# Atom interferometer analog of the double slit experiment

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Naval Air Systems Command

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Discussions with M. Larsen
(Northrop Grumman)

$$$$$$$$$$
$ PMA264$
$ ONR $
$ Sec. 219 $
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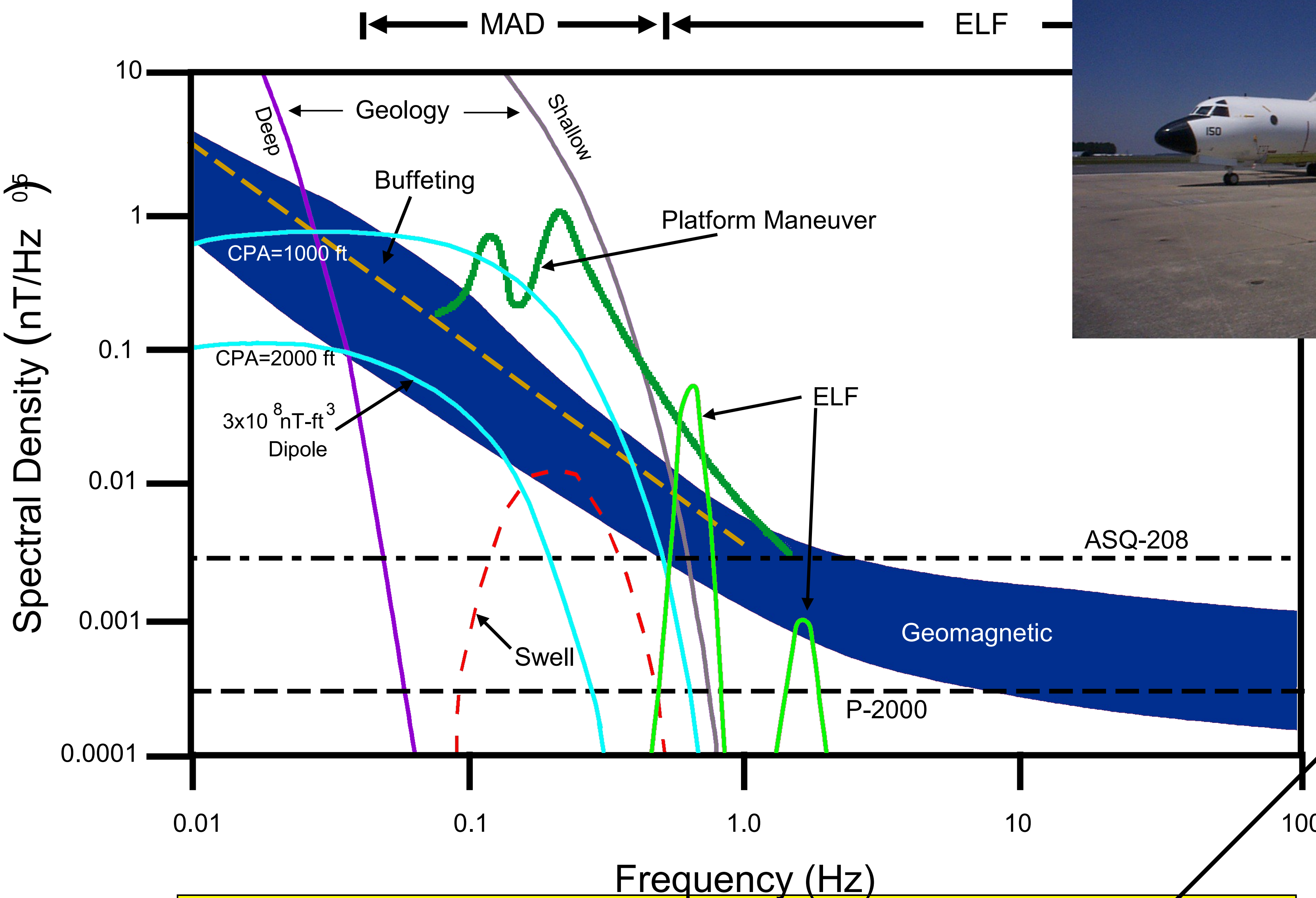
# Outline

- Motivation-Gradiometers for Navy applications
- Atom interferometers (for magnetic field measurements)
- Making the atom beam-splitter: Raman transitions in real atoms in arbitrary magnetic fields
- Interferometer Experiments ….

# Outline-Interferometer Experiments

- Single Pulse
  - Time Domain
  - Frequency Domain
- Double Pulse
  - Time Domain
  - Frequency Domain
- Triple Pulse
  - Time Domain
  - Frequency Domain
- Outlook
- Conclusions

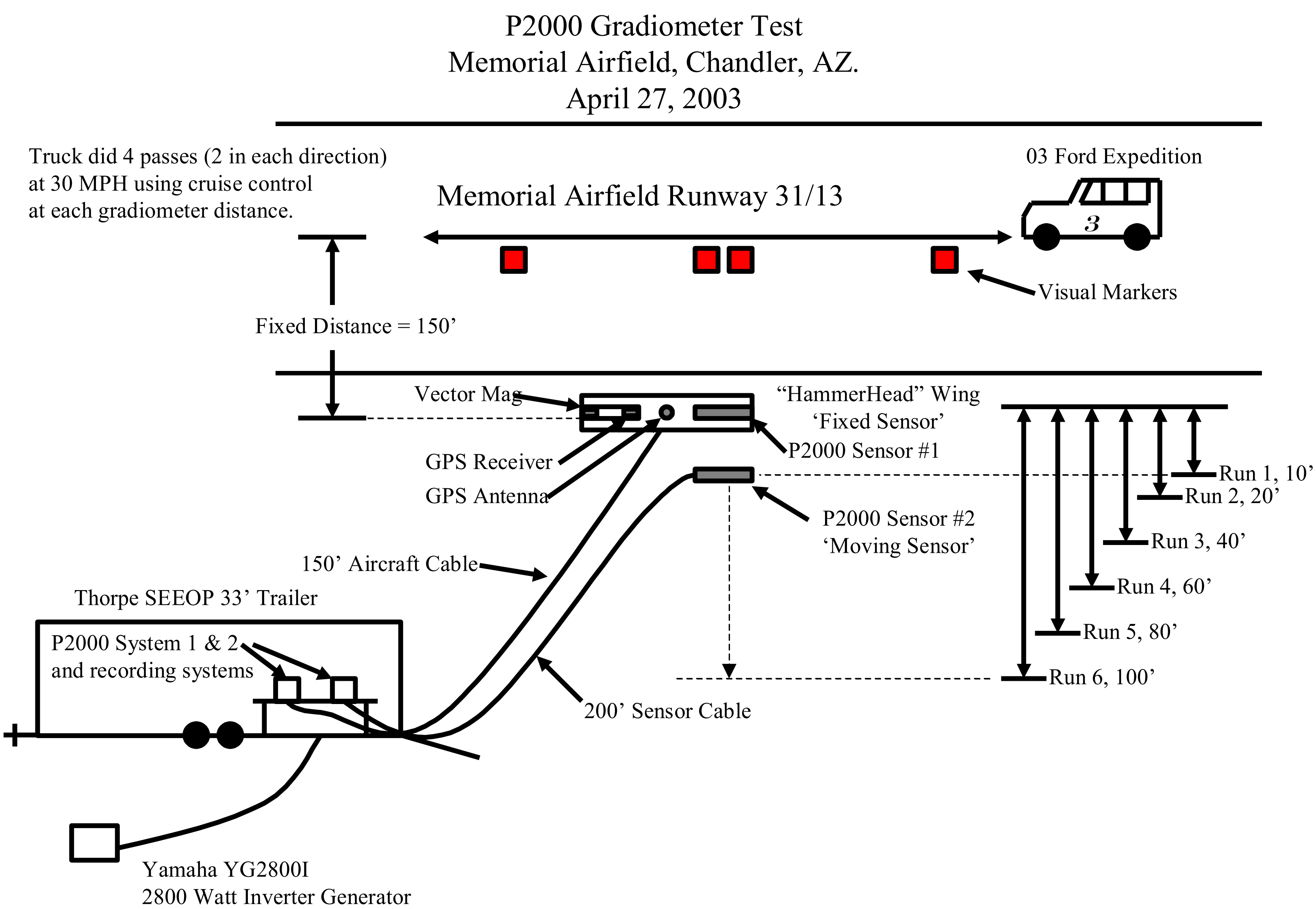
# Airborne Magnetic Noises




NIST
Welch
Budker
Romalis

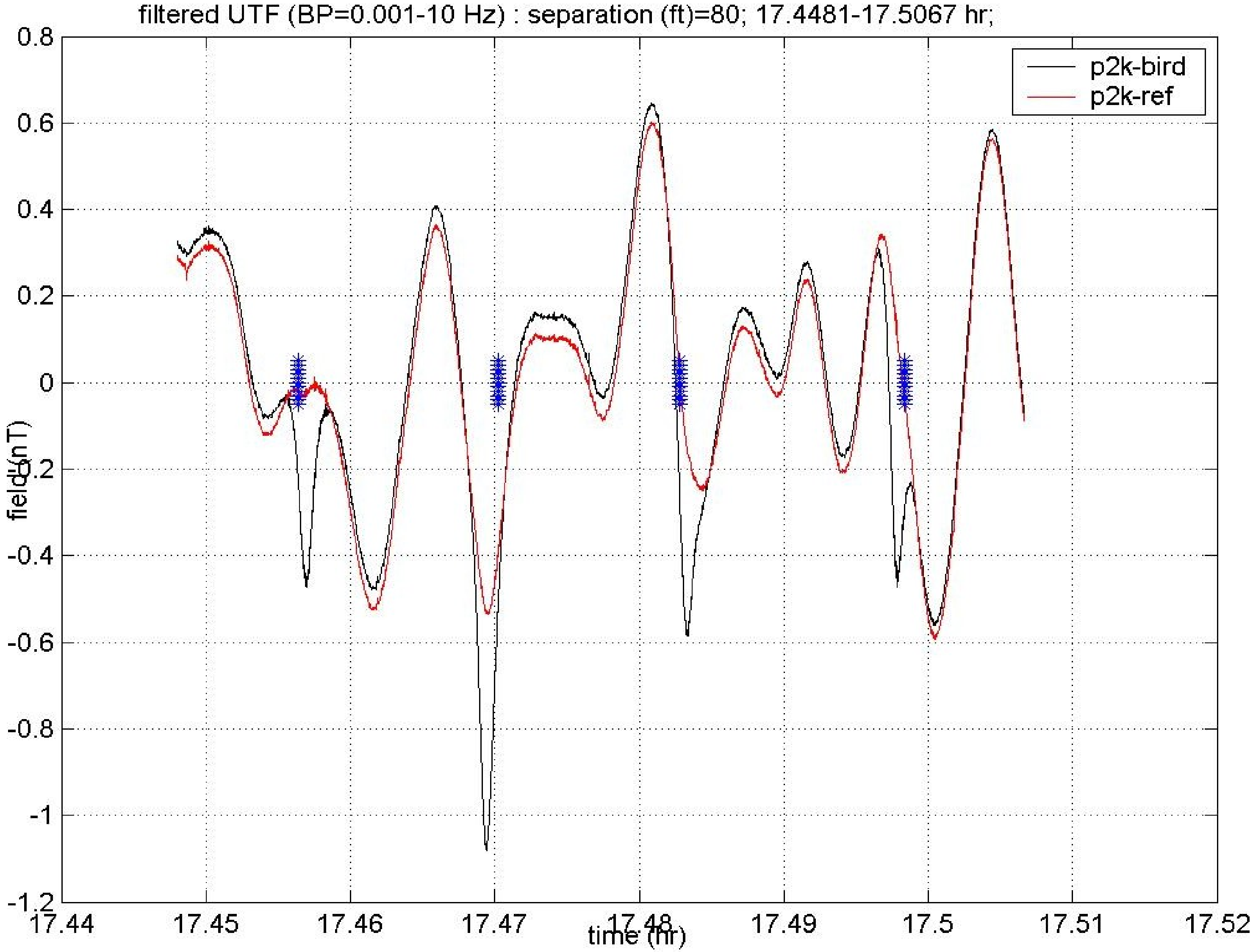
~ $fT/Hz^{1/2}$

# Gradiometer (Reference sensor)

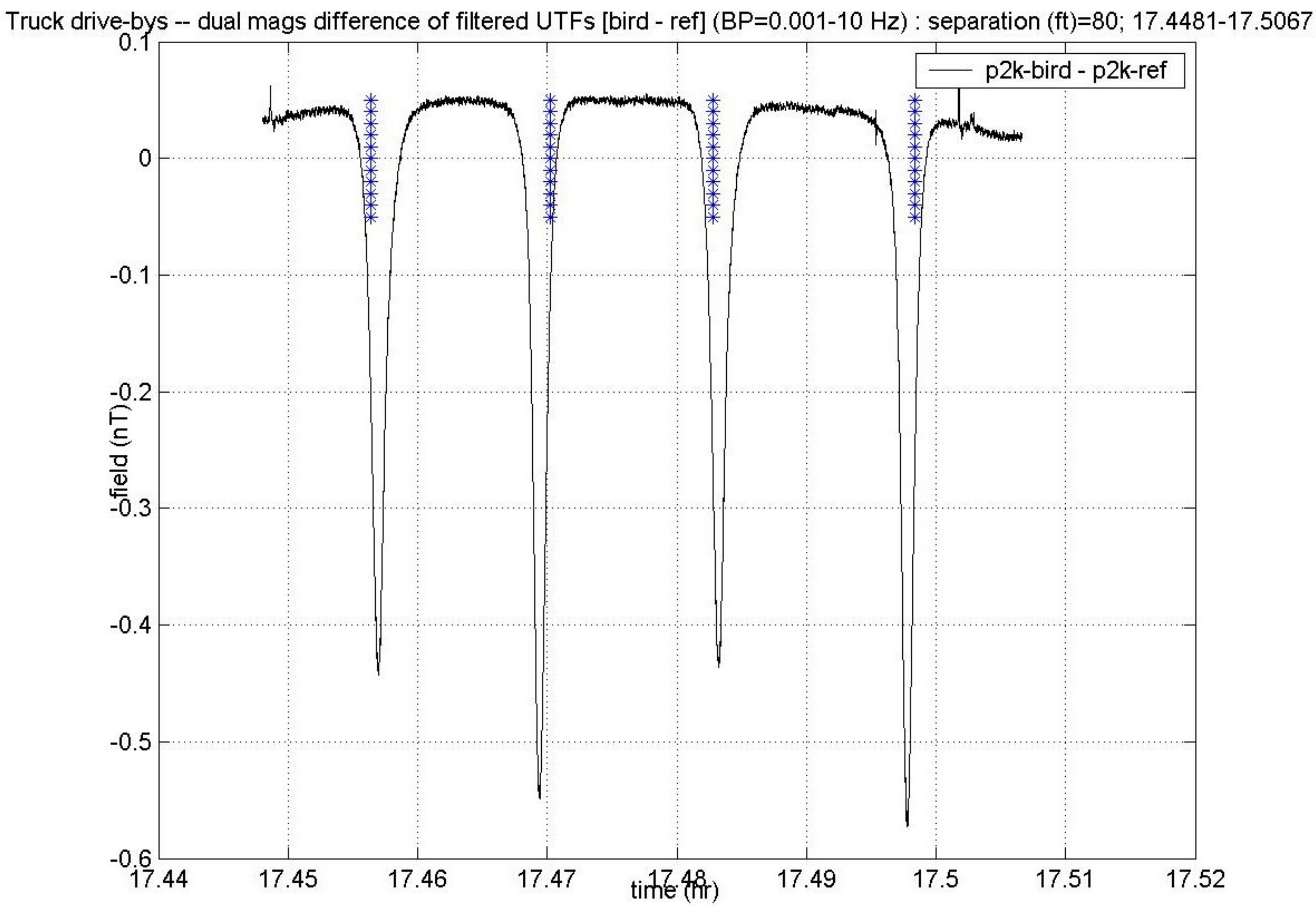


# Gradiometer (Reference sensor)

Fluctuations are all geomagnetic noise!

