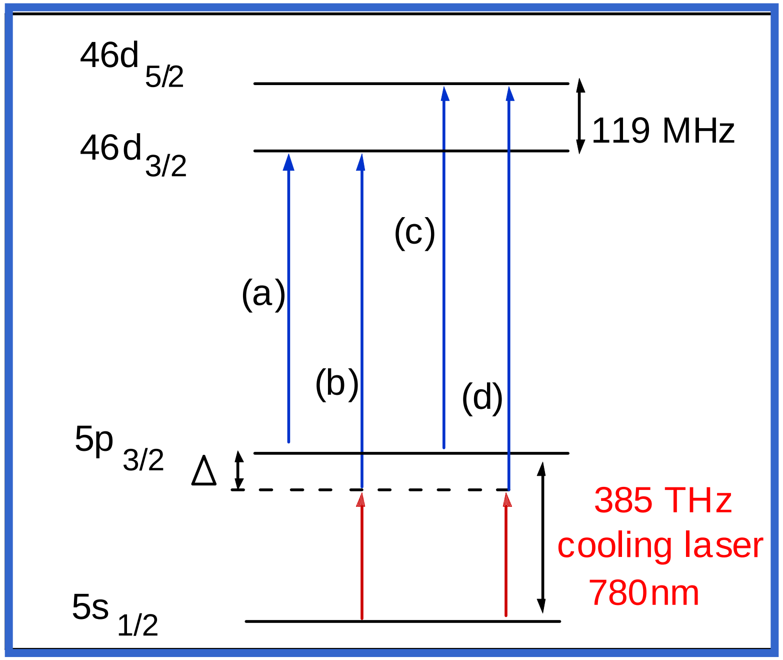
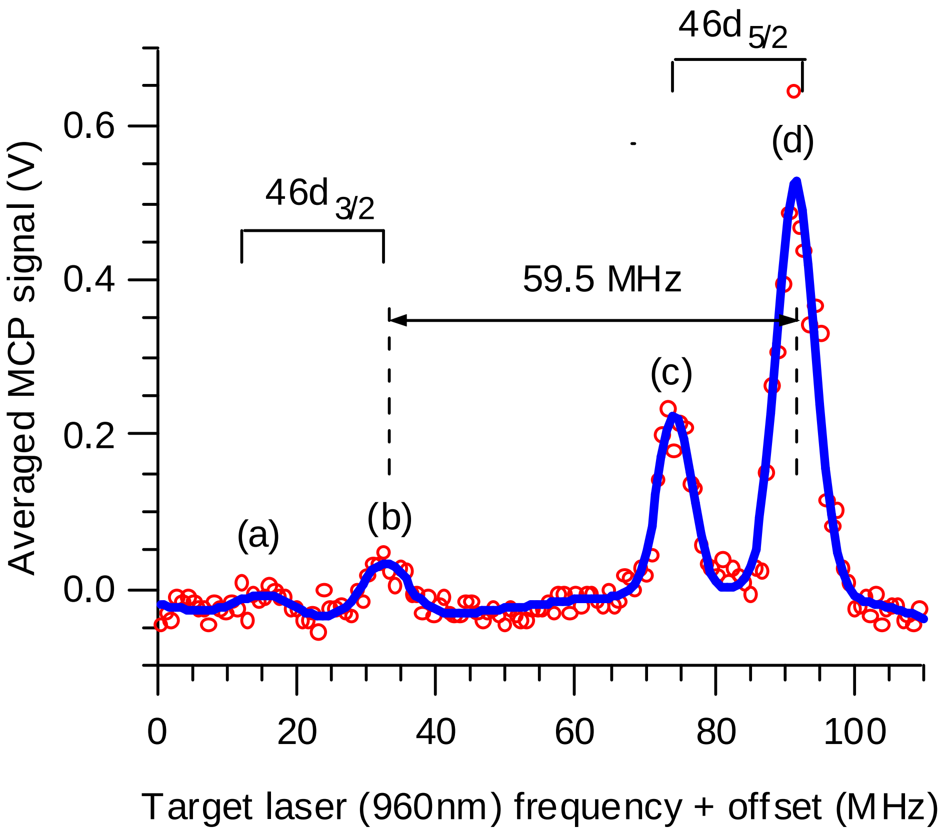
Rydberg atom excitation (^{85}Rb)





Autler –Townes splitting : B. K. Teo et al., Phys. Rev. A. 68, 053407 (2003).

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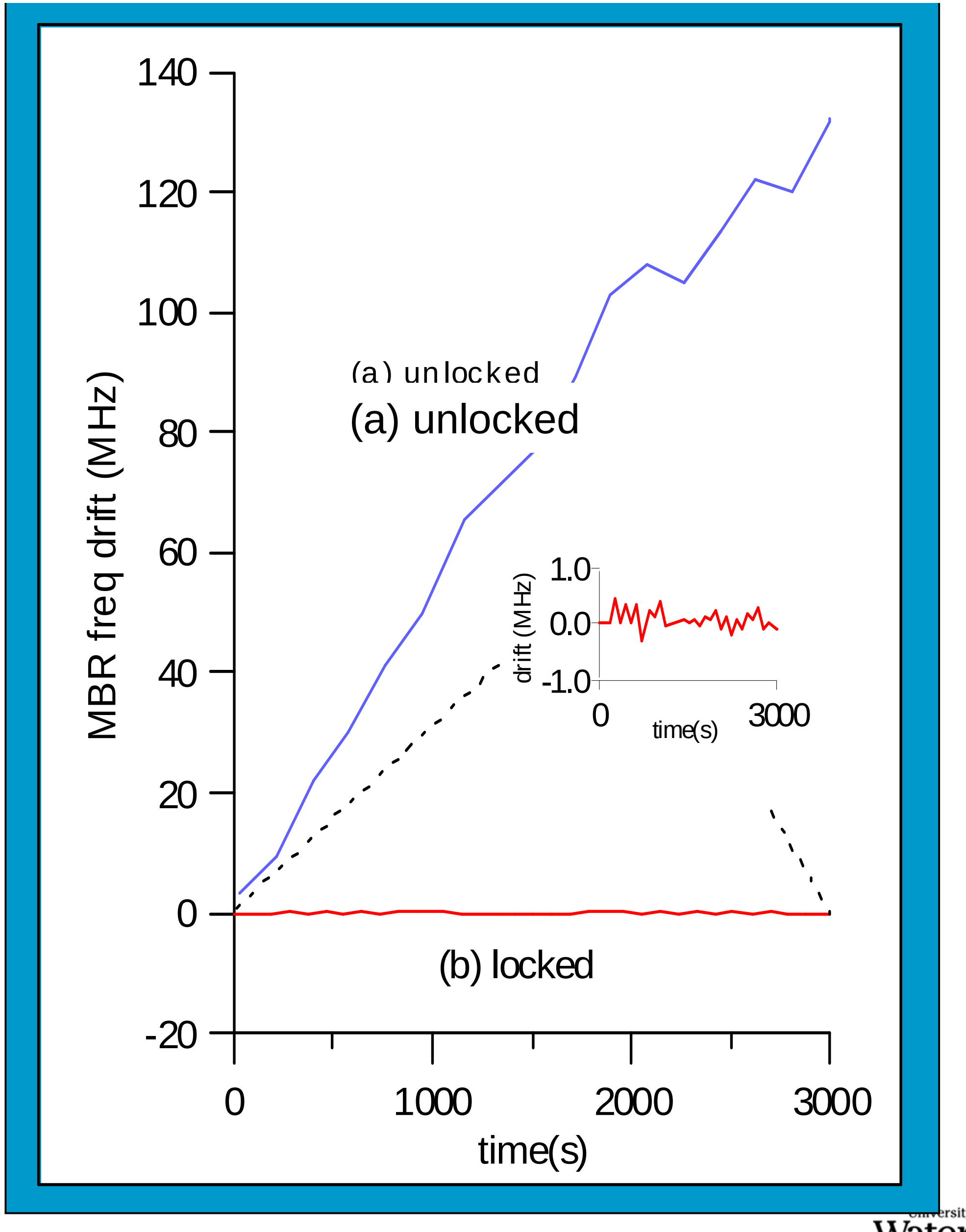
Frequency stability

- Frequency fluctuation of the target laser (Ti:sapphire, 960 nm)
  - (a) unlocked 140 MHz
  - (b) locked < 0.25 MHz

- Not limited to certain wavelengths
- Tuning frequency with RF precision.
- Frequency shifts without using AOMs or EOMs.



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Properties of Rydberg atoms

Property	n^* dependence
Binding energy	n^{*-2}
Energy between adjacent n states	n^{*-3}
Orbital radius	n^{*2}
Electric dipole moment	n^{*2}
Geometric cross section	n^{*4}
Polarizability	n^{*7}
Radiative lifetime (low-l states)	n^{*3}
Radiative lifetime (high-l states)	n^{*5}
Fine structure interval	n^{*-3}

$$E_{n,\ell} = \mathrm{IP} - \frac{R}{(n-\delta_\ell)^2}$$

$$n^* = n - \delta_\ell$$

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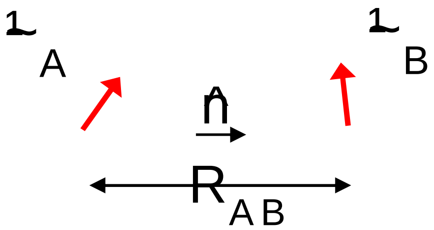
- P. Filipovicz *et al.*, Optica Acta, **32**, 1105 (1985)

Electric Dipole-Dipole Interactions between Rydberg Atoms

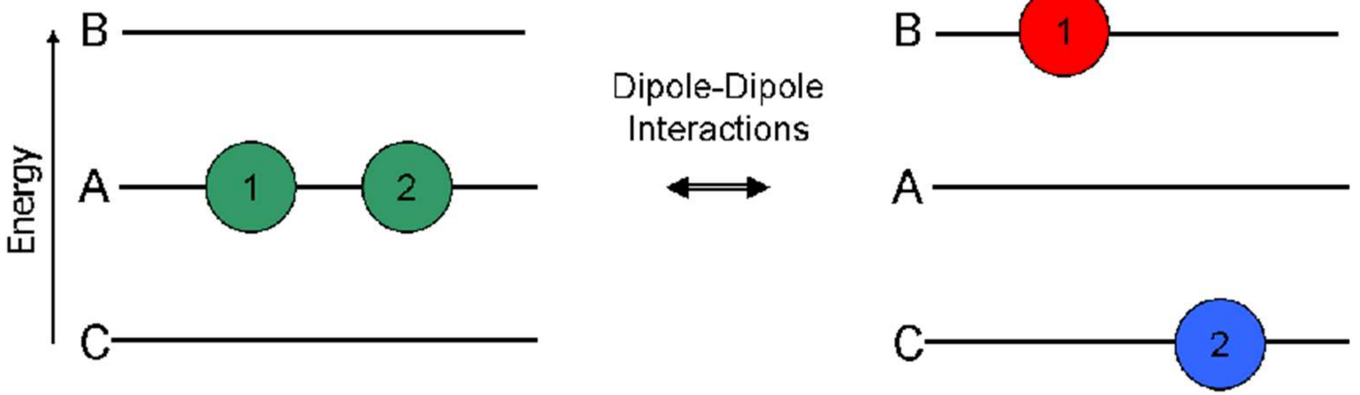


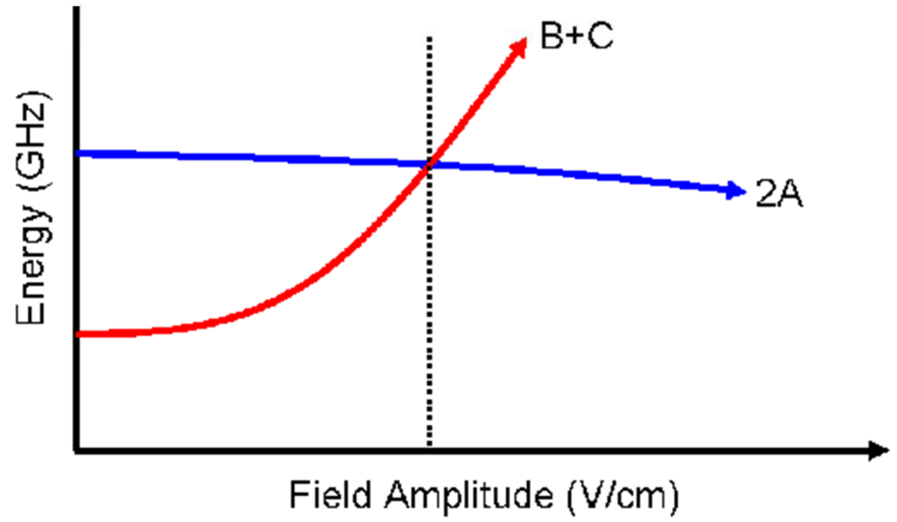
$$\hat{V}_{dd} = \frac{\mu_A \cdot \mu_B - 3(\mu_A \cdot \hat{n})(\mu_B \cdot \hat{n})}{R_{AB}^3}$$

- dipole-dipole interaction strong for Rydberg states -- even over long distances.
- atoms temporarily excited to Rydberg states strongly interact due to dipole-dipole interaction -- but don't interact when in ground state.

Resonant Energy Transfer (RET) through dipole-dipole interactions

A + A ! B + C





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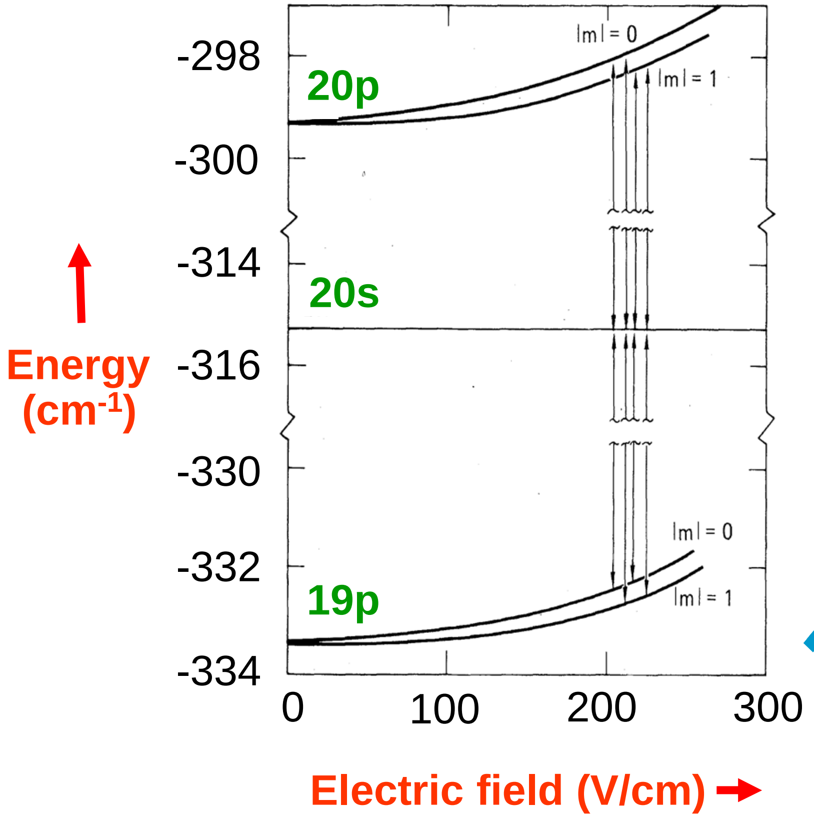
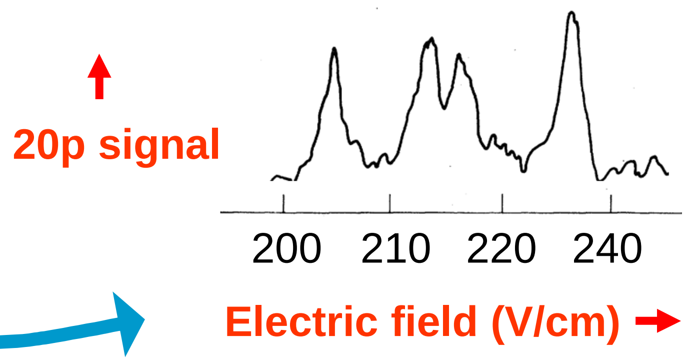
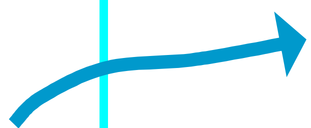
Resonance condition may be achieved using Stark effect:



After excitation of 20s states:





VOLUME 47, NUMBER 6 PHYSICAL REVIEW LETTERS 10 AUGUST 1981

Resonant Rydberg-Atom–Rydberg-Atom Collisions

K. A. Safinya,[a] J. F. Delpech,[b] F. Gounand,[c] W. Sandner,[d] and T. F. Gallagher
Molecular Physics Laboratory, SRI International, Menlo Park, California 94025
(Received 22 June 1981)

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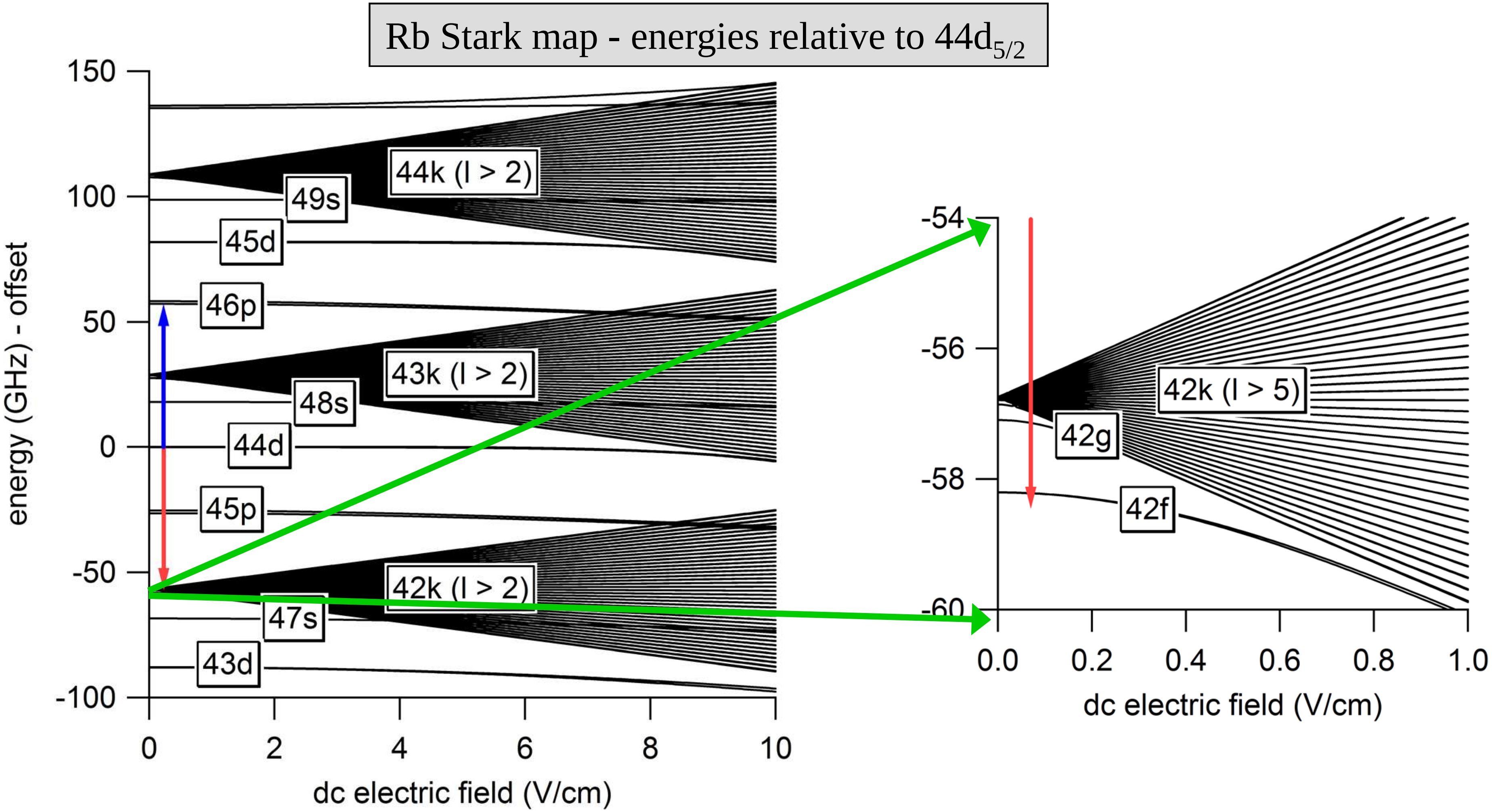
Achieving resonance condition in Rb



$$44d_{5/2} + 44d_{5/2} \rightarrow 42f_{5/2} + 46p_{3/2}$$

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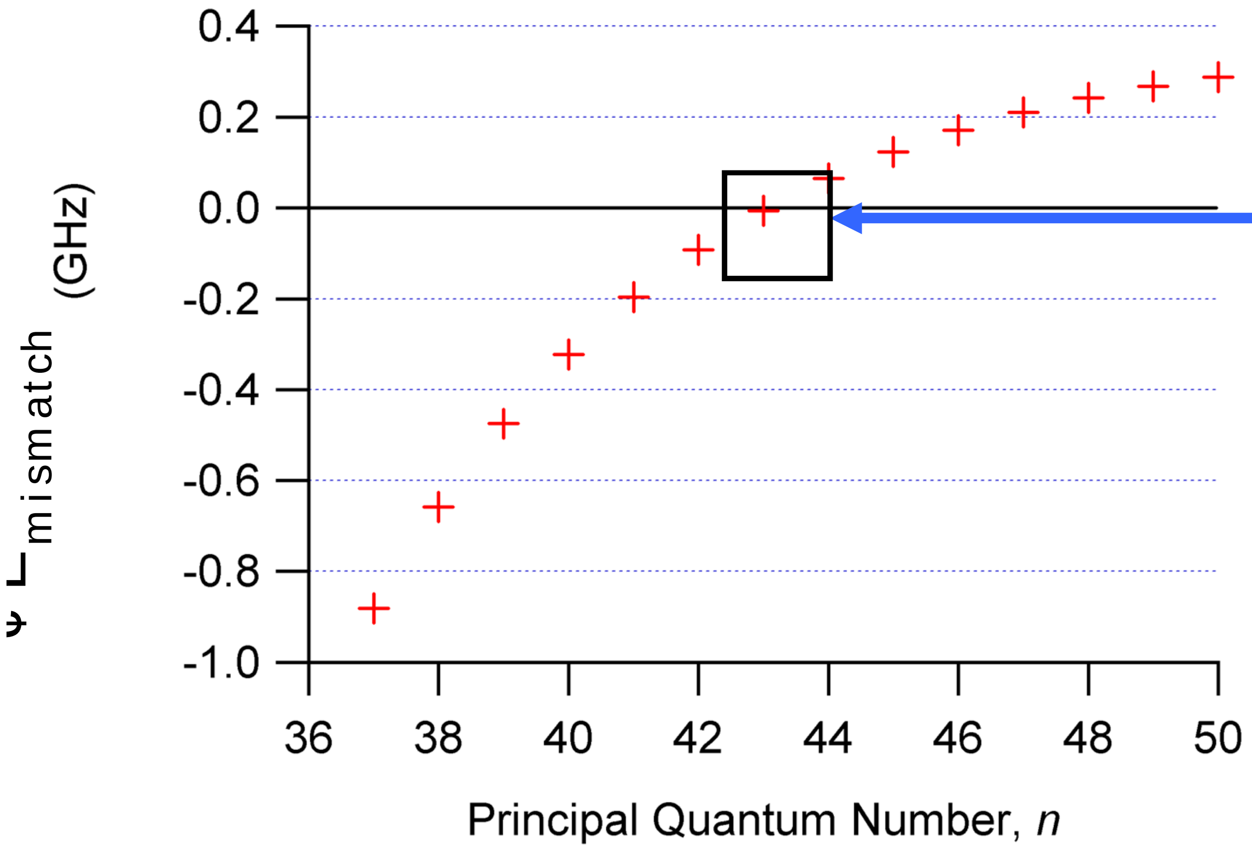
Mismatch as a function of *n*