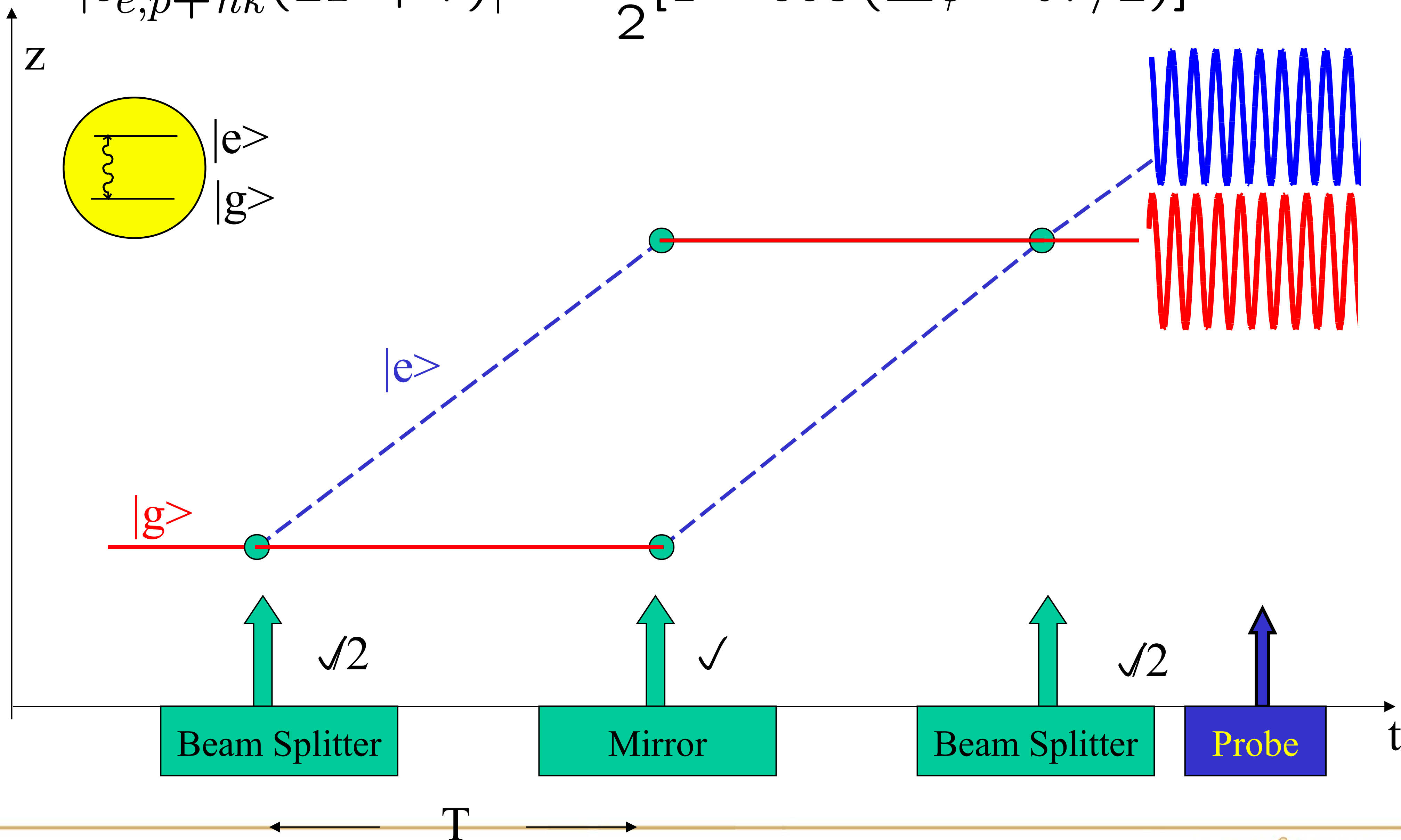


# Gradiometer (Reference sensor)



# Technical Overview of AI sensors

$$|c_{e,p+\hbar k}(2T+\tau)|^2 = \frac{1}{2}[1-\cos(\Delta\phi - \delta\tau/2)]$$

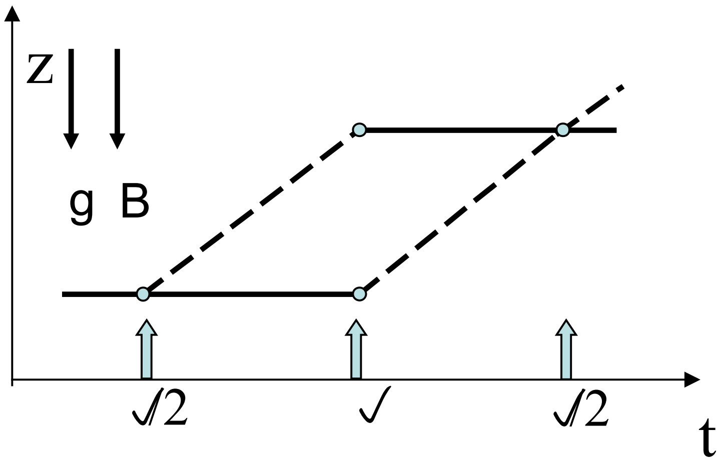


# We have shown…

**A proposal for a gradient magnetometer atom interferometer**

J.P. Davis and F.A. Narducci*

*Journal of Modern Optics*
Vol. 55, Nos. 19–20, 10–20 November 2008, 3173–3185



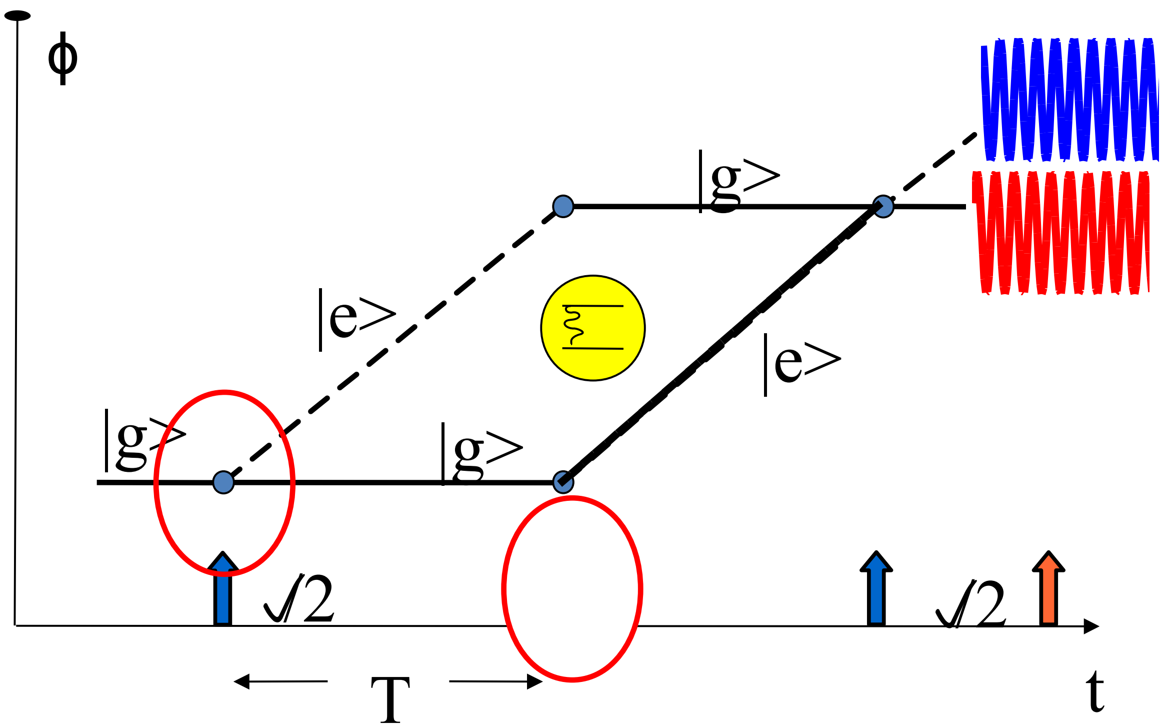

- For uniform B field

$$\Delta\phi = 0$$

An inherent gradiometer

- For gradient B-field

$$\Delta\phi = -k_{eff}\left(g + \frac{\mu}{m}\frac{dB}{dz}\right)T^2$$



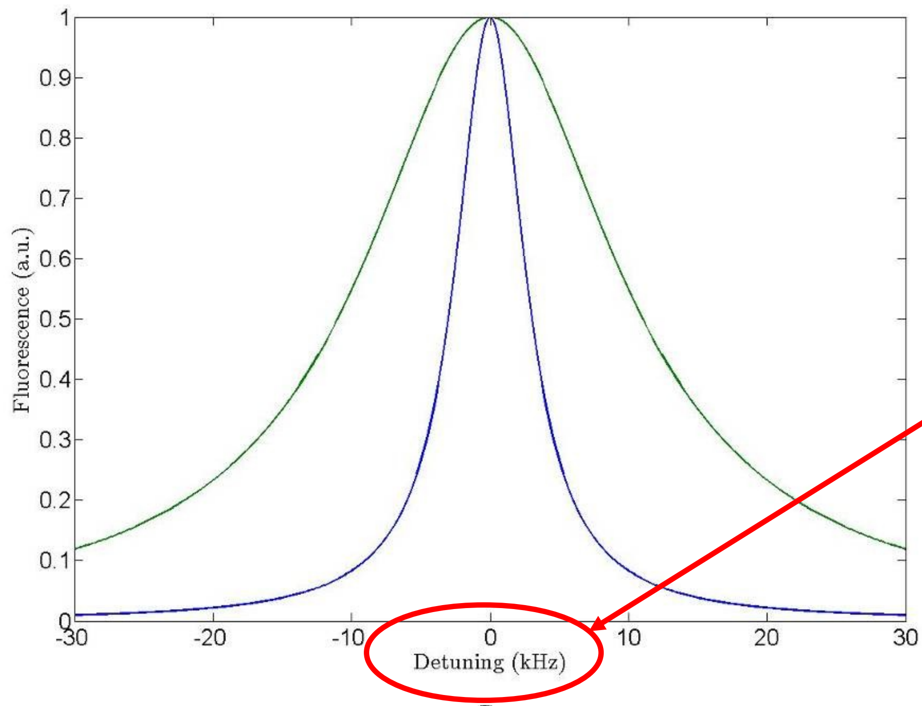

- Co-propagating Raman beams for Doppler-free, acceleration free configuration
- Coherent superposition of magnetic sublevels

$$\Delta\phi = \frac{\Delta S}{\hbar} = \frac{\mu_B}{\hbar}\left(g_{F'}m_{F'} - g_F m_F\right)\left(\frac{\partial B}{\partial z}\right) v_o T^2$$

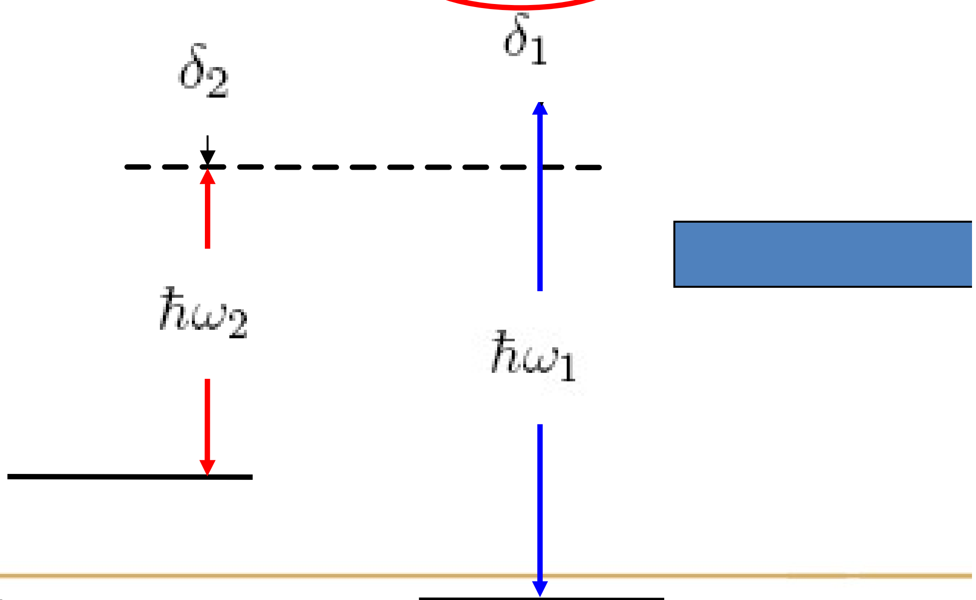
$$= \frac{\mu B}{\hbar}\left(g_{F'}m_{F'} - g_F m_F\right)\left(\frac{\partial B}{\partial z}\right)\frac{\Delta z}{2} T$$