Consider the process: $nd_{5/2} + nd_{5/2} \rightarrow (n+2)p_{3/2} + (n-2)f$



$\Delta E_{mismatch} = E_f - E_i$

n	Mismatch (MHz)
43	-6.05
44	65.0

Energy shifts of this magnitude can be easily obtained using the ac or dc Stark effect

Energies determined using quantum defects from:

J. N. Han *et al.*, PRA 74, 054502 (2006); W. H. Li *et al.*, PRA 67, 052502 (2003)

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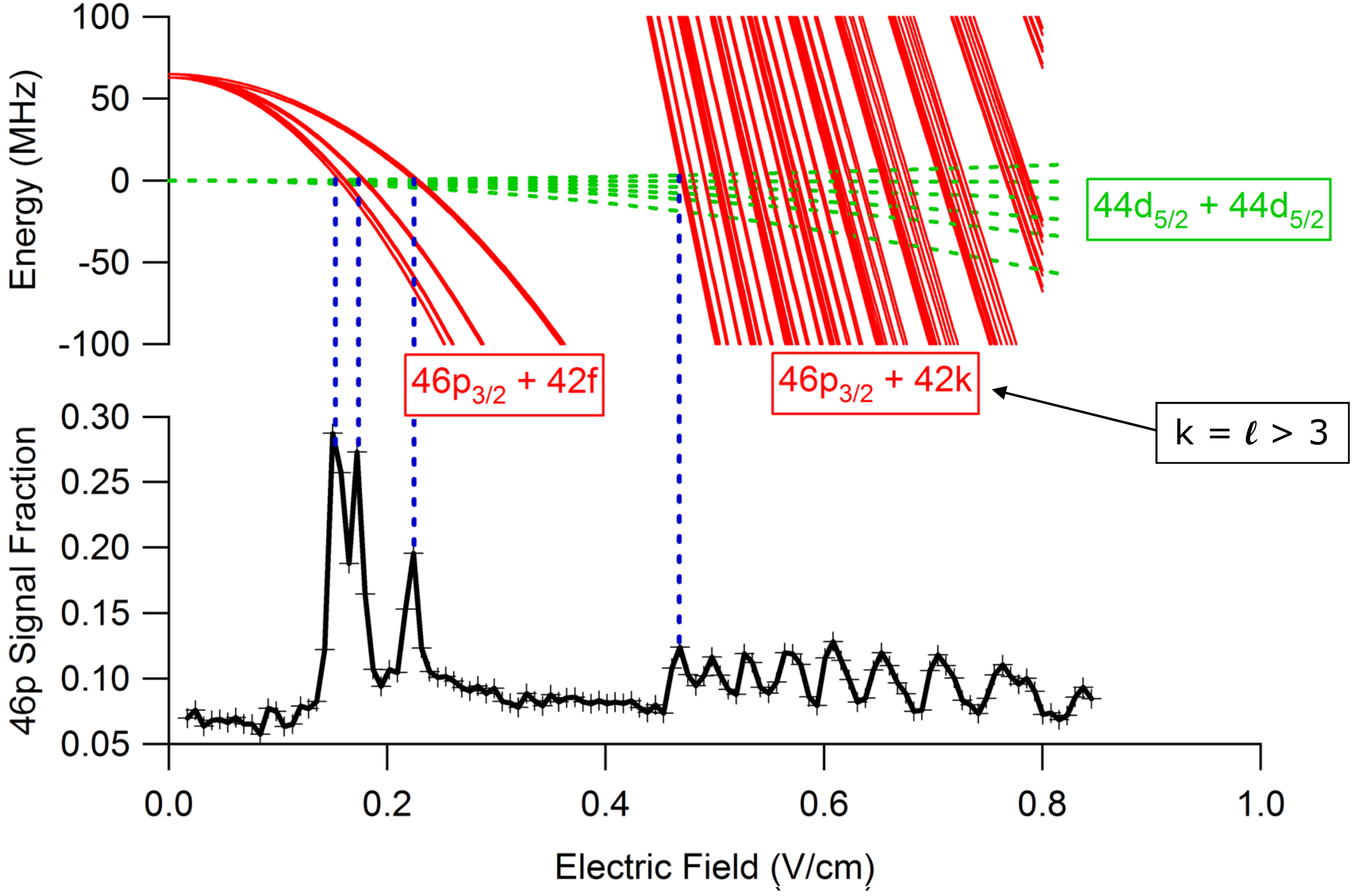
Observation of dc field induced RET at n = 44

$$44d_{5=2} + 44d_{5=2} \; ! \; 46p_{3=2} + 42f$$



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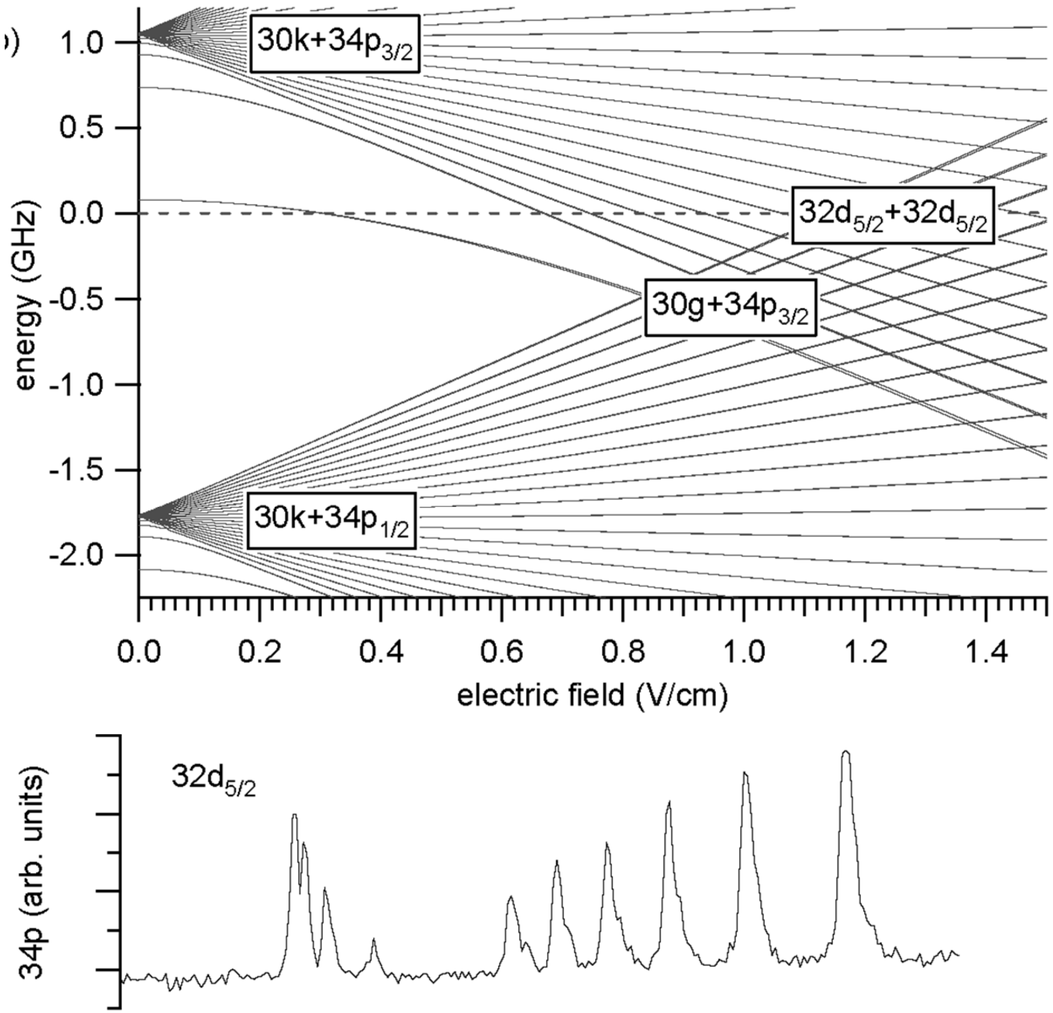
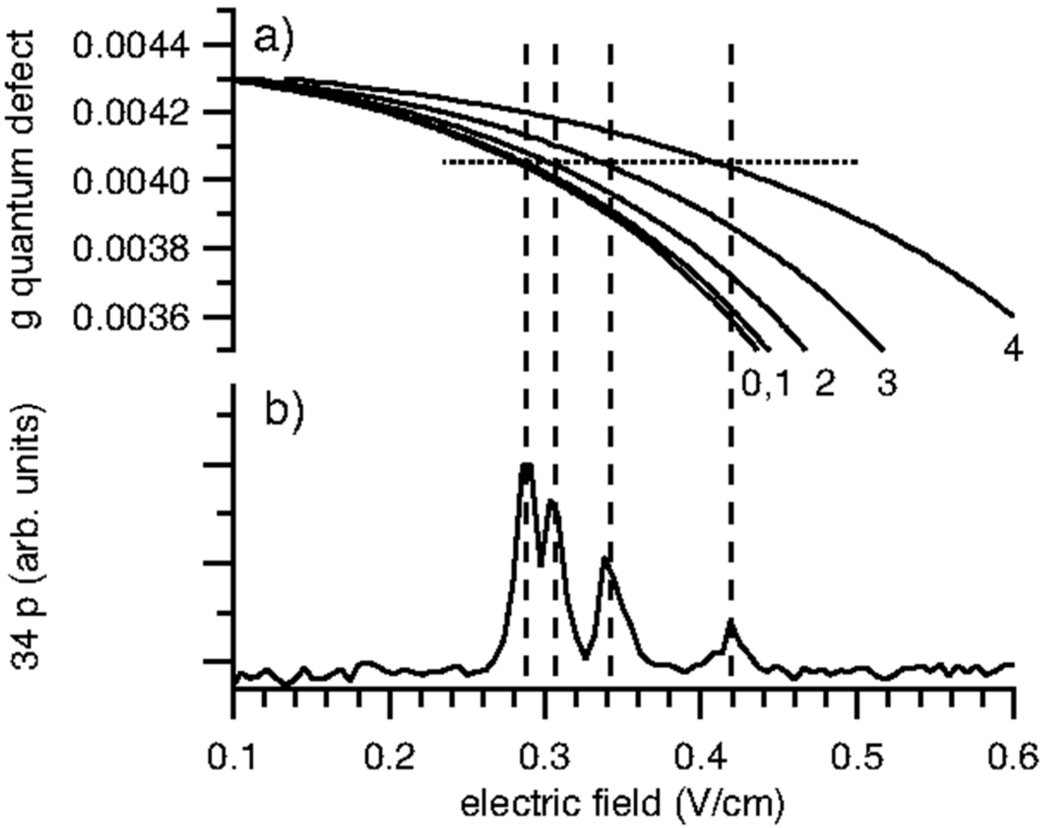
Observation of dc field induced RET at n = 32

$$32d_{5=2} + 32d_{5=2} \; ! \;\; 34p_{5=2} + 30g$$



Resonant electric fields can be used to determine energy levels



$32d_{5=2} + 32d_{5=2}\ !\ \ 34p_{5=2} + 30g$

known energies

unknown!!

$\pm_g(n = 30) = 0{:}00405(6)$

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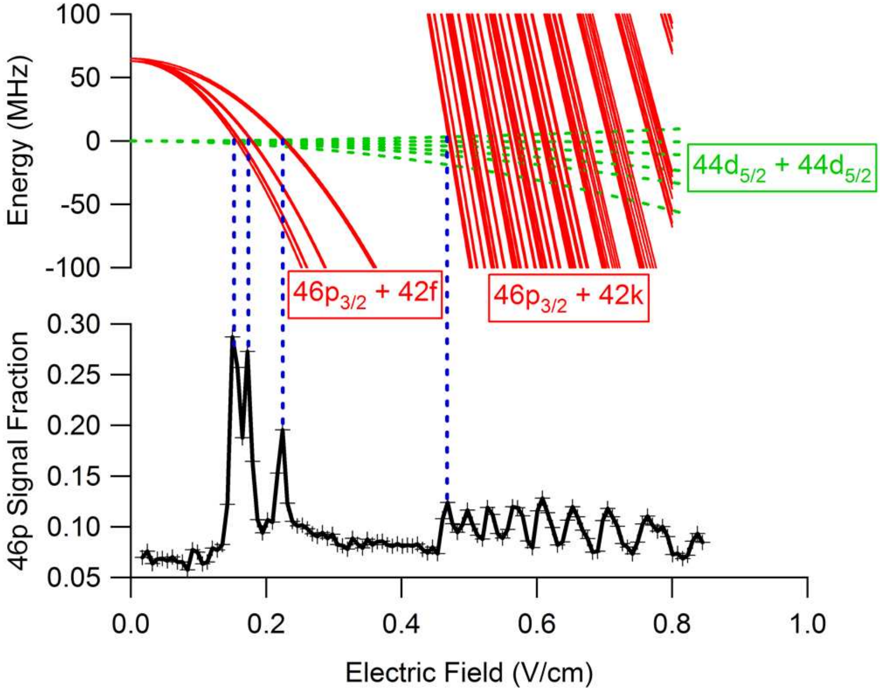
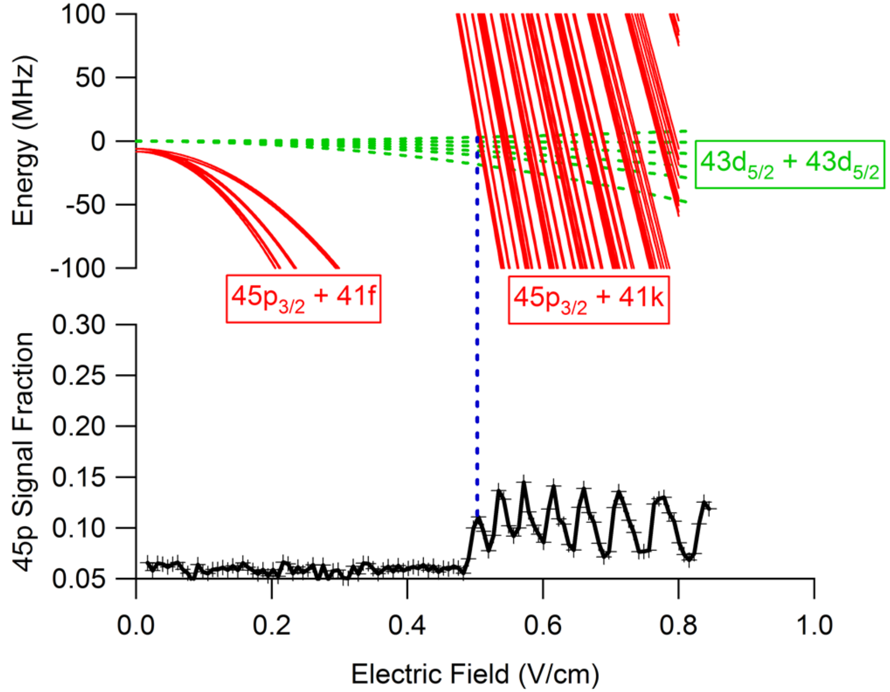
Lower *n* by 1 and process cannot be tuned into resonance

$$nd_{5/2} + nd_{5/2} \rightarrow (n+2)p_{3/2} + (n-2)f_{5/2;7/2}$$

n = 44



n = 43



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Can an ac field be used?

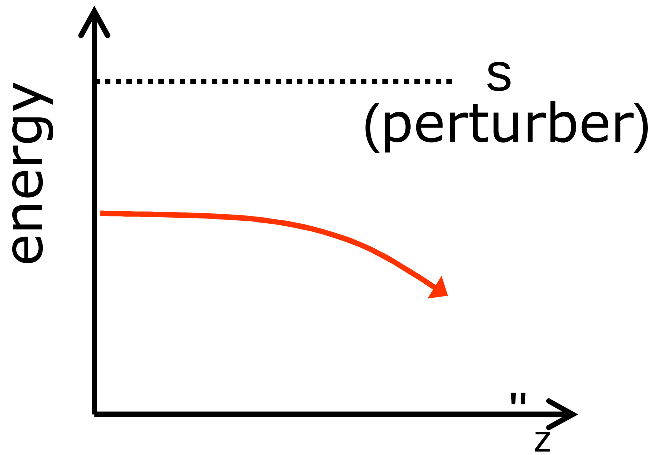
Perturbative dc Stark effect

$$\Delta E_n = \varepsilon_z^2 \sum_s \frac{|\langle n|\mu_z|s\rangle|^2}{E_{ns}}$$

field strength

transition dipole moment

$$E_{ns} = E_n - E_s$$

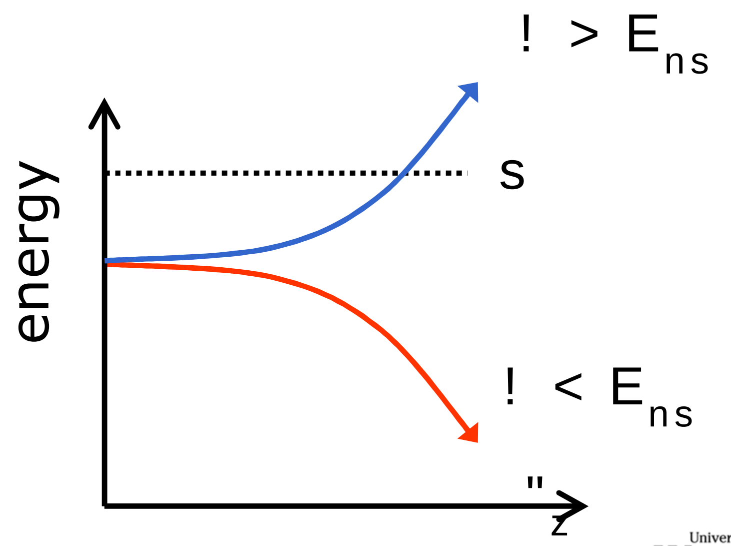


Perturbative ac Stark effect

$$\Delta E_n = \frac{1}{2}\varepsilon_z^2 \sum_s \frac{E_{ns}|\langle n|\mu_z|s\rangle|^2}{E_{ns}^2 - (\hbar\omega)^2}$$

field amplitude

frequency



ω gives flexibility in shift direction!

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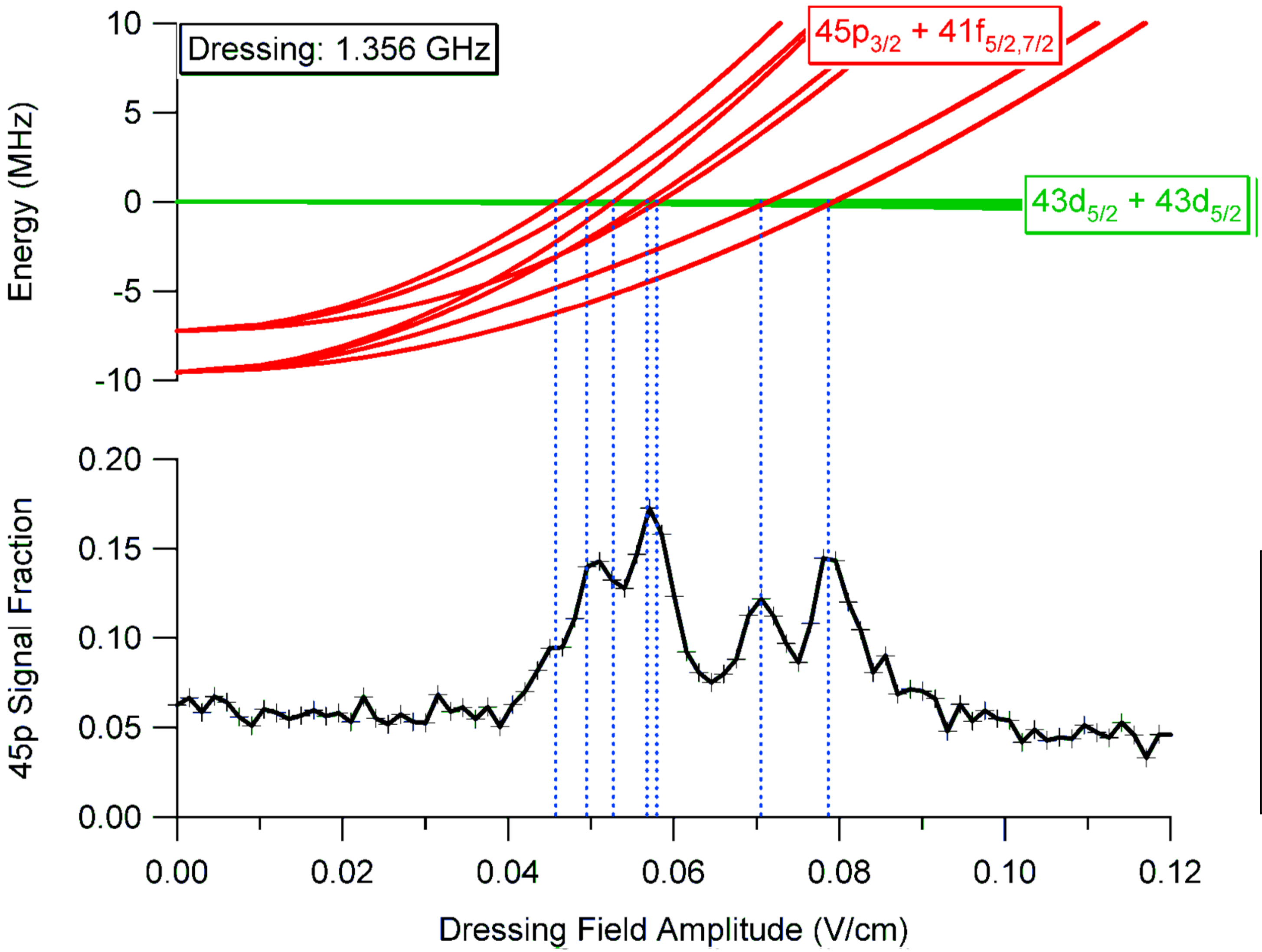
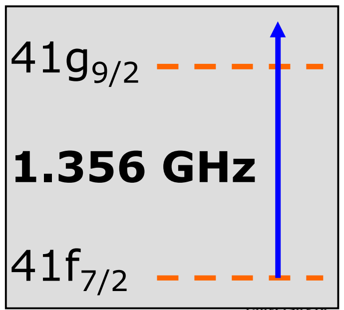
Observation of ac field induced RET at n = 43