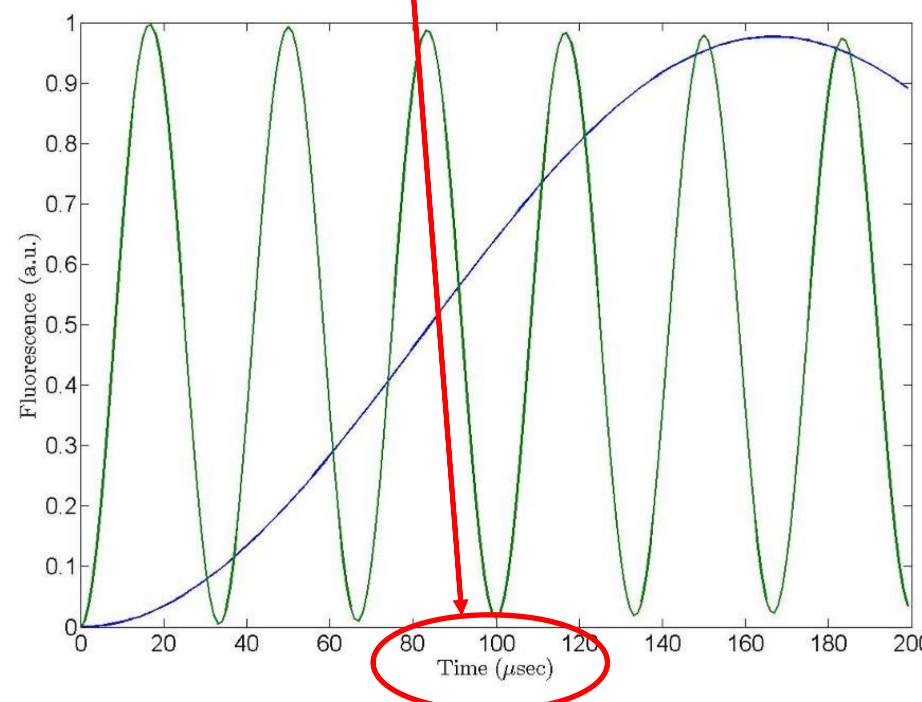
Same picture allows us to see how this runs as a magnetometer (possibly with stationary atoms)