$$43d_{5=2} + 43d_{5=2} \; ! \quad 45p_{3=2} + 41f_{5=2;7=2}$$

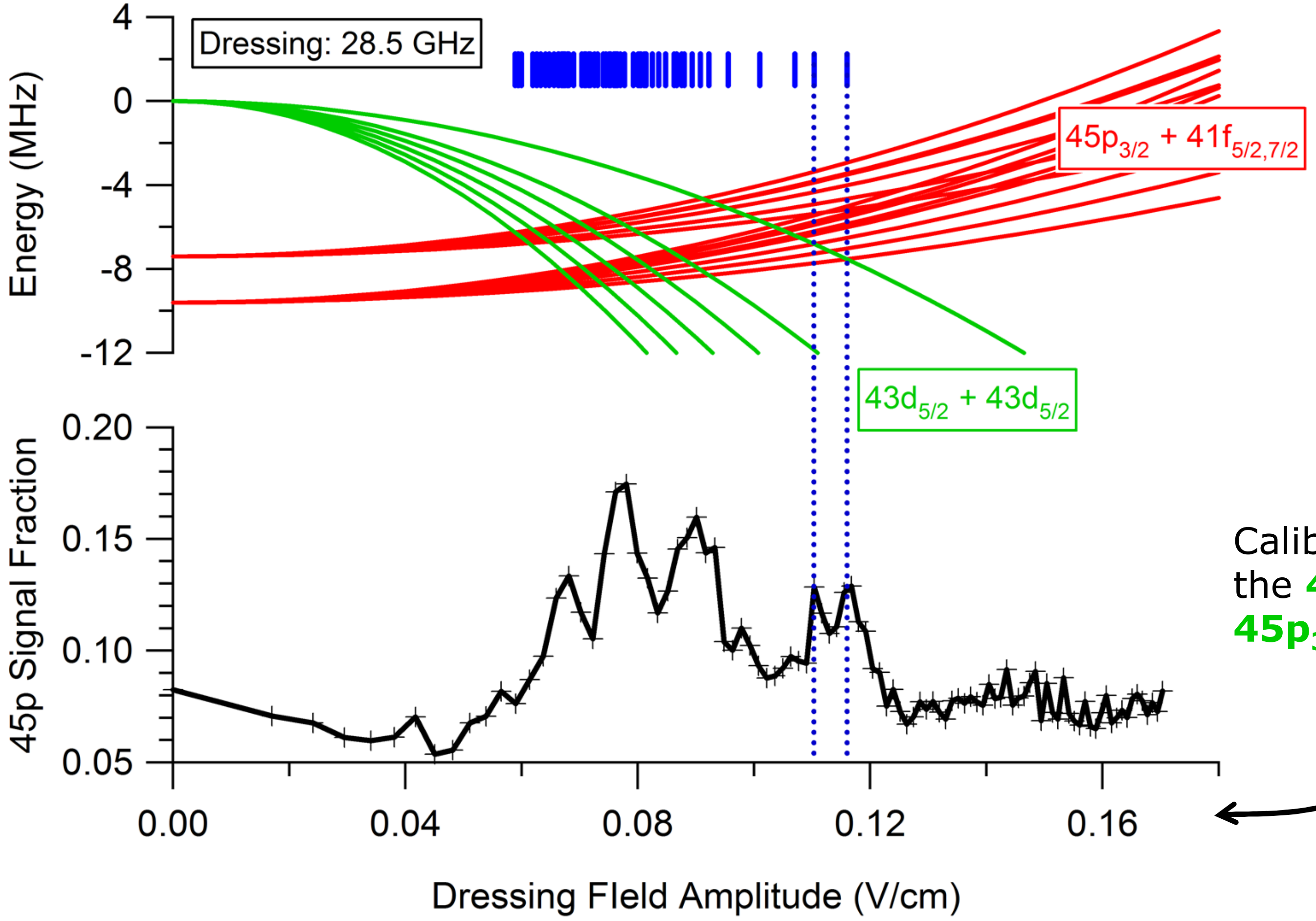




Observation of ac field induced RET at high frequency

$$43d_{5=2} + 43d_{5=2} \; ! \; 45p_{3=2} + 41f_{5=2;7=2}$$

Many different magnetic sublevels possible, but only **blue** lines are “allowed”



More complicated: All states involved shift significantly

Calibrated using the **$43d_{5/2}$** to **$45p_{3/2}$** transition

Summary

- Developed a general technique for laser frequency stabilization at arbitrary wavelengths
- Determined unknown energy levels using **dc** field induced RET
- Demonstrated **ac** field induced RET at two different frequencies in Rb
  - **ac** fields can be used in some situations where **dc** fields cannot
- Using a microwave, one could turn interactions on and off quickly (due to modulation capabilities of the source)

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Acknowledgment : J. D. D. Martin, J. Petrus, D. Vagale, M. Fedorov, A. Mogford, K. Afrousheh, J. Carter, Owen Cherry.

Funding: NSERC, CFI, OIT, AECL, University of Waterloo

Thank you!

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ac field induced RET vs. dc field induced RET

Consider this process:

$$a + b \rightarrow c + d$$

RET condition:

$$E_c + E_d - E_a - E_b = 0$$

zero field energy

$$E_n = E_{n_0} + \epsilon_z^2 k_n$$

Stark shift

$$(E_{C_0} + E_{D_0} - E_{A_0} - E_{B_0}) + \epsilon^2 (k_c + k_d - k_A - k_B) = 0$$

$$\Delta E_{mismatch} + \epsilon^2 k = 0$$

ac Stark shift

$$\Delta E_n = \frac{1}{2}\epsilon_z^2 \sum_s \frac{E_{ns} |\langle n|\mu_z|s\rangle|^2}{E_{ns}^2 - (\hbar\omega)^2}$$

dc Stark shift

$$\Delta E_n = \epsilon_z^2 \sum_s \frac{|\langle n|\mu_z|s\rangle|^2}{E_{ns}}$$

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Observation of Echo effect using cold Rydberg atoms in a magnetic field inhomogeneity

Objectives

- Study the interaction and dynamics of the transitionally cold Rydberg atoms, by controlling and minimizing the dephasing processes.

Motivations

- Identify reversible and irreversible dephasing processes in the study of electric dipole-dipole interactions between cold Rydberg atoms[(1)].
- Diagnose electric field inhomogeneity in Rydberg atoms' surface interactions due to patch fields.
- Maintain the internal coherence of a single trapped Rydberg atom[(2)].

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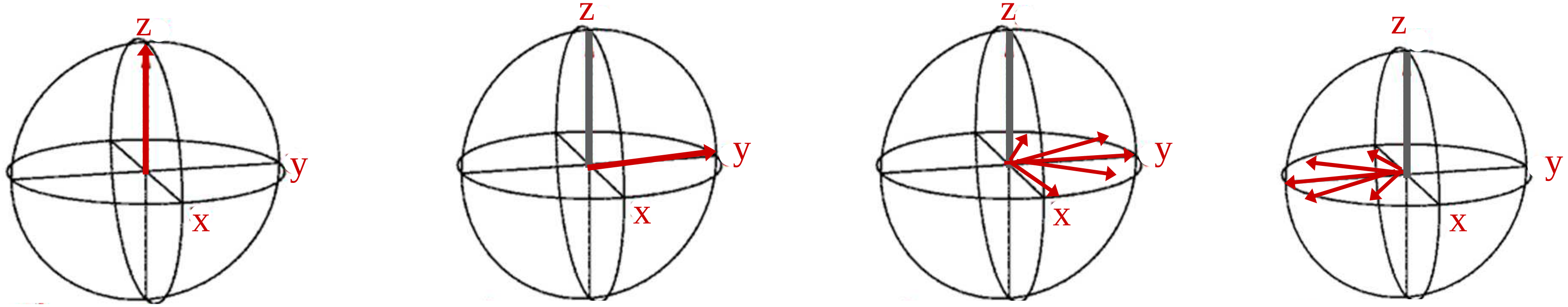
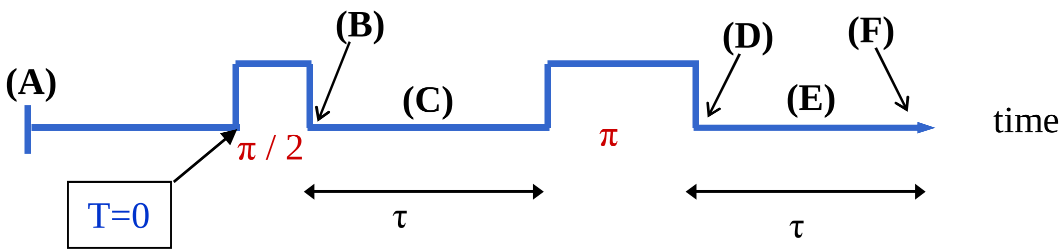
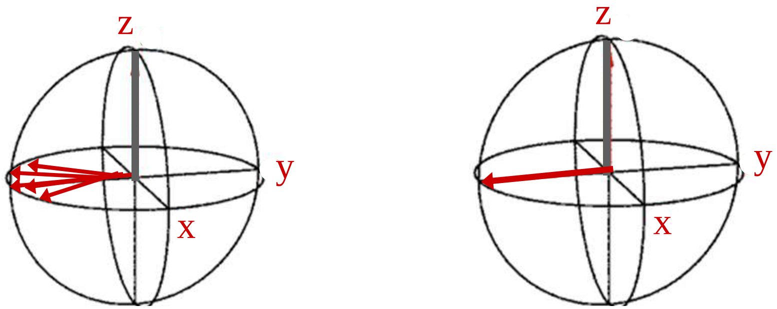
1) K. Afrousheh, et al, *Phys. Rev. Lett.*, **93**, pp. 233001 (2004). 2) P. Hyafil, et al, *Phys. Rev. Lett.*, **93**, 103001 (2004)

Geometrical representation of the Spin echo:



Initial state $(0,0,M_z)$





(E) (F)

Magnetization → $\mathbf{M} = \{M_x, M_y, M_z\}$

$$\frac{d\mathbf{M}}{dt} = \gamma(\mathbf{M}\times\mathbf{H})$$

Total magnetic field

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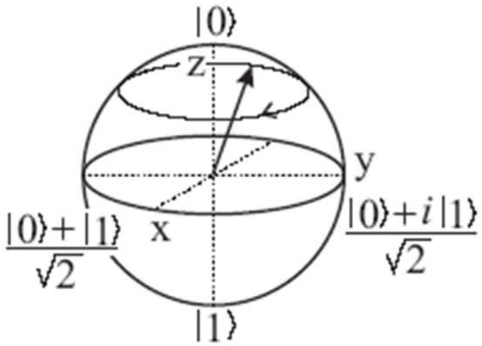
Cold Rydberg atoms' echo effect in correspondence to Spin echo technique

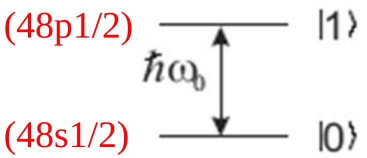
- Spin Echo technique in NMR



  - Magnetization

$$\mathbf{M}=\{M_x, M_y, M_z\}$$
$$\frac{d\mathbf{M}}{dt}=\gamma(\mathbf{M}\times\mathbf{H})$$

- Rydberg atoms Echo effect



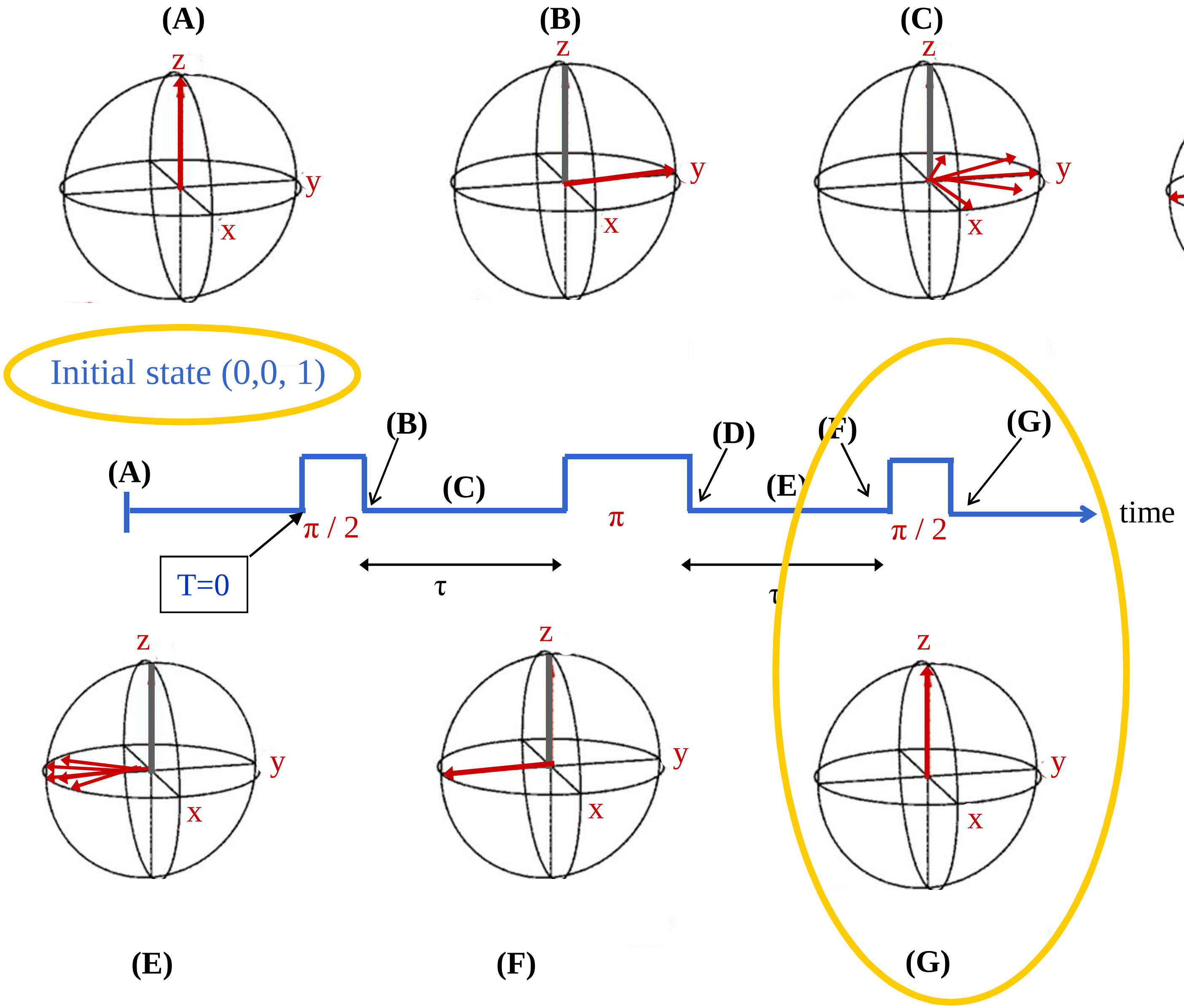
$$\psi(t)=a(t)|0\rangle+b(t)|1\rangle$$

$$\mathbf{r}=\{r_1, r_2, r_3\}$$
$$\frac{d\mathbf{r}}{dt}=\mathbf{r}\times\omega$$

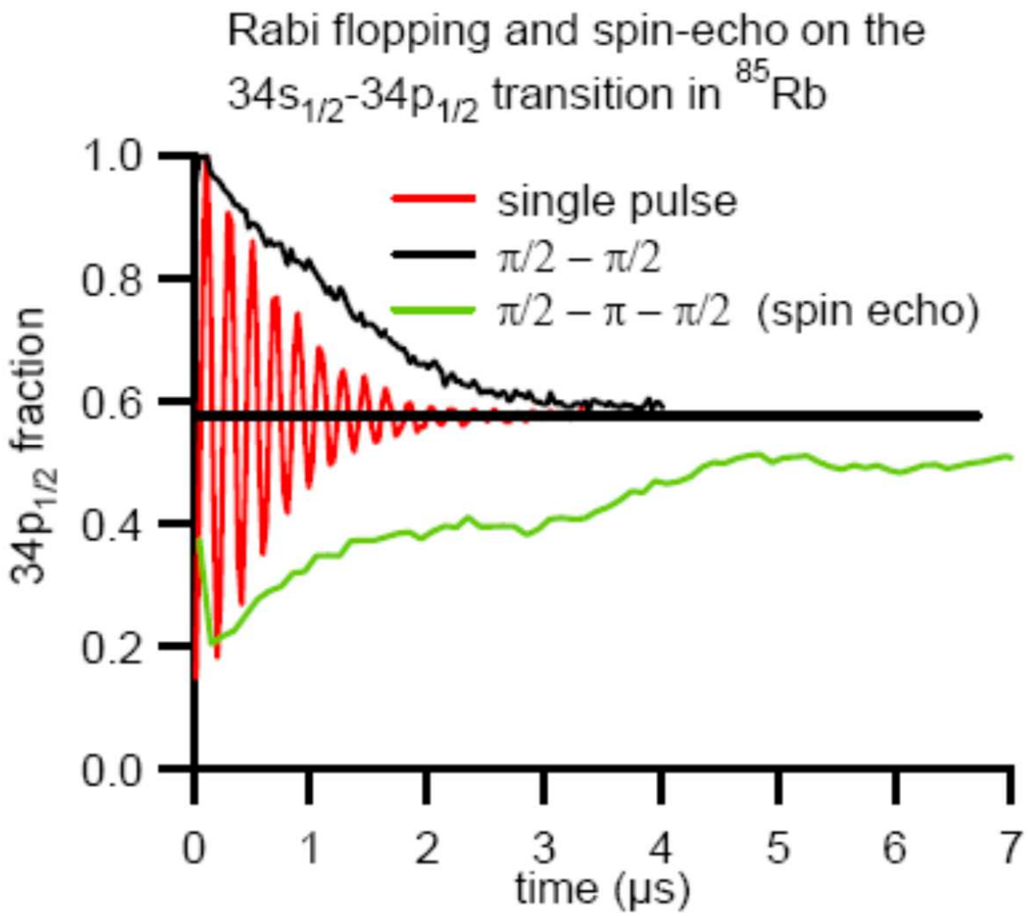
With perturbation V

$$r_1 \equiv ab^* + ba^* \qquad \omega_1=(V_{ab}+V_{ba})/\hbar$$
$$r_2 \equiv i(ab^* - ba^*) \qquad \omega_2=i(V_{ab}-V_{ba})/\hbar$$
$$r_3 \equiv aa^* - bb^* \qquad \omega_3=\omega_0$$

Geometrical representation of the Spin echo:

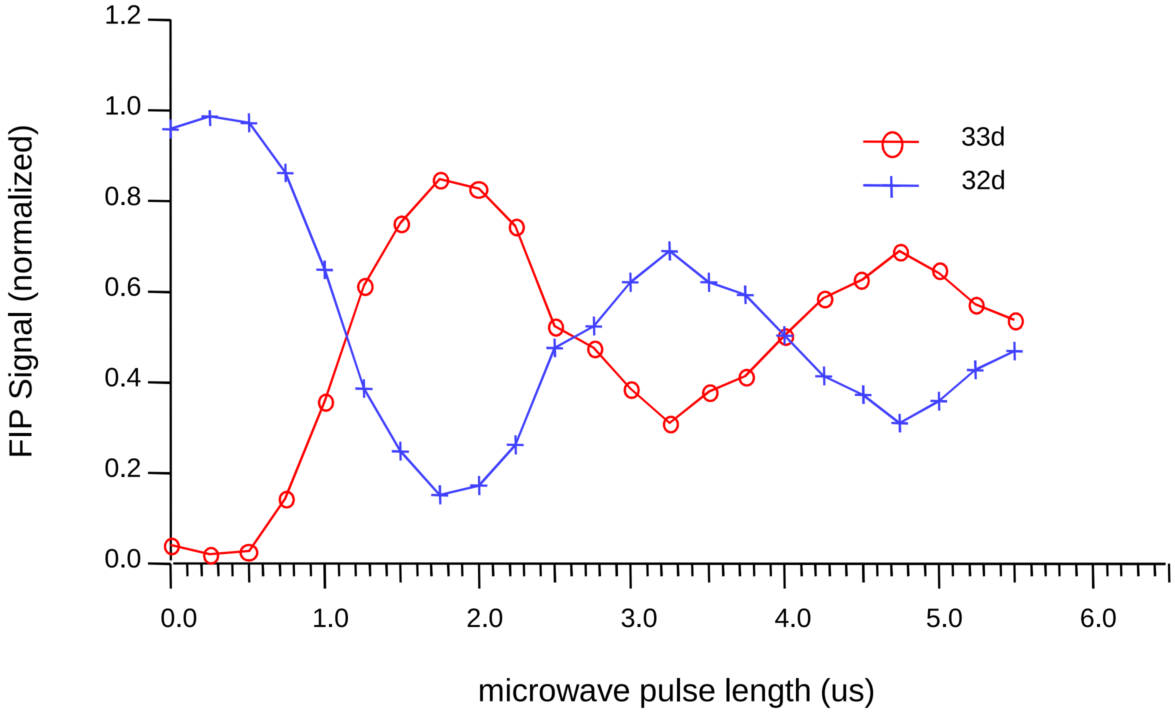


Rabi Oscillation on $34s_{5/2}$-$34p_{5/2}$ one-Photon Microwave Transition

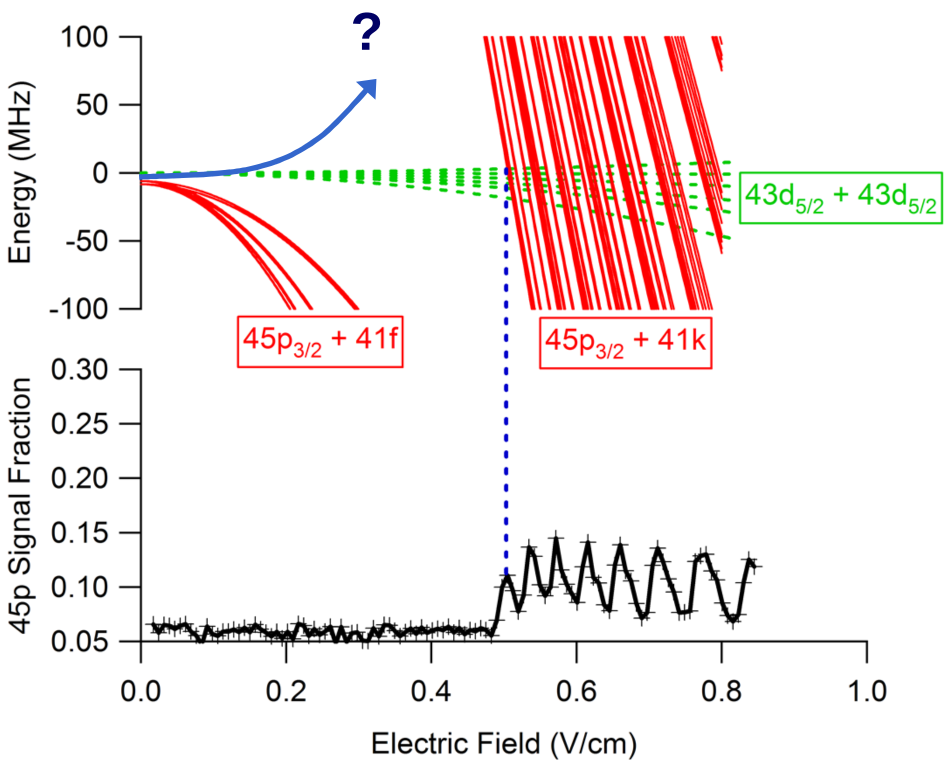


Rabi Oscillation on $32d_{5/2}$-$33d_{5/2}$ Two-Photon Microwave Transition

- Two-photon transitions between Rydberg states with the same g_J factors show negligible broadening in a MOT.
  - E.g., $nd_{5/2} \longrightarrow (n+1)d_{5/2}$



Can an ac field be used?