# Raman Resonances



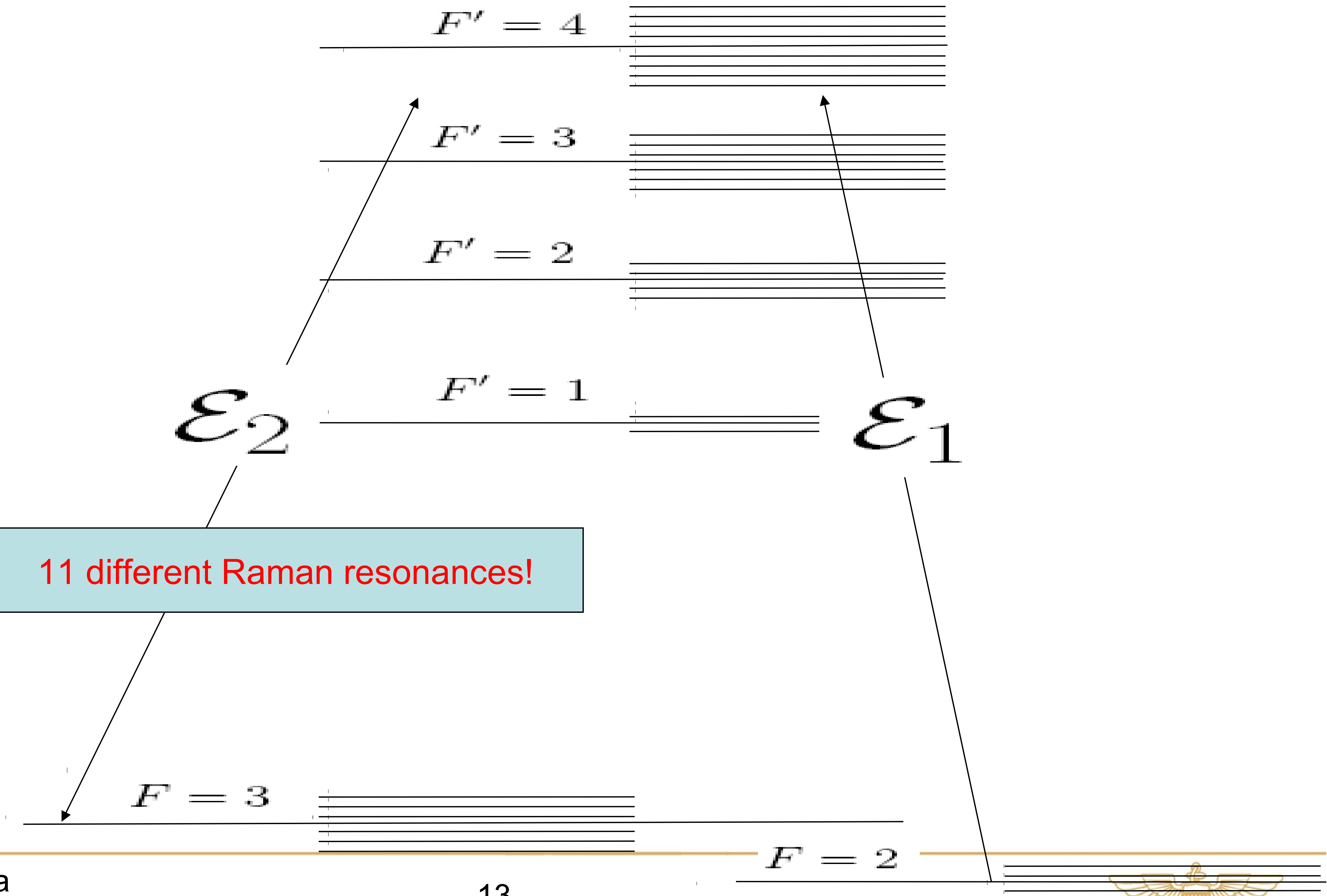

Now controlled by ground state decoherence time which can be made very small



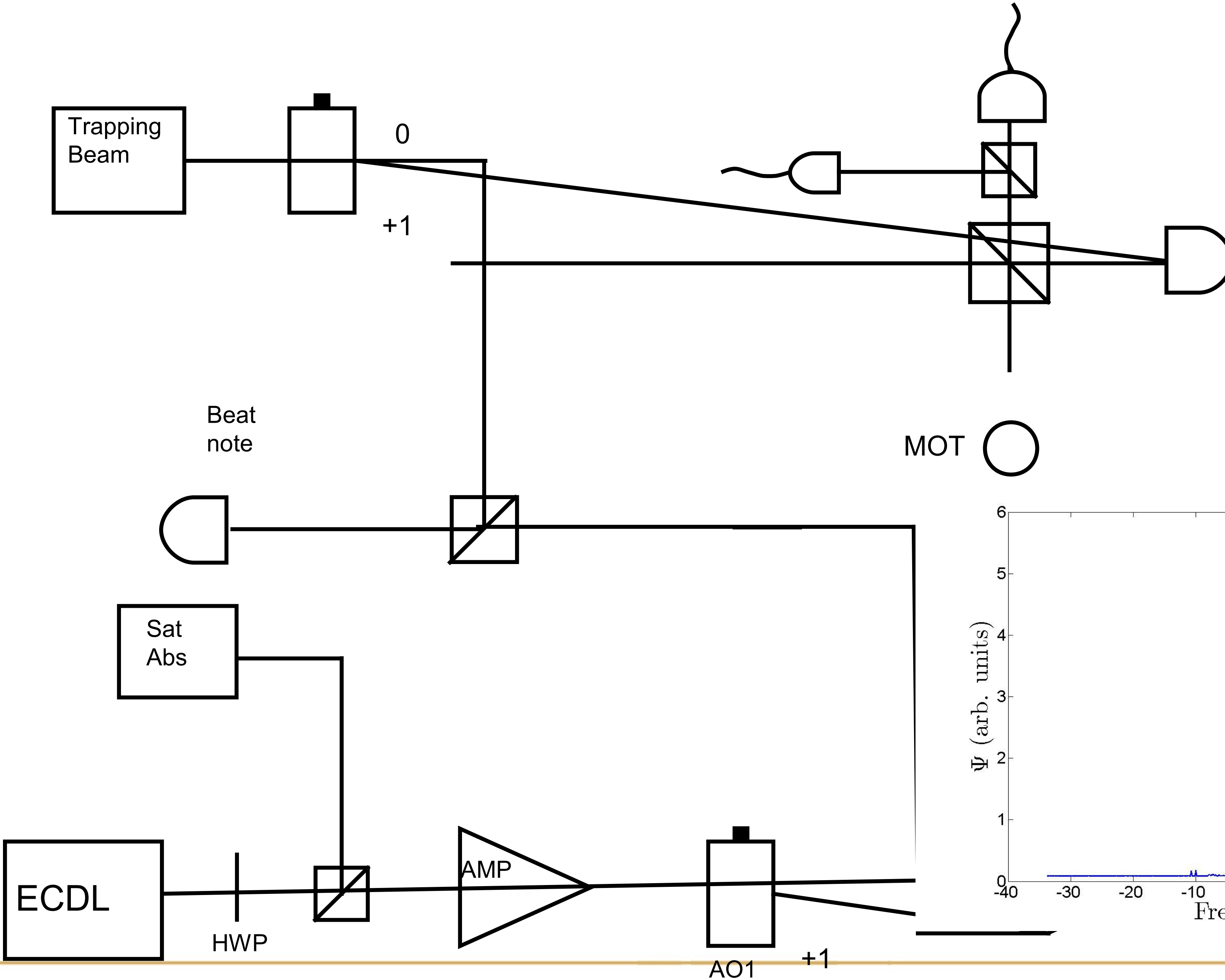
# Raman resonances in arbitrary fields

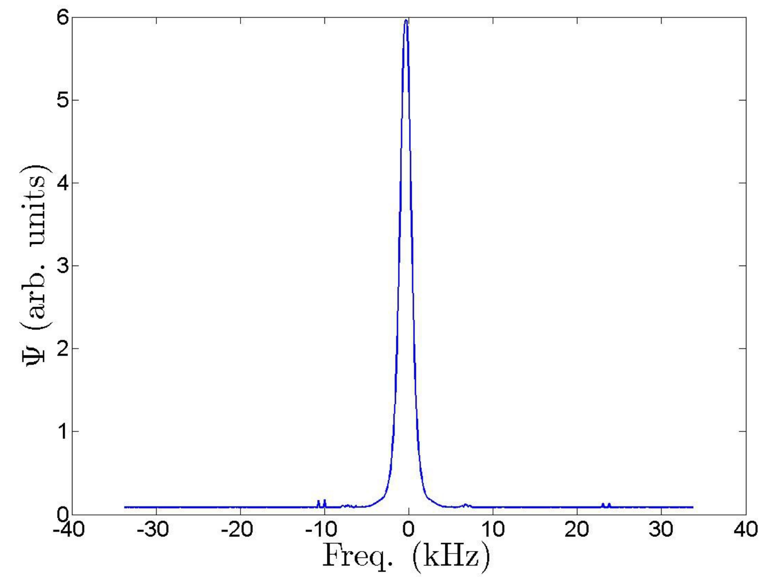
# A real atom: $^{85}Rb$

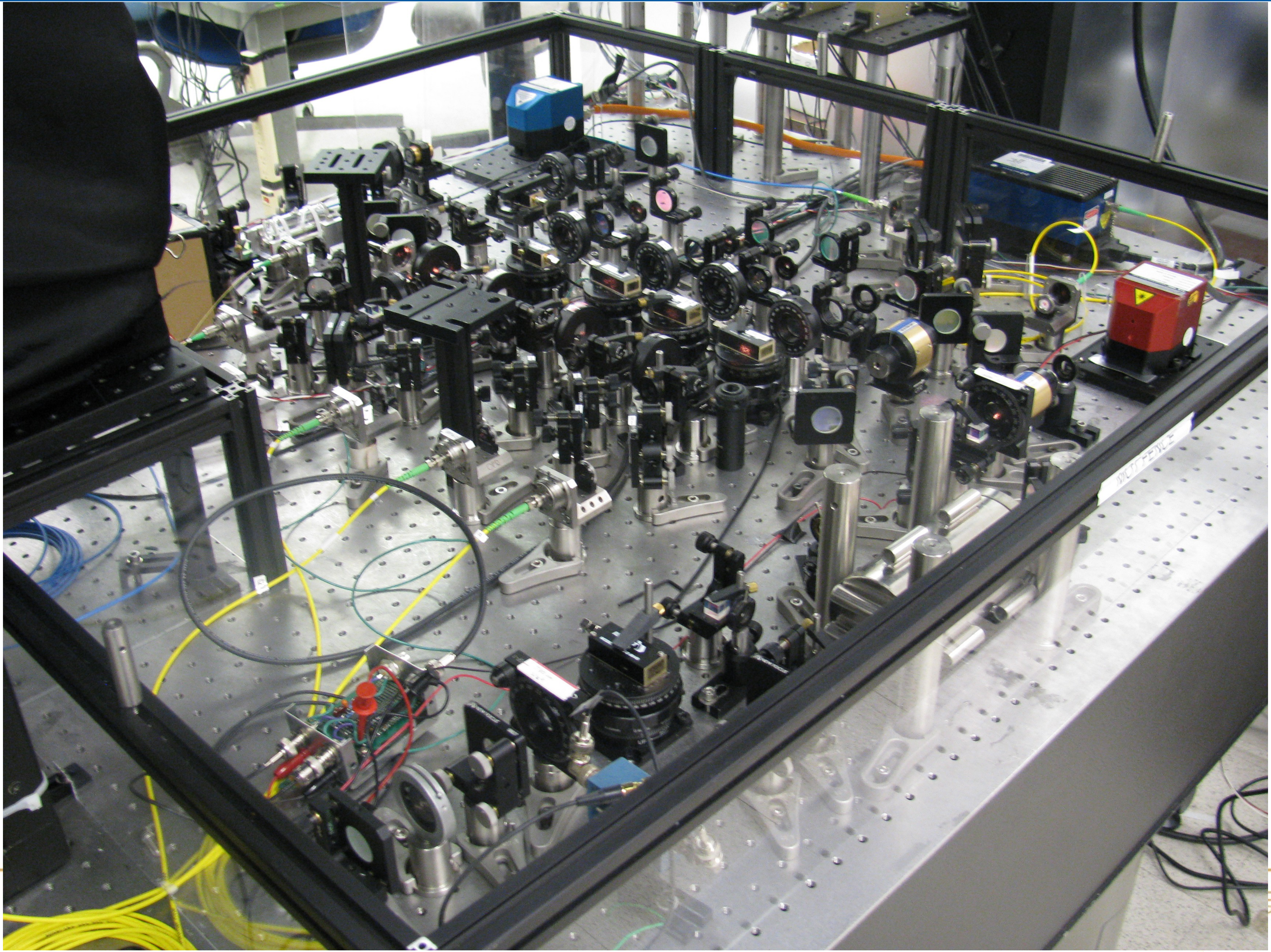


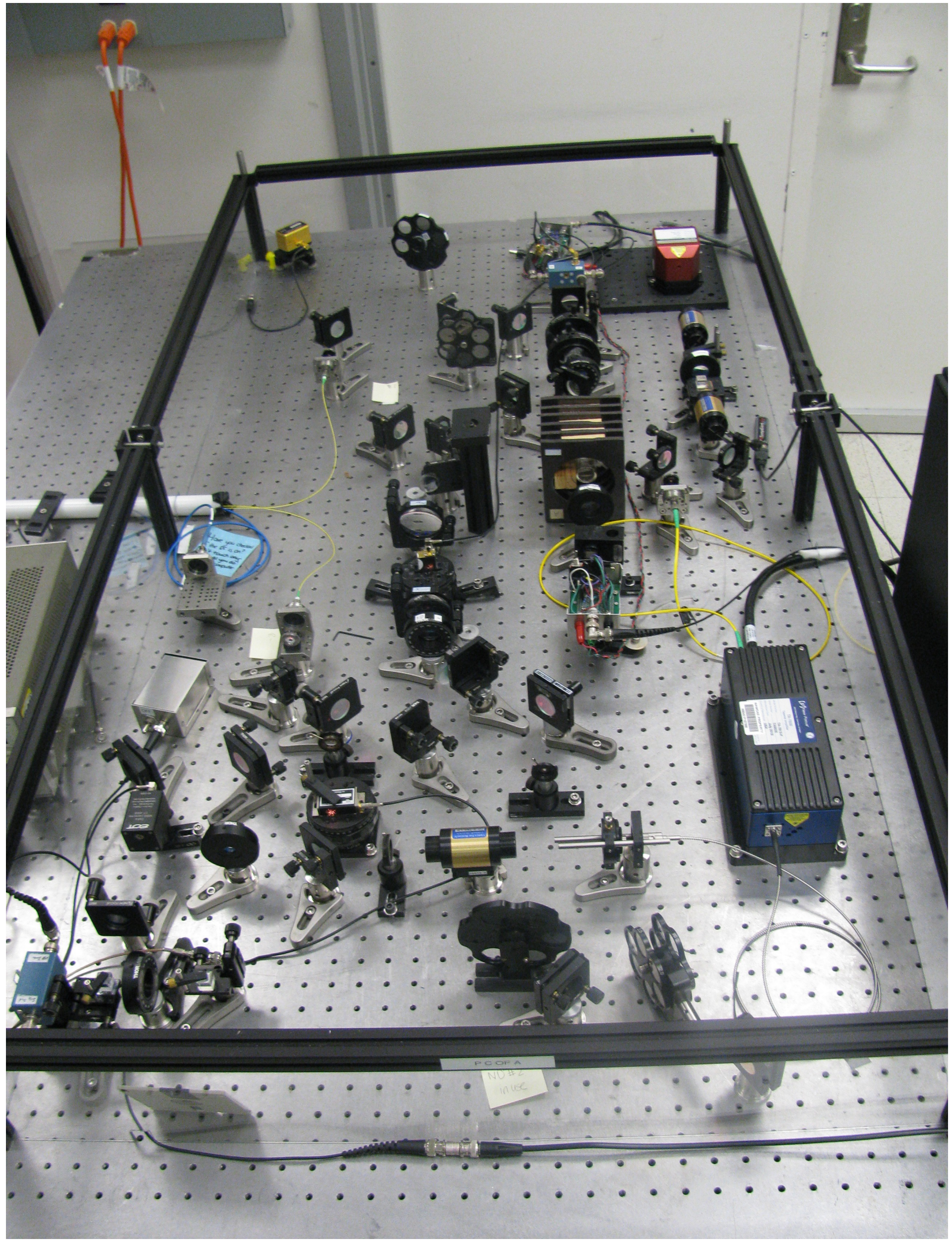

11 different Raman resonances!