With: $\Delta E_n = -\kappa_n(\omega) F_z^2$

	κ in GHz/(V/cm)^2		
State	dc	ac, −150 MHz	ac, +150 MHz
$41f_{7/2}$	-2.0867	-4.8949	3.6986
$43d_{5/2}$	0.0061	0.0030	0.0030
$45p_{3/2}$	-0.0828	-0.0415	-0.0415
$42f_{7/2}$	-2.4708	-5.3801	4.0829
$44d_{5/2}$	0.0074	0.0037	0.0037
$46p_{3/2}$	-0.0973	-0.0488	-0.0488

ac frequencies relative to:

$41f_{7/2} - 41g_{9/2}$ (top three)

$42f_{7/2} - 42g_{9/2}$ (bottom three)

Conclusion: Should be able to make: $43d_{5/2} + 43d_{5/2} \to 45p_{3/2} + 41f_{5/2,7/2}$

resonant with a dressing field at **1.356 GHz**!

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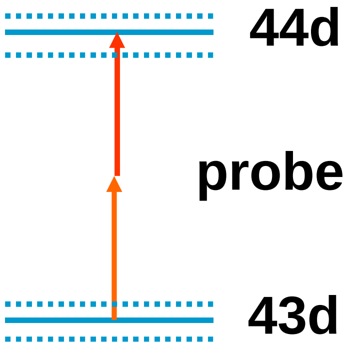
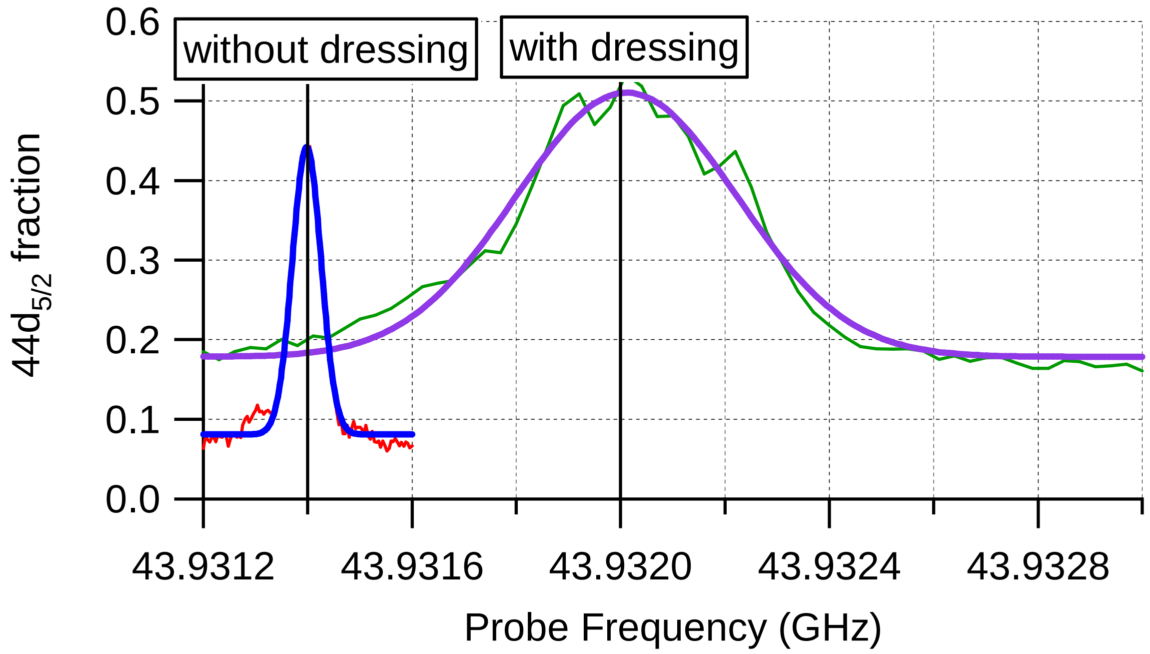
Field strength at this frequency is calibrated using 2-photon probe shifts





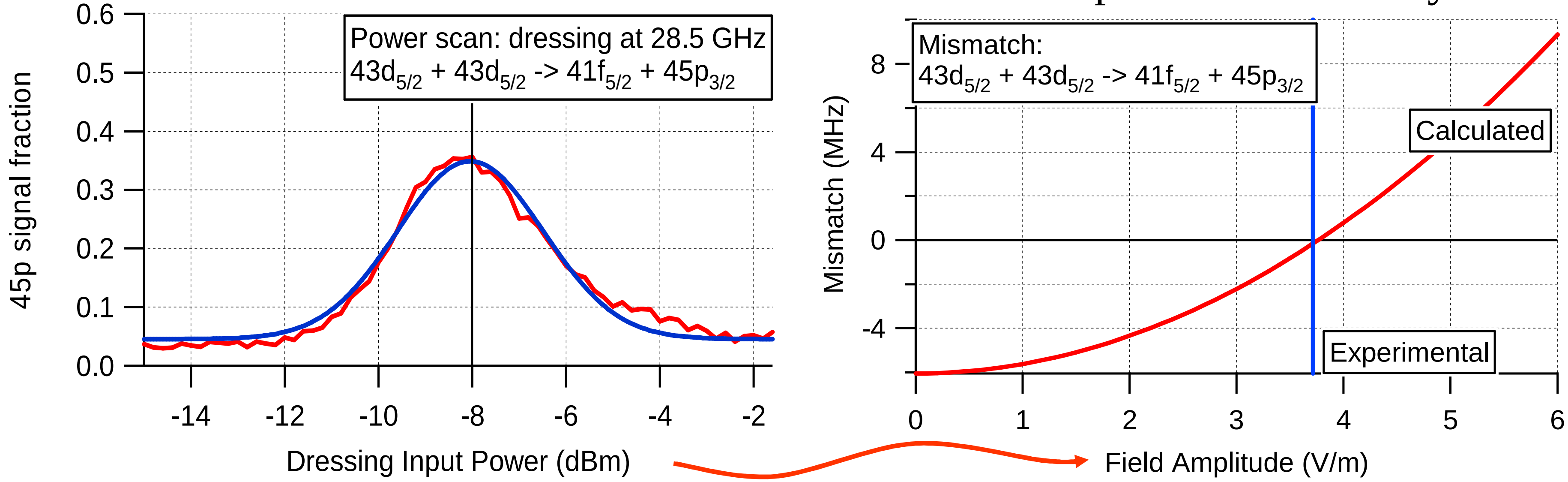
Assume Stark shifts given by:

$$\Delta E_n = \sum_s \frac{E_{ns}|<n|\mu_z|s>|^2}{E_{ns}^2 - \omega^2} < E_z^2 >$$

to determine field strengths.

AC dressing field power calibration

Comparison with theory



Using 2-photon probe shifts calibration

- Calculated and experimental field amplitude agree well at ~ 3.7V/m!

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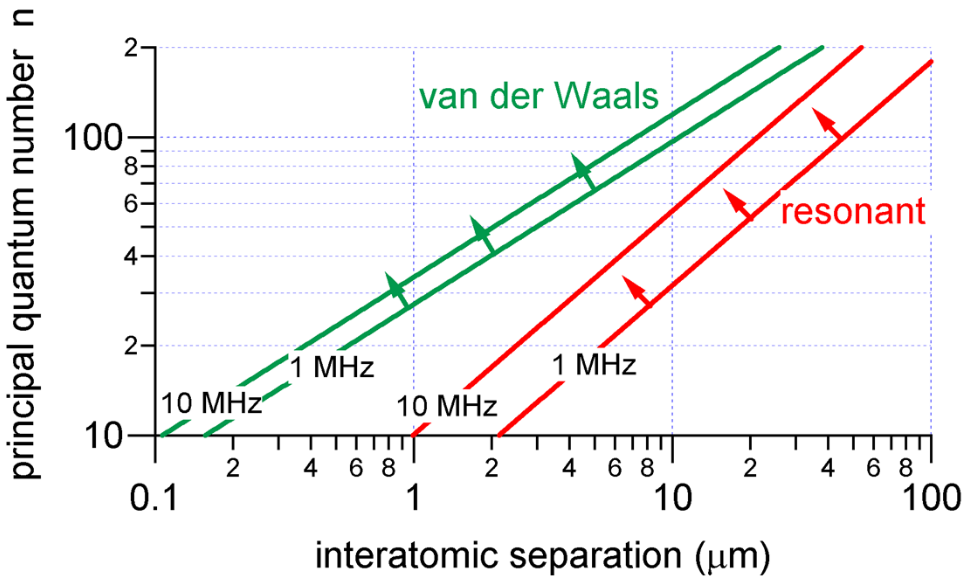
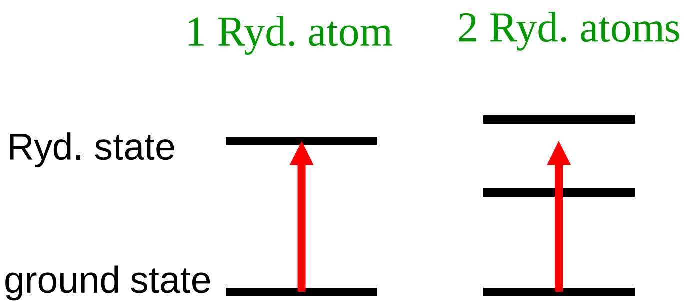
vdW and resonant dipole-dipole interaction strengths

- plot thresholds for observation of shifts of 1 and 10 MHz



- between 1 and 10 mm, threshold *n* differs by factor of 3.
- advantages of lower *n* (resonant interaction):
  - easier to make transitions from ground state (n^{-3}).
  - less sensitivity to external perturbations (n^{7}).
- disadvantages of van der Waals (higher *n*):
  - $1/R^3$ is longer range -- multi-body effects more important.

dipole blockade

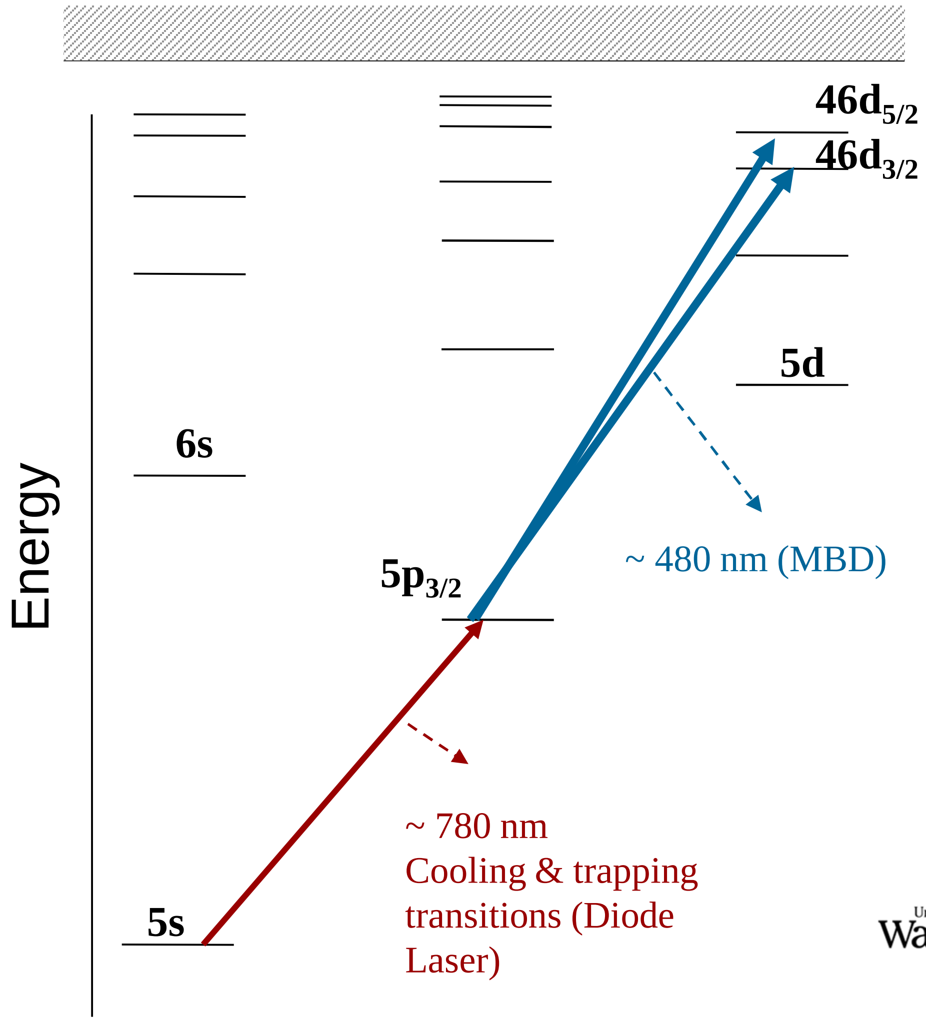


Dipole-dipole interaction ‘blocks’ excitation of 2 or more Rydberg atoms

Verify the stability of the target laser

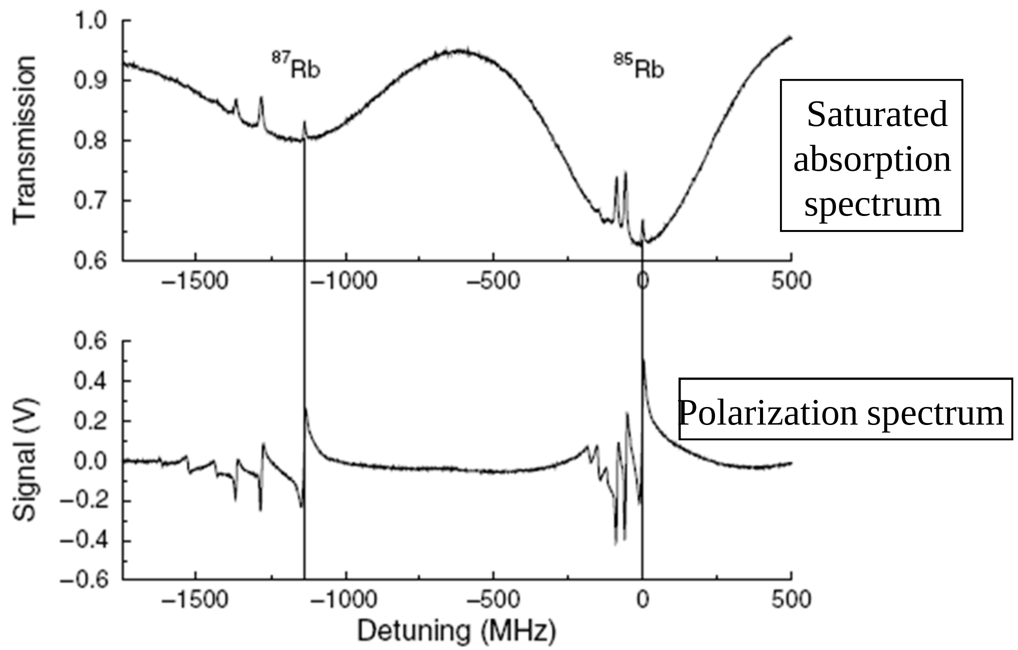
Rydberg atom excitation (^{85}Rb)

- The tuning accuracy and the drift behavior of the frequency locked target laser is characterized using Rydberg atom excitation in a ^{85}Rb magneto-optical trap (MOT)

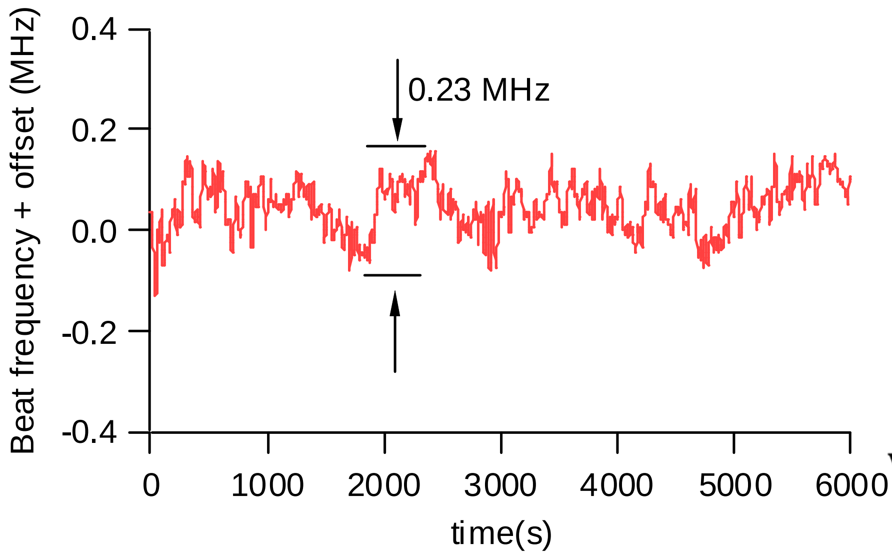


Target laser stability depends on the stability of reference laser

- Polarization Spectroscopy locking [1]



- Reference laser stability is characterized by another laser which is locked using sauturated absorption locking by dither/third harmonic lock-in detection [2]



[1] C.P. Pearman et al., J. Phys. B., **35**, 5141 (2002)

[2] Jun Ye, Steve Swartz, Peter Jungner,* and John L. Hall , Opt. Lett. **21**, 1280 (1996).

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Summary and Future work

- A general technique for laser frequency stabilization at an arbitrary wavelength with frequency stability on the order of 1MHz/hr.
- Involves equipment and techniques commonly used in laser cooling and trapping laboratories.
- Does not require special modulators and drivers.
- The frequency of the target laser can be tuned with RF precision.

……….

- Evacuate the cavity to minimize environmental effects.
- Improve the stability of the reference laser.

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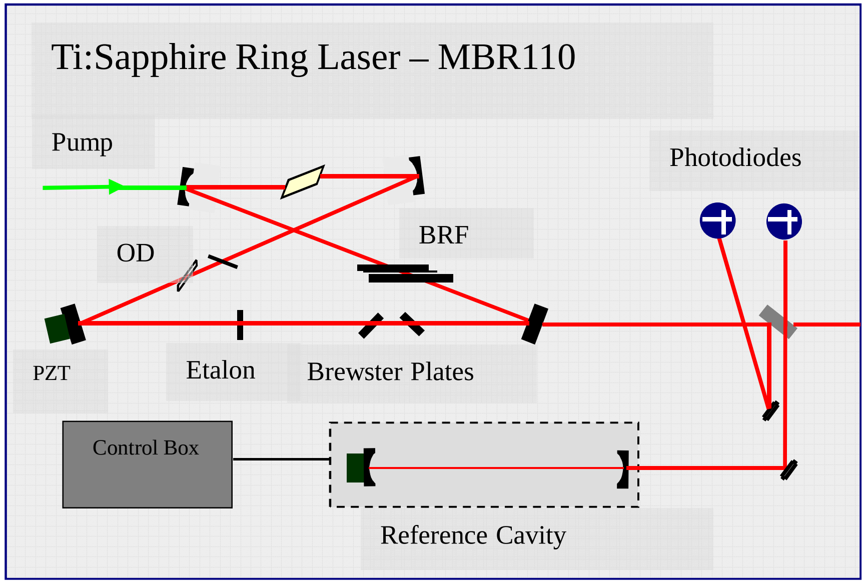
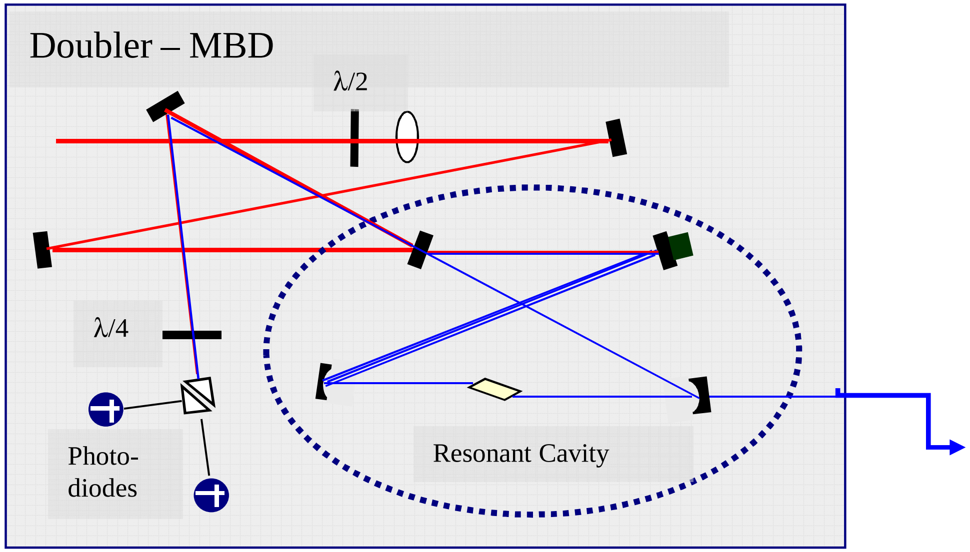
Rydberg atom excitation laser, target laser

- 960nm commercial ring Ti:sapphire laser.



- Frequency doubler, external ring resonator



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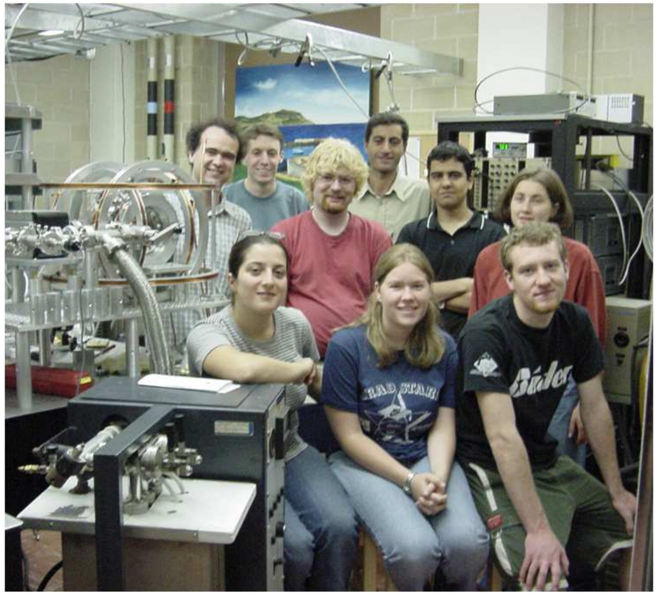

Bideo