# Experimental Arrangement

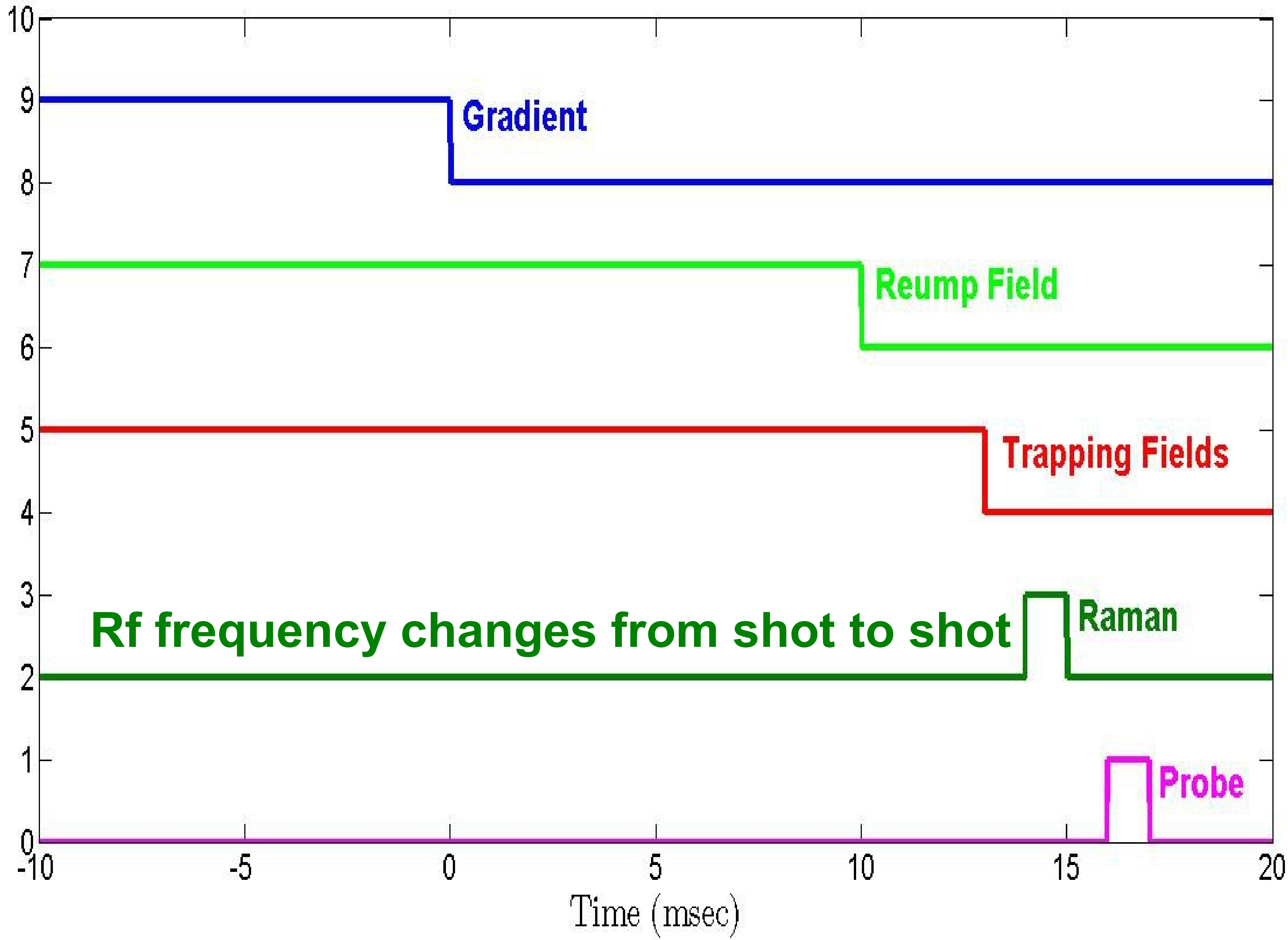


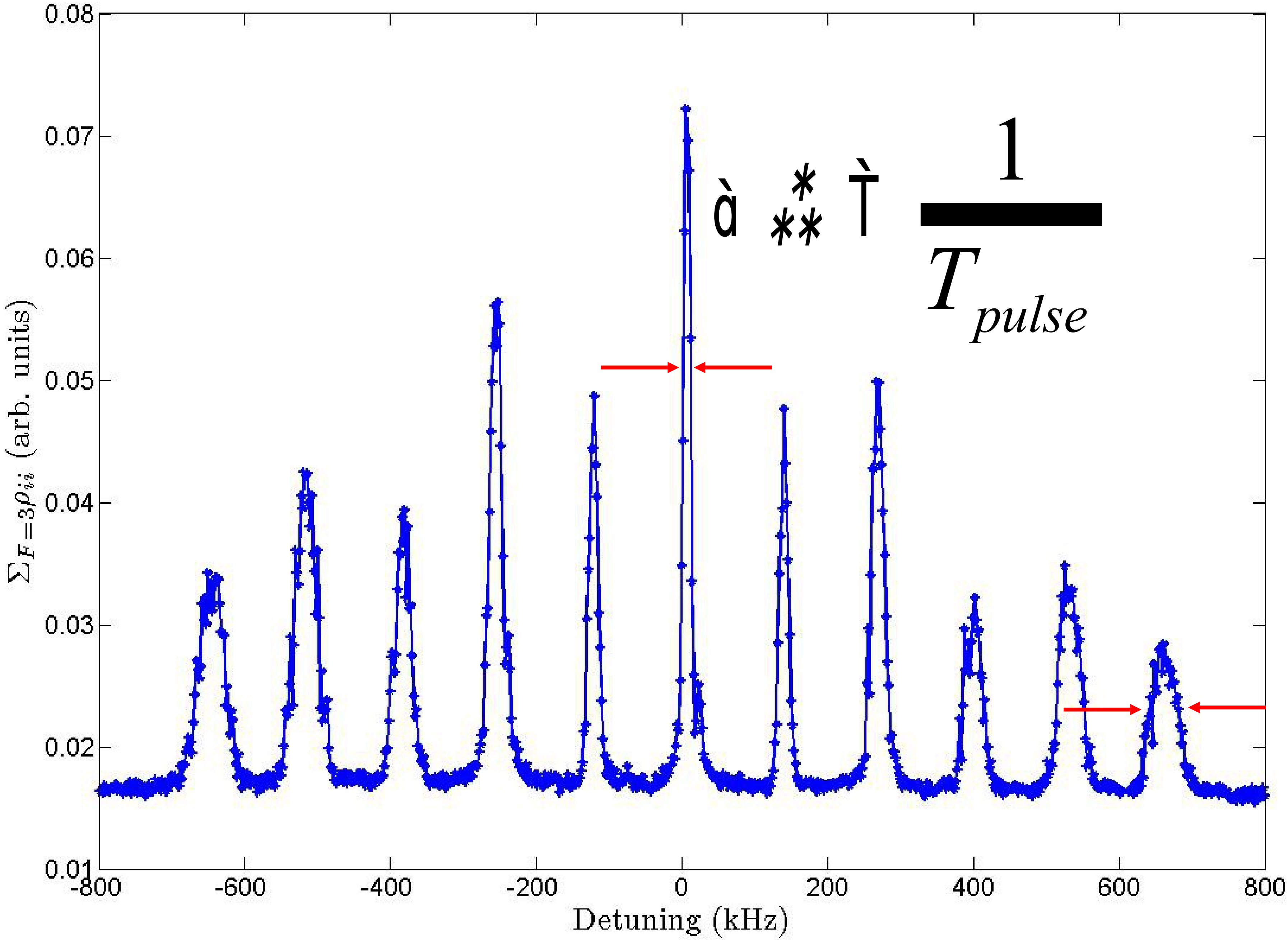




# Timing sequence



# Raman Spectra-Arbitrary Field



# Selection Rules

“Even” transitions driven by

x-y polarization

---ĜH́--Ḣ polarizations

à m=0

“Odd” transitions driven by

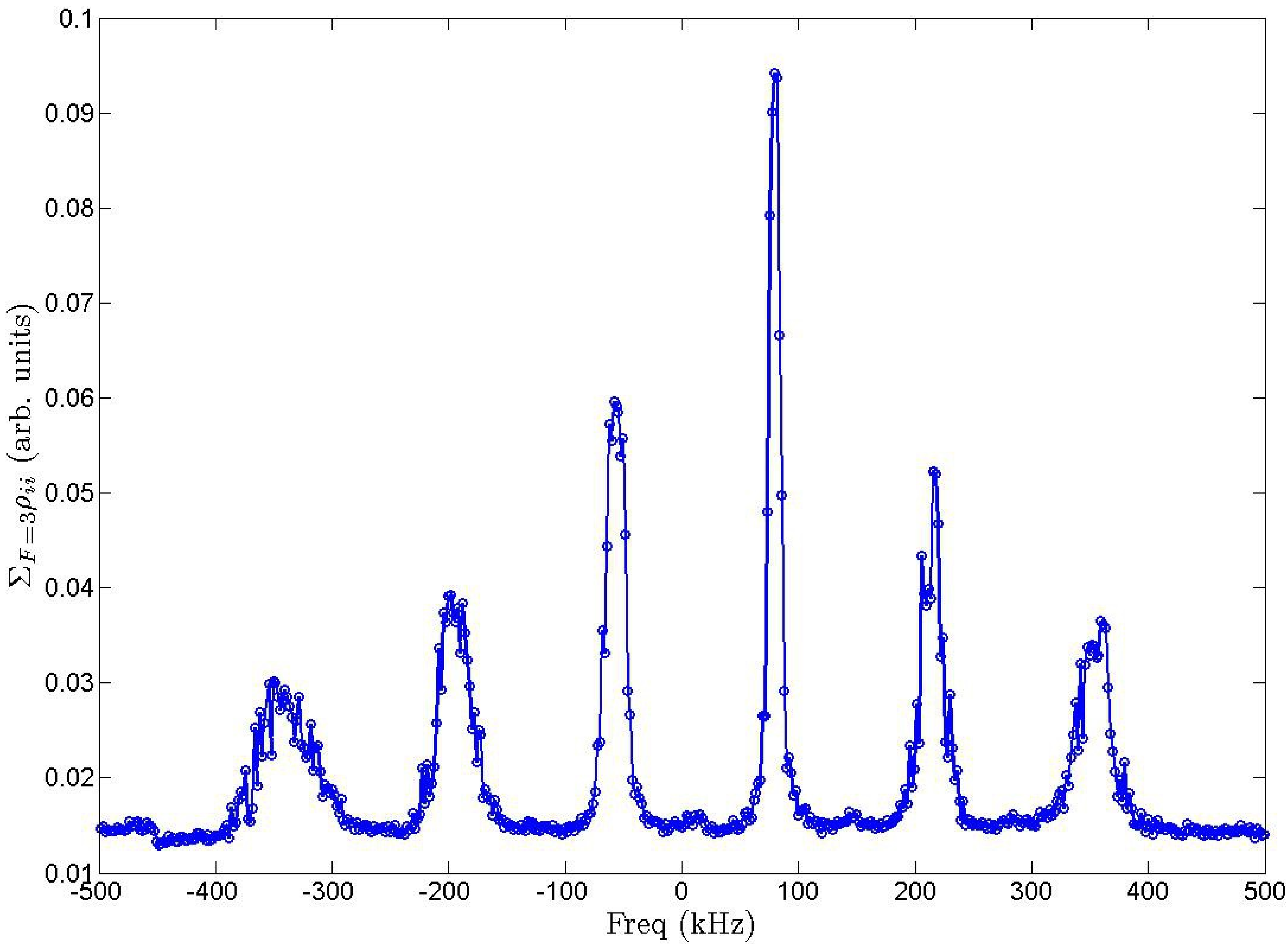
---+-z, ----z, x-z, y-z

|à m|=1

Here, z is defined by the direction of the magnetic field

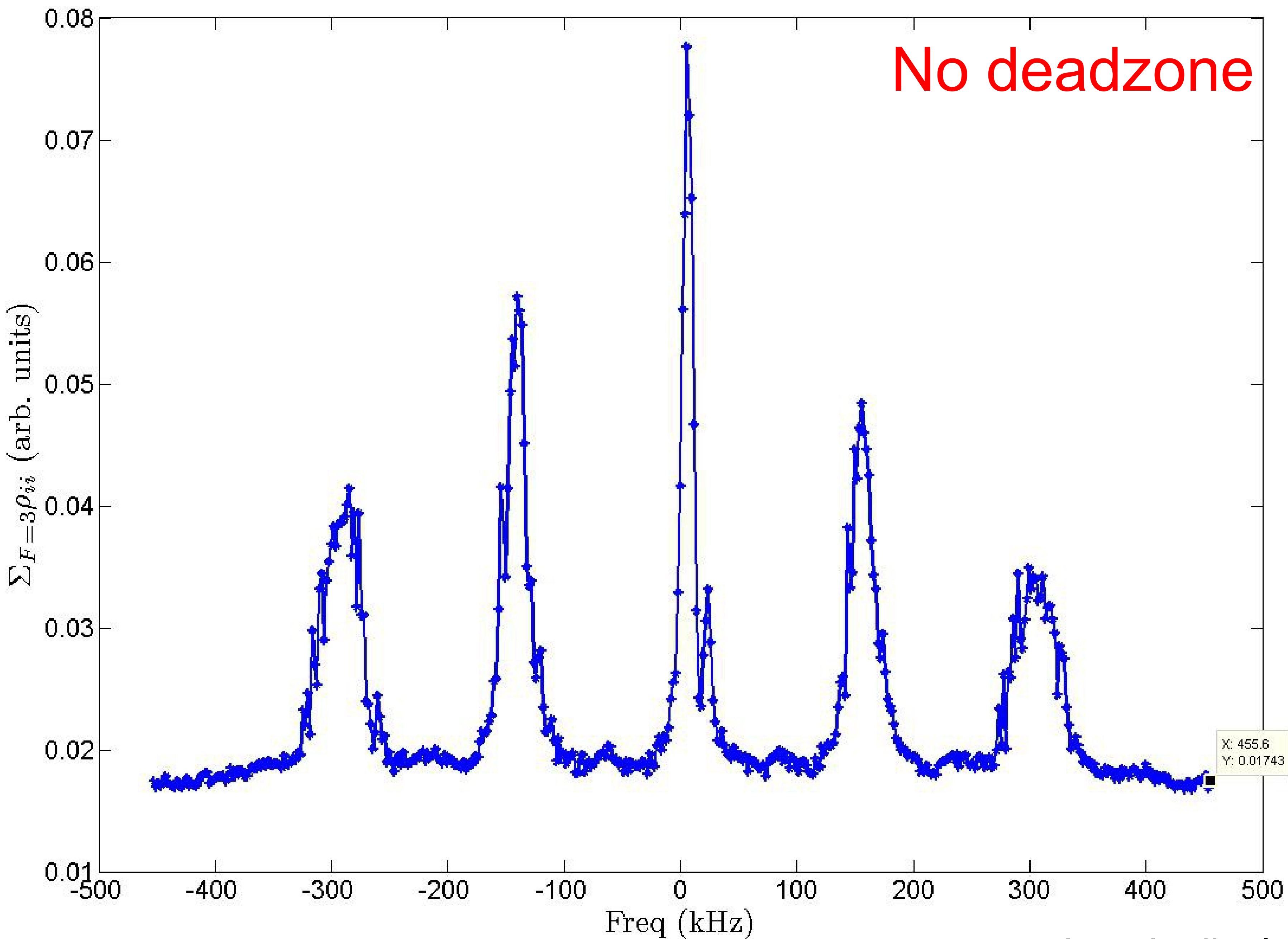
g factor between ground states changes sign

# Six Peaked Spectrum




Transverse

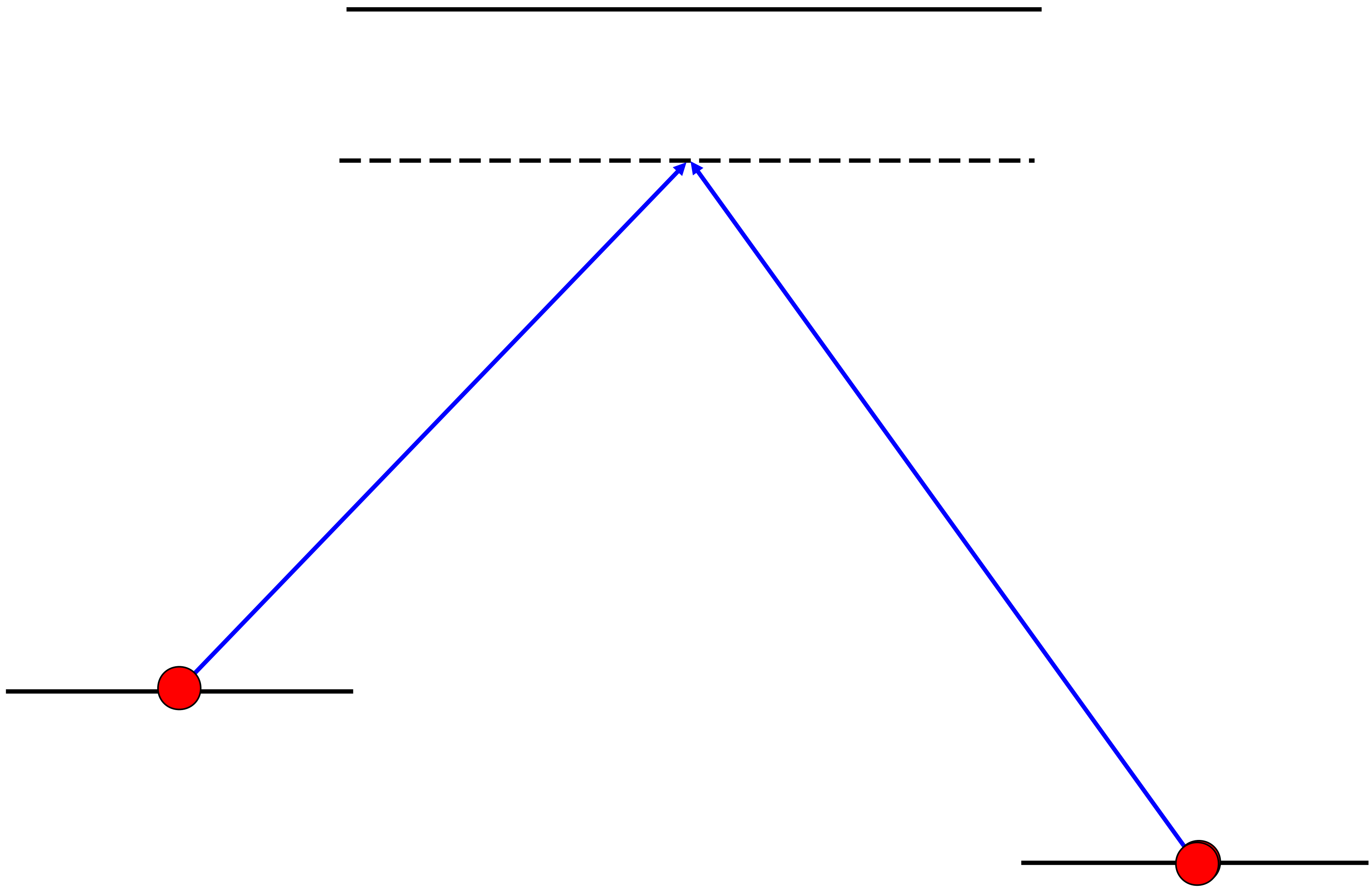
# Five Peaked Spectrum



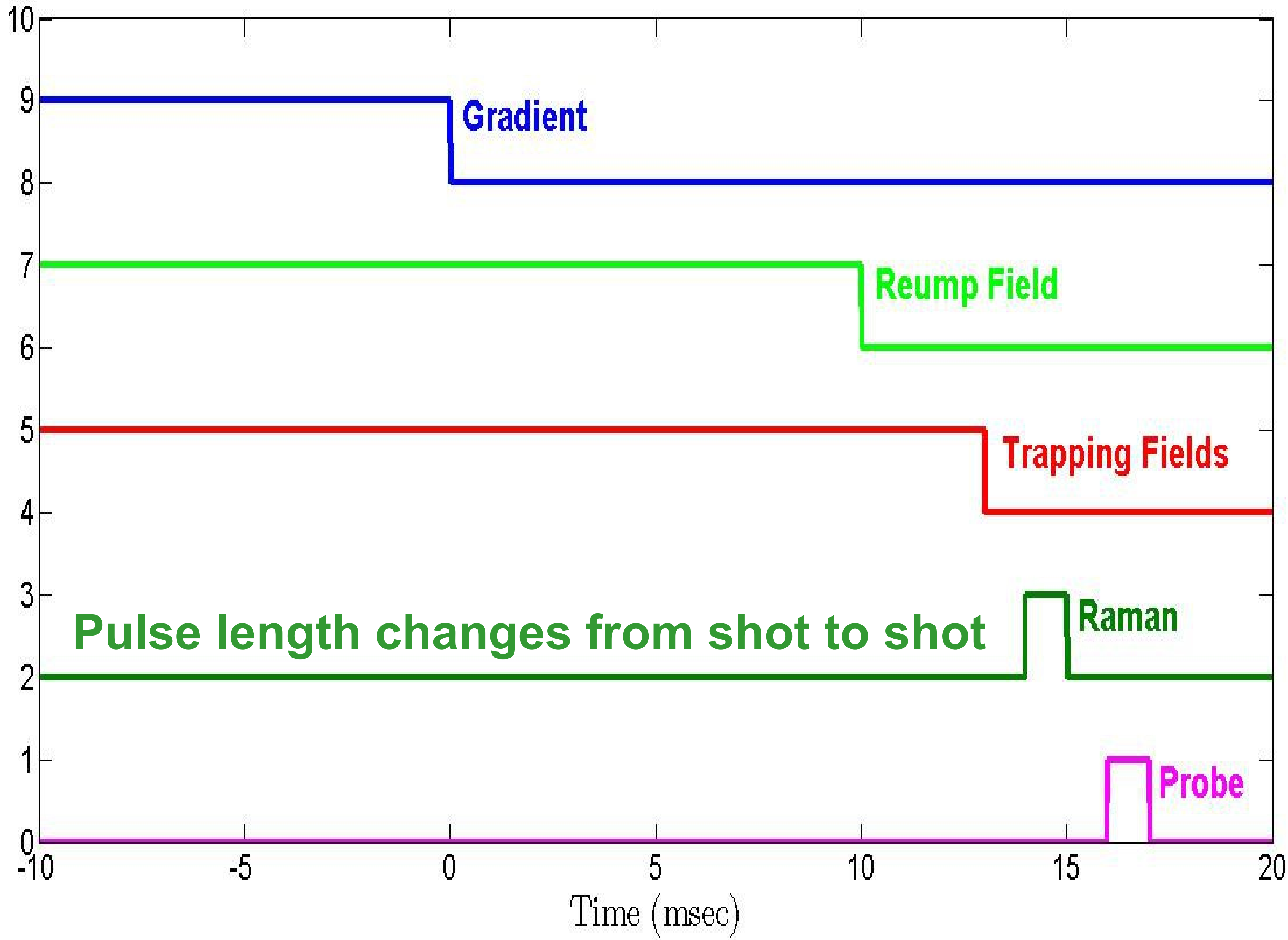

Longitudinal

# Double Pulse Experiment (Ramsey) Time Domain

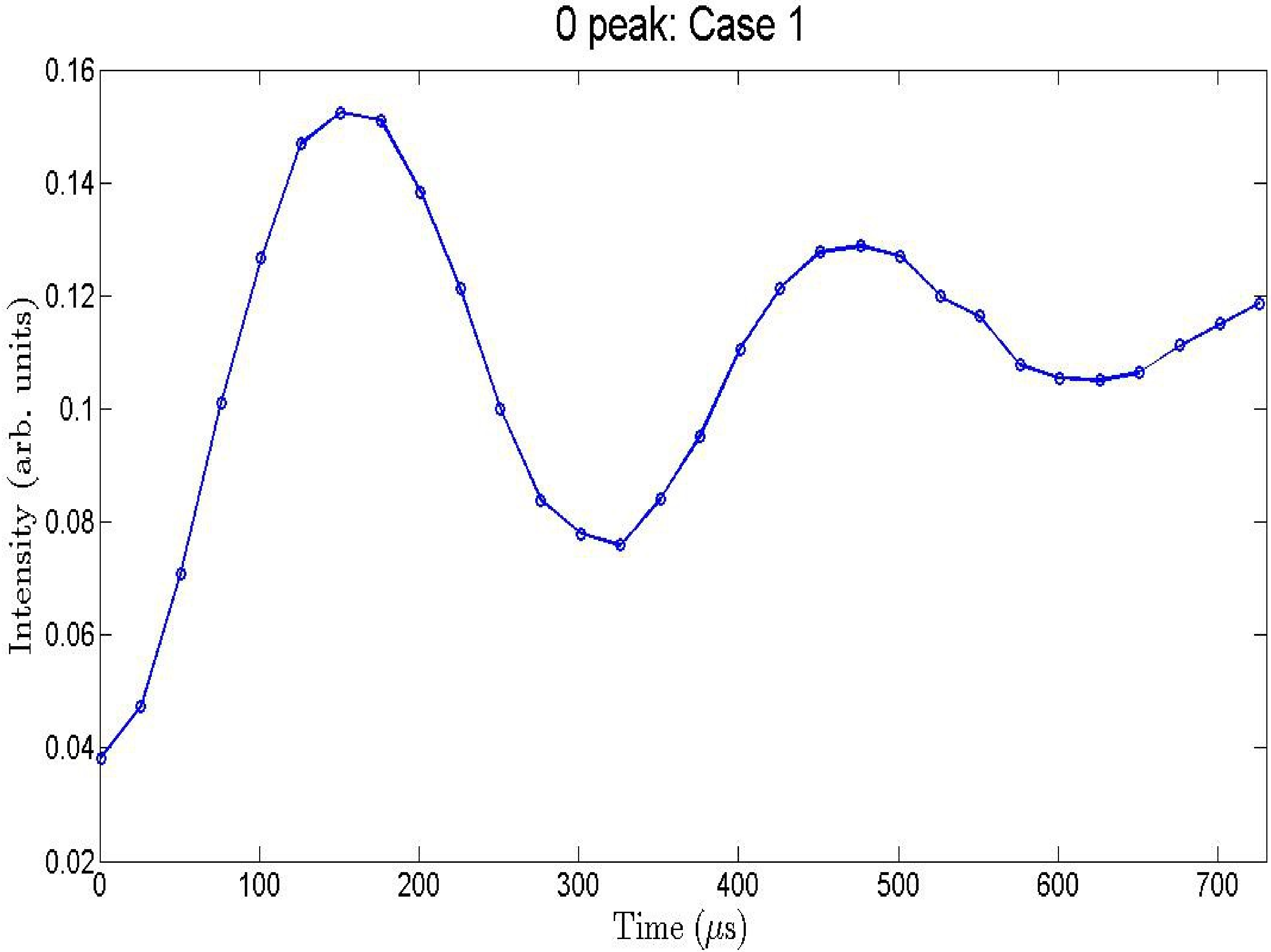
# Raman Transfer (Cycling)



# Timing sequence



# Rabi cycling: 0 peak (Expt.)



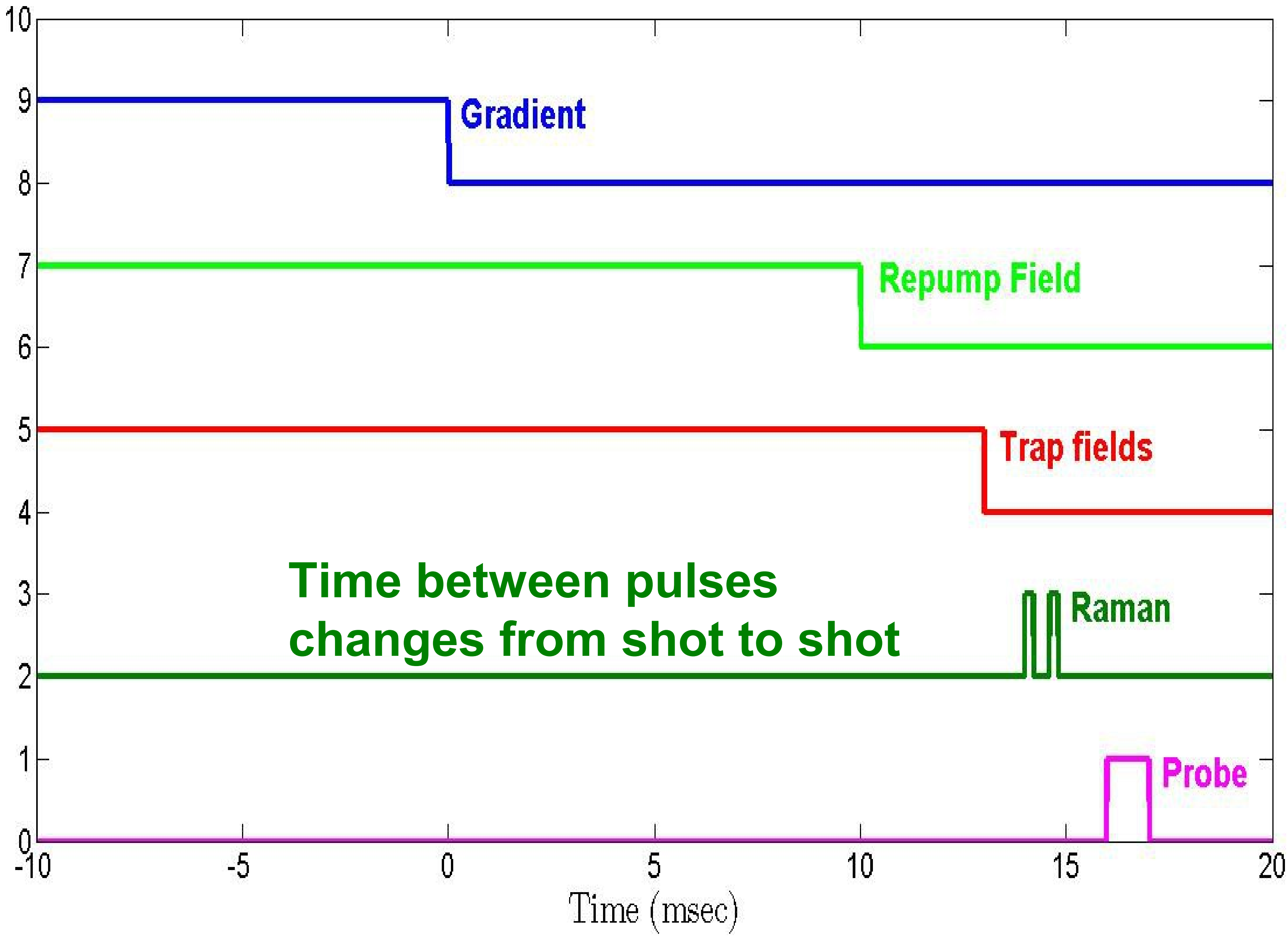
# A little math...

$$\left|c_2(t_1+T+t_2)\right|^2 = \left|2\frac{\Omega_+}{\Omega^*}\left[\frac{\Omega^*}{2\Omega_g}\tilde{c}_2(t_1)e^{\imath\delta(t_1+T)} - \frac{\Omega_-}{\Omega_g}\tilde{c}_1(t_1)\right]e^{\imath\Omega_+ t_2} + 2\frac{\Omega_-}{\Omega^*}\left[\frac{\Omega_+}{\Omega^*}\tilde{c}_1(t_1) - \frac{\Omega^*}{2\Omega_g}\tilde{c}_2(t_1)e^{-\imath\delta(t_1+T)}\right]e^{\imath\Omega_- t_2}\right|^2$$

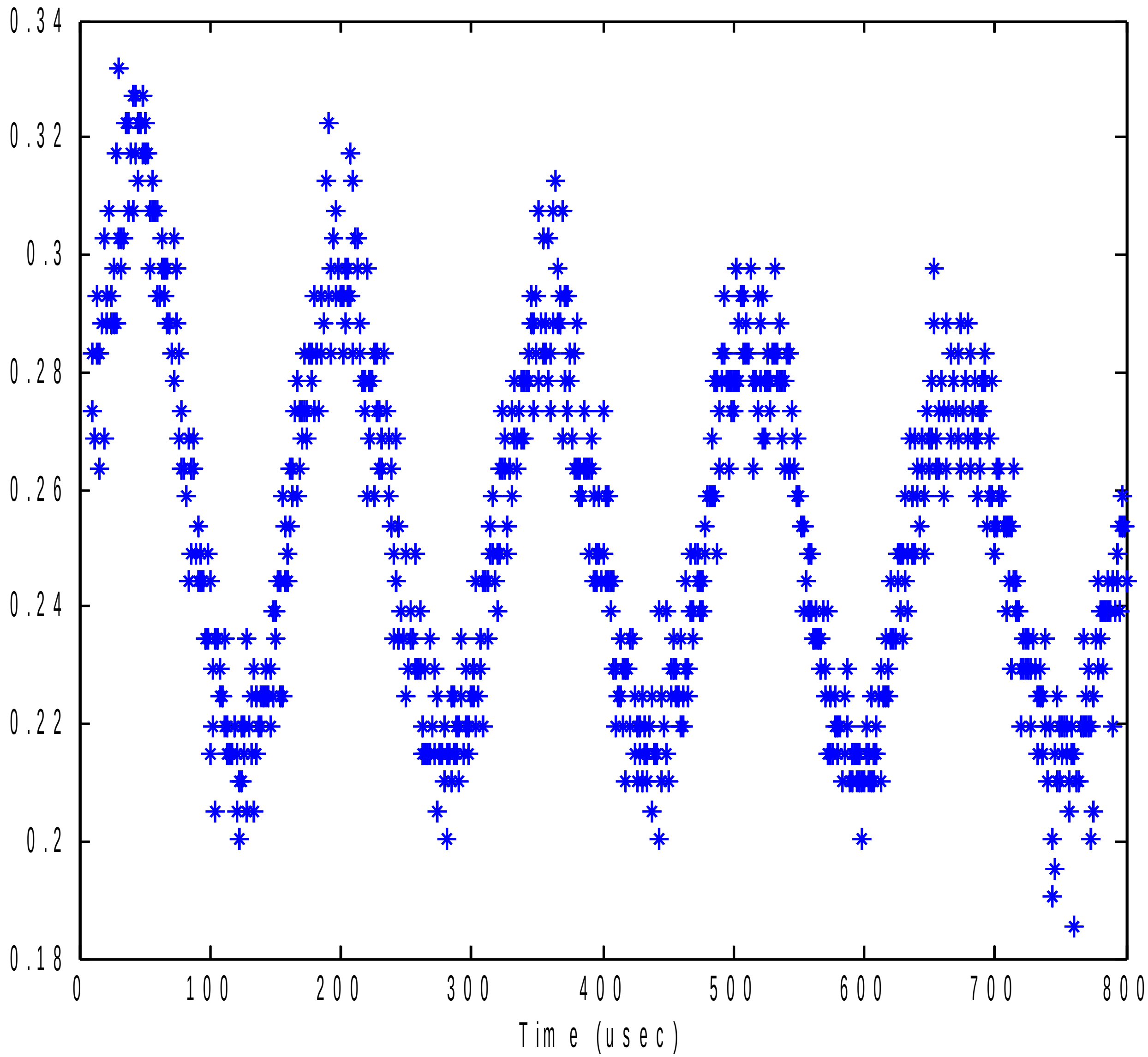
$$\Omega_\pm = \frac{1}{2}\left(\delta \pm \Omega_g\right) \qquad \Omega_g = \sqrt{\left|\Omega\right|^2 + \delta^2}$$

Picture two lasers beating against each other where here the Raman fields plays the role of the first laser and the atomic ground state transition plays the role of the second laser.

# Timing sequence

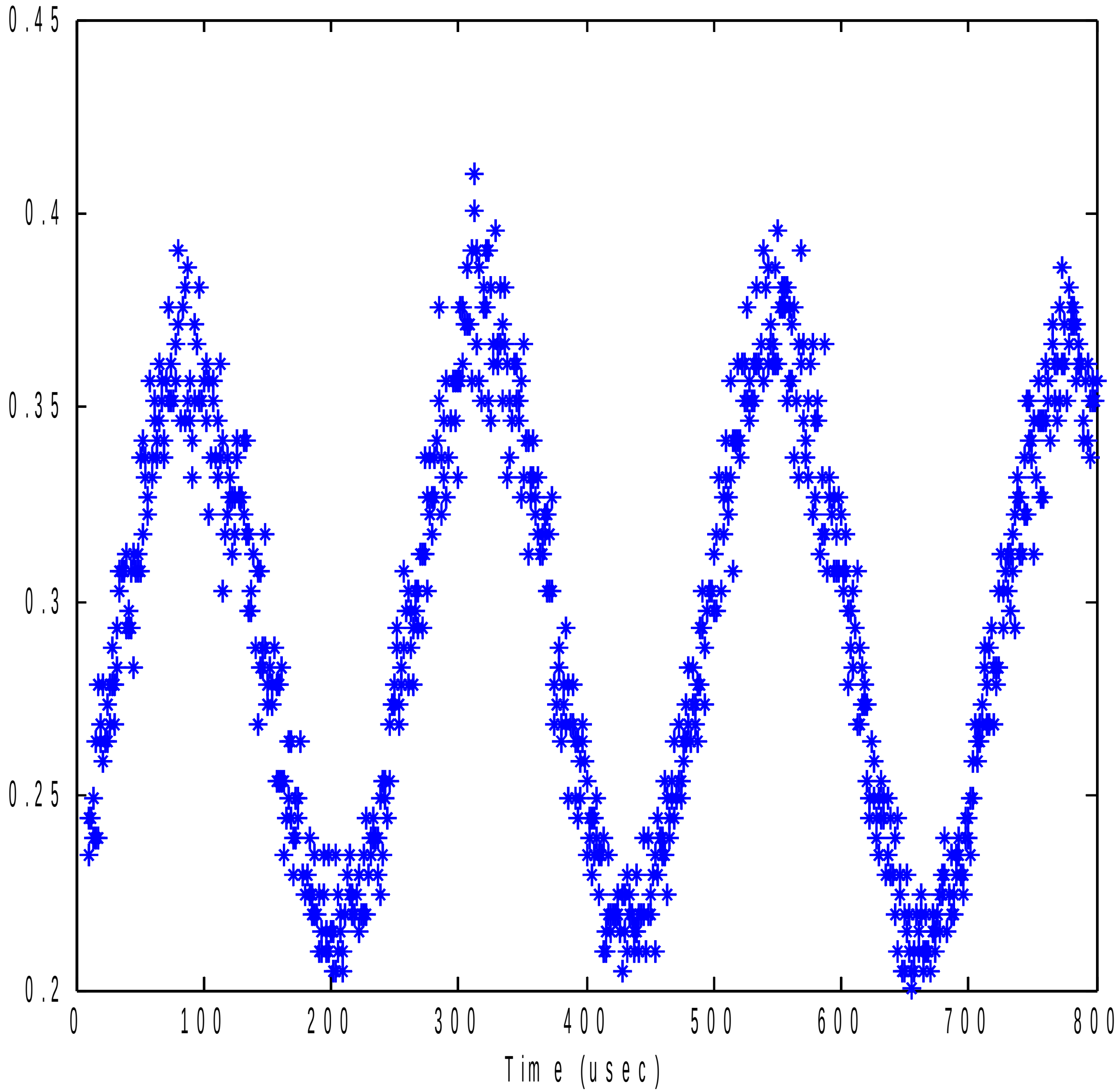


# f=1.517862 GHz




T=delay time between pulses

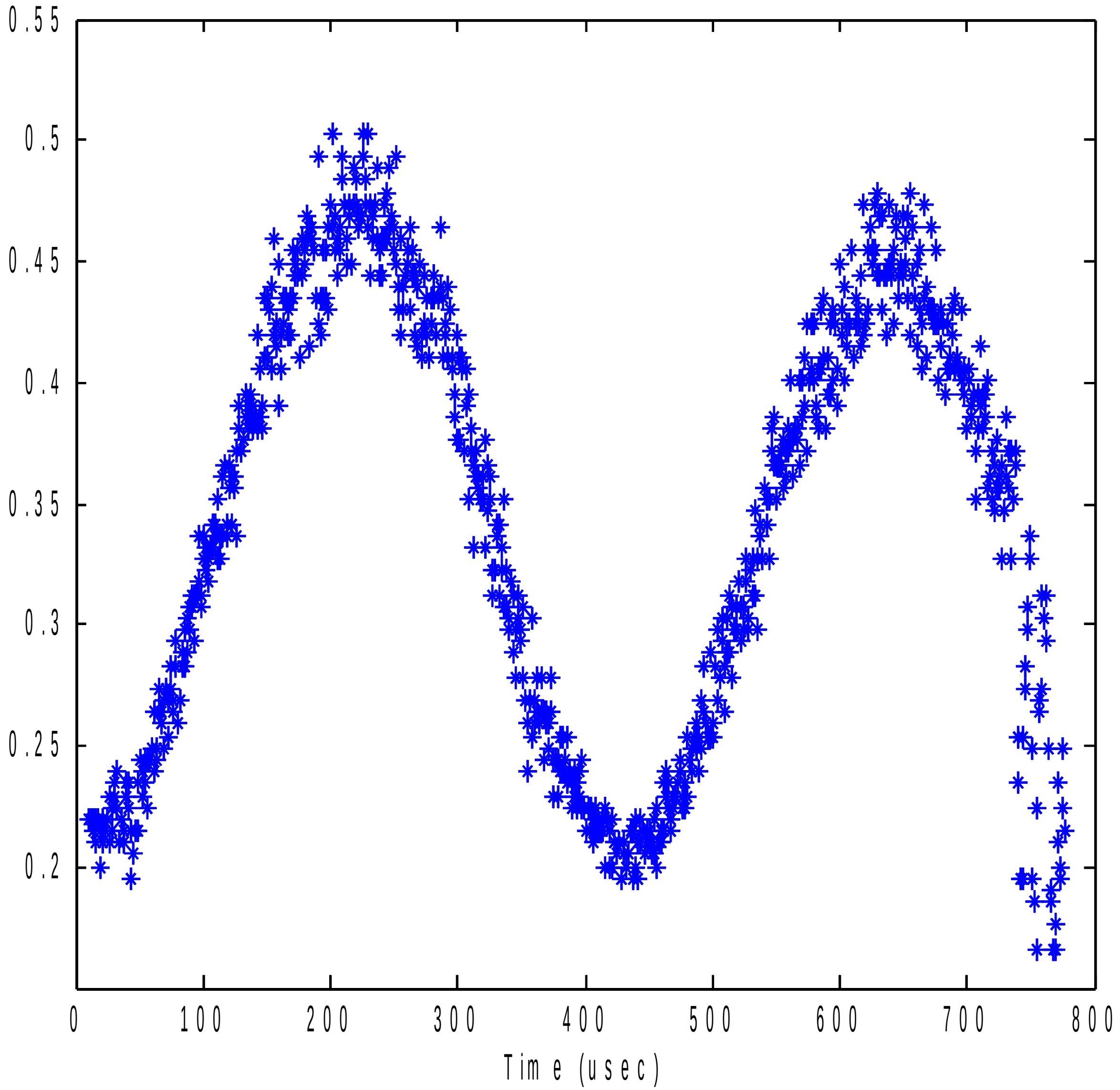
# f=1.517863 GHz




T=delay time between pulses

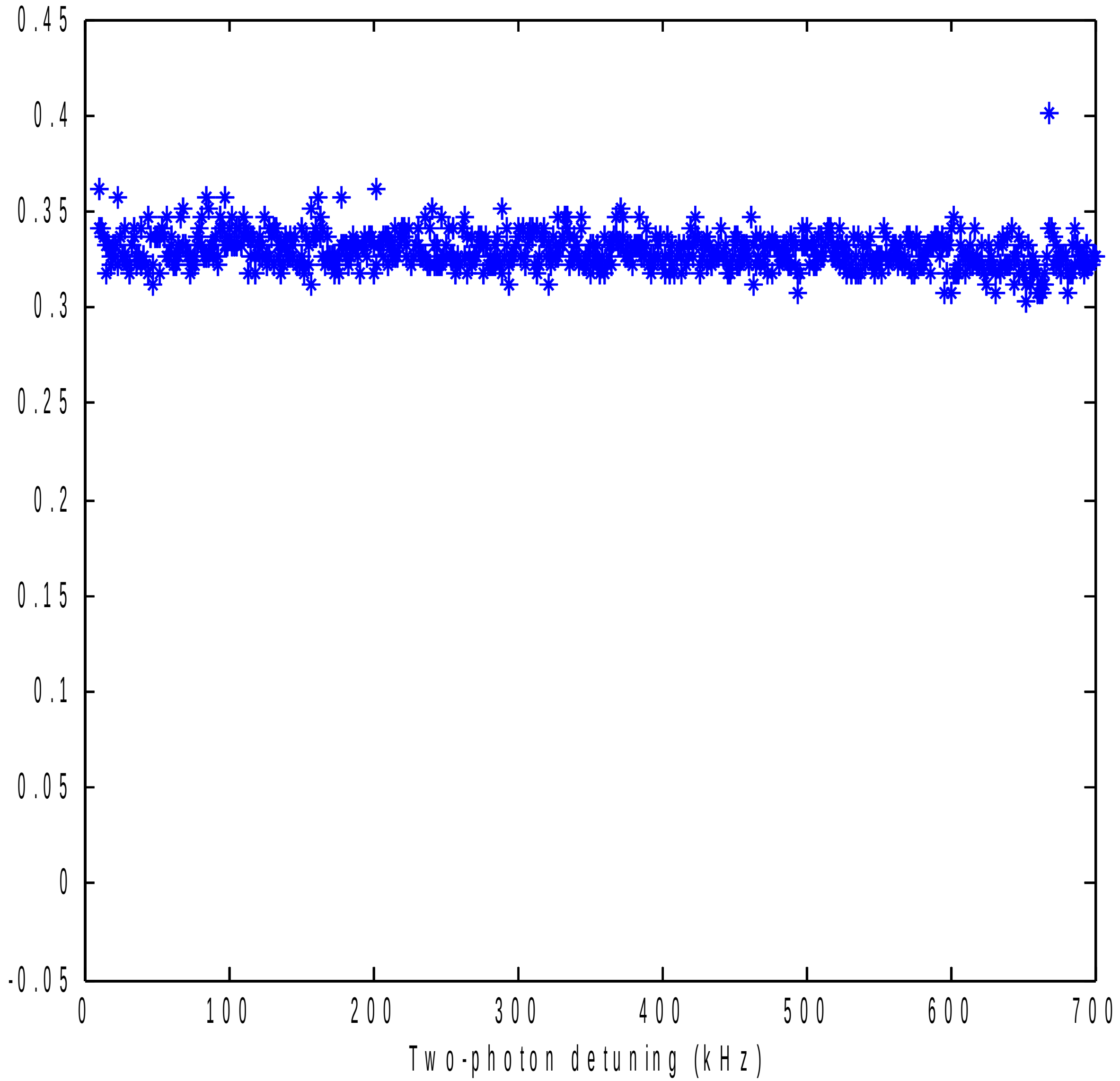
# f=1.517864 GHz

NAVAIR




T=delay time between pulses

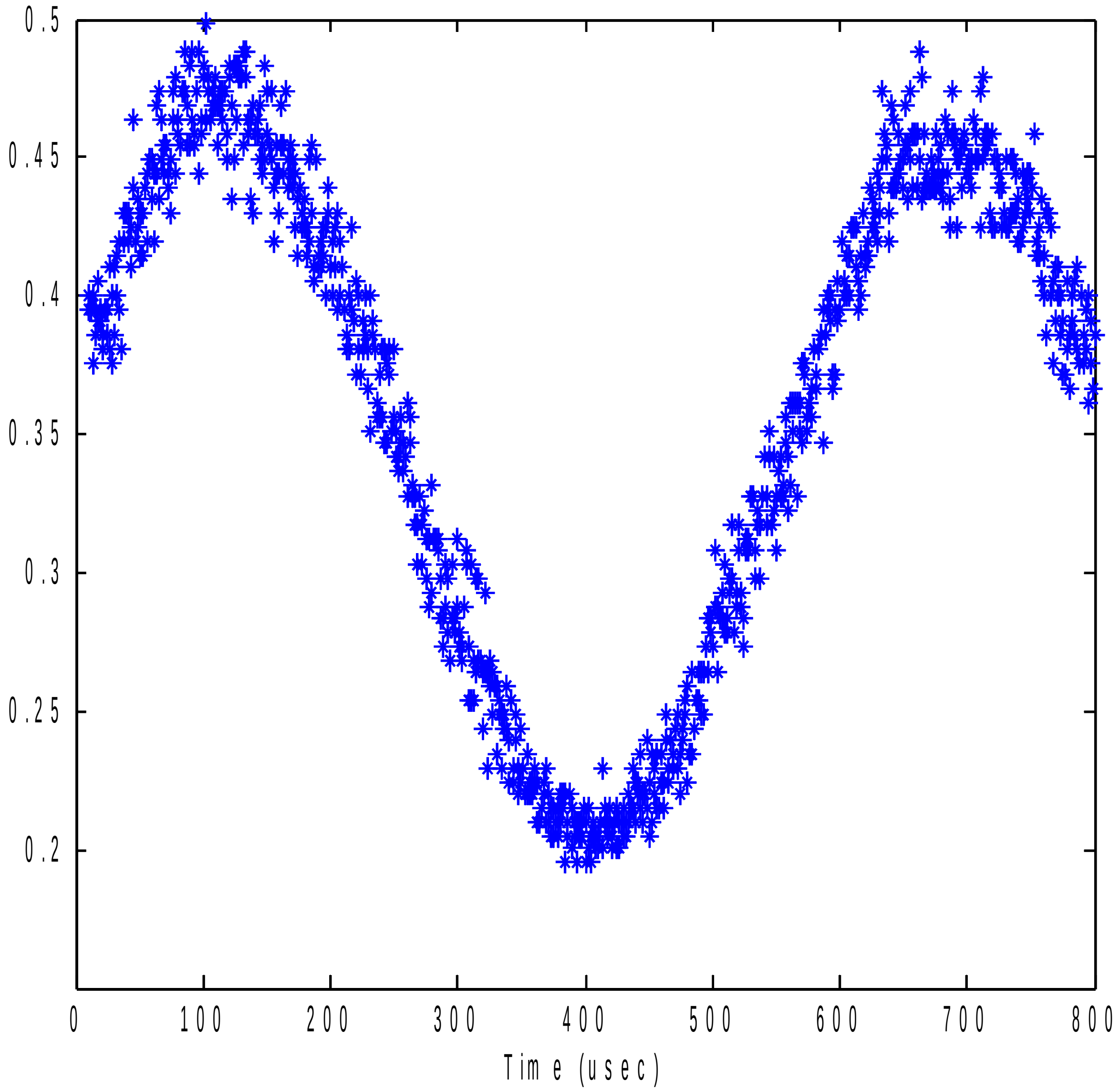
# f=1.517865 GHz




T=delay time between pulses

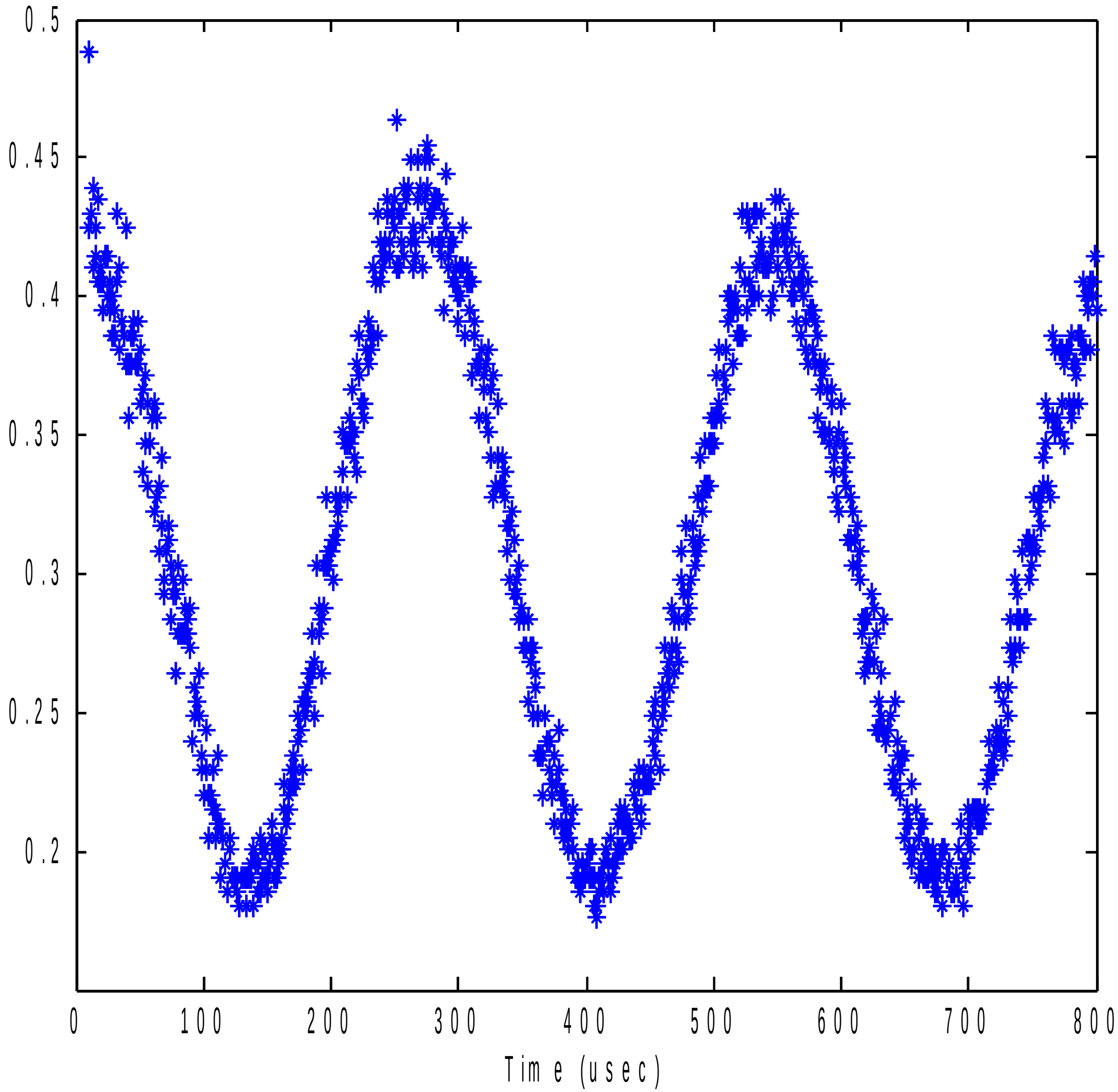
# f=1.517866 GHz

NAVAIR



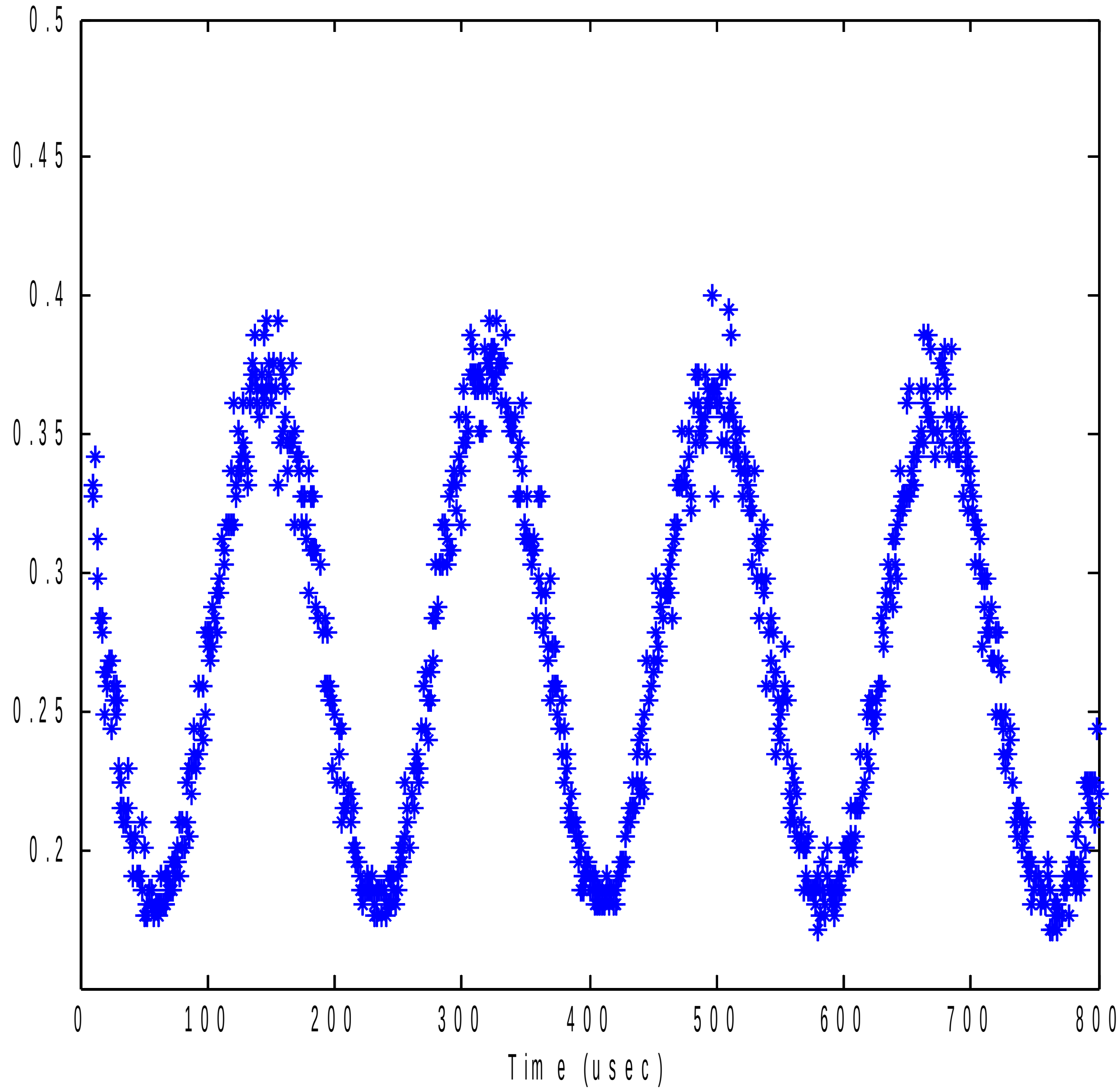

T=delay time between pulses

# f=1.517867 GHz



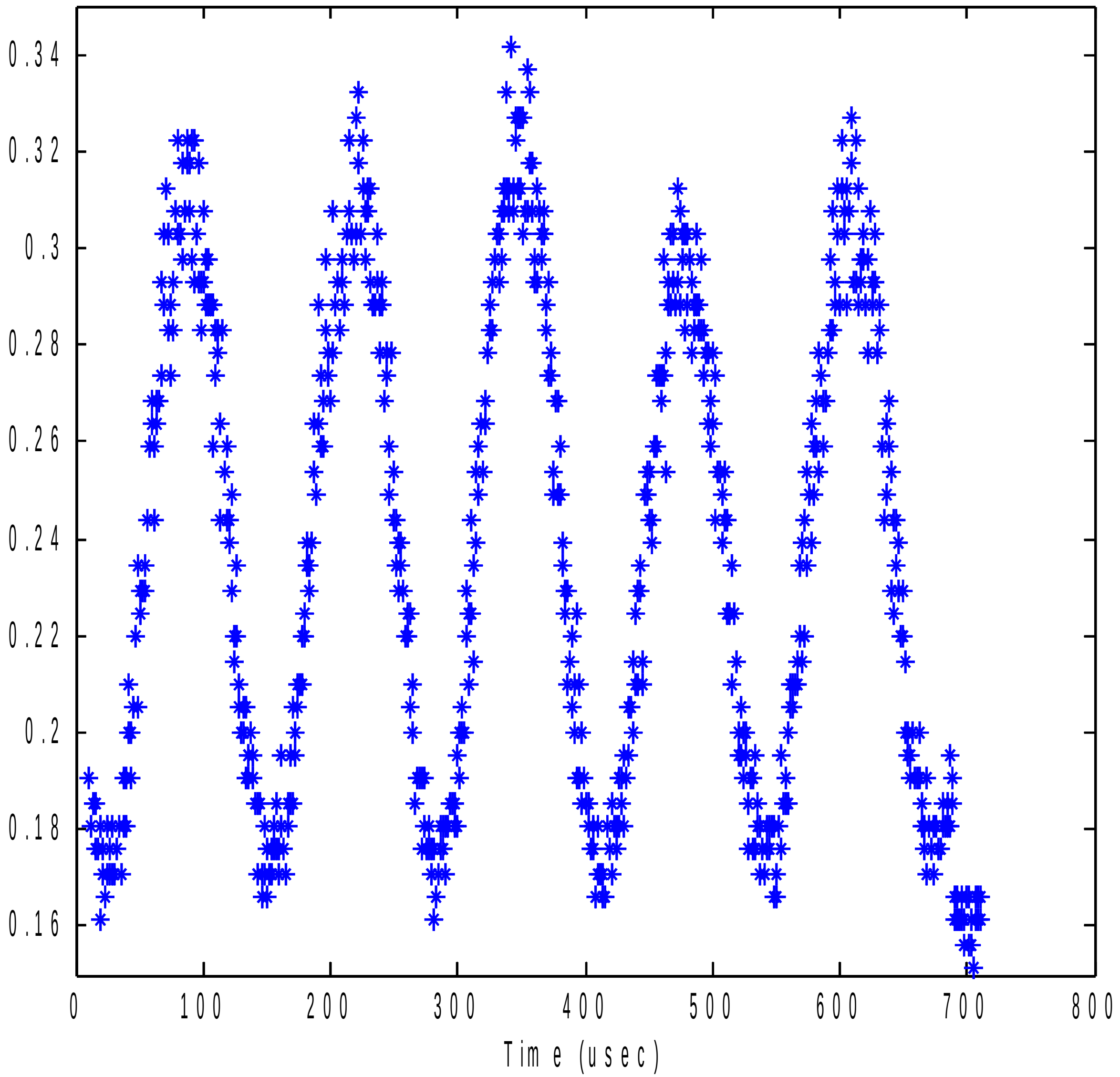

T=delay time between pulses

# f=1.517868 GHz



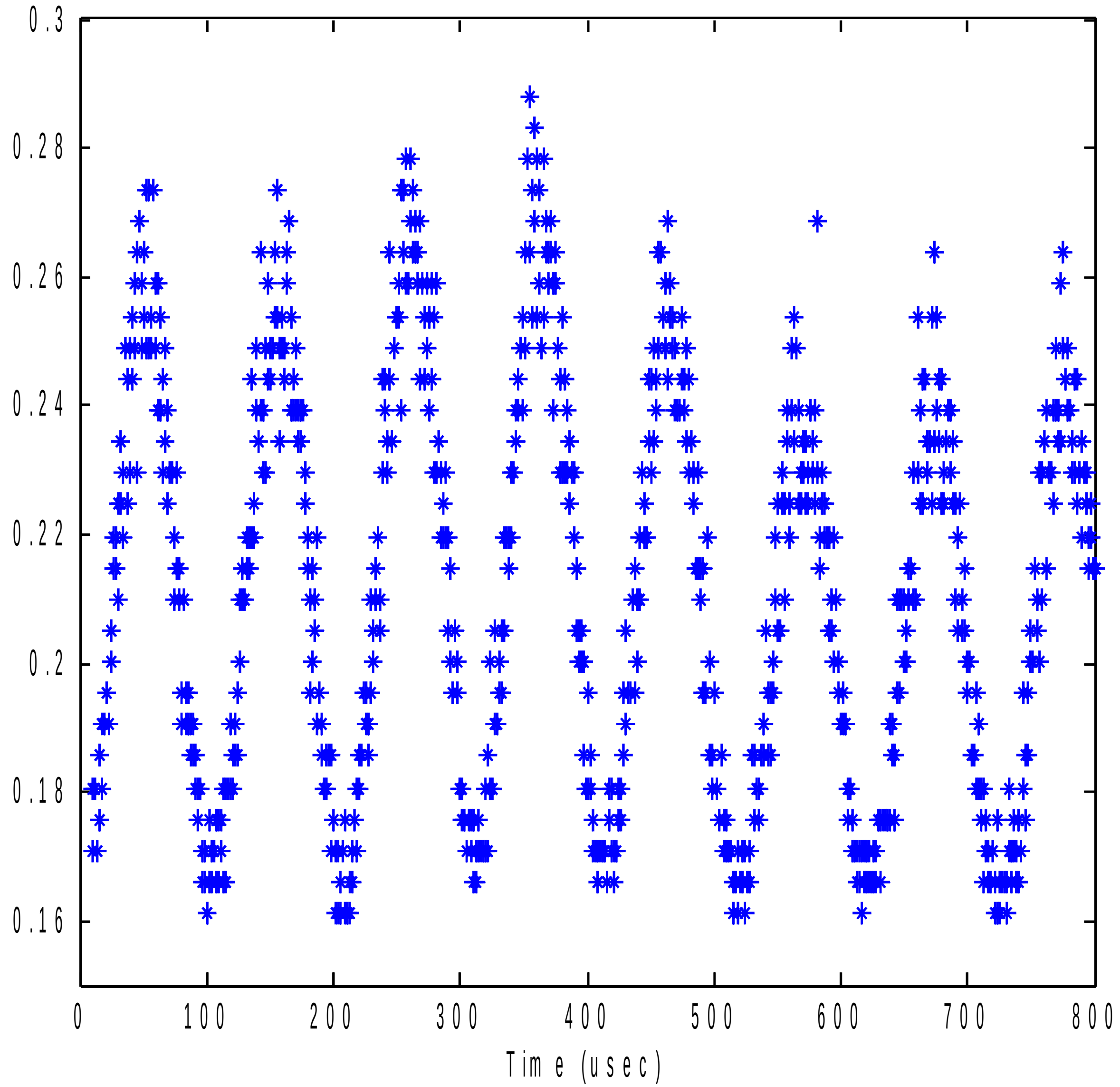

T=delay time between pulses

# f=1.517869 GHz




T=delay time between pulses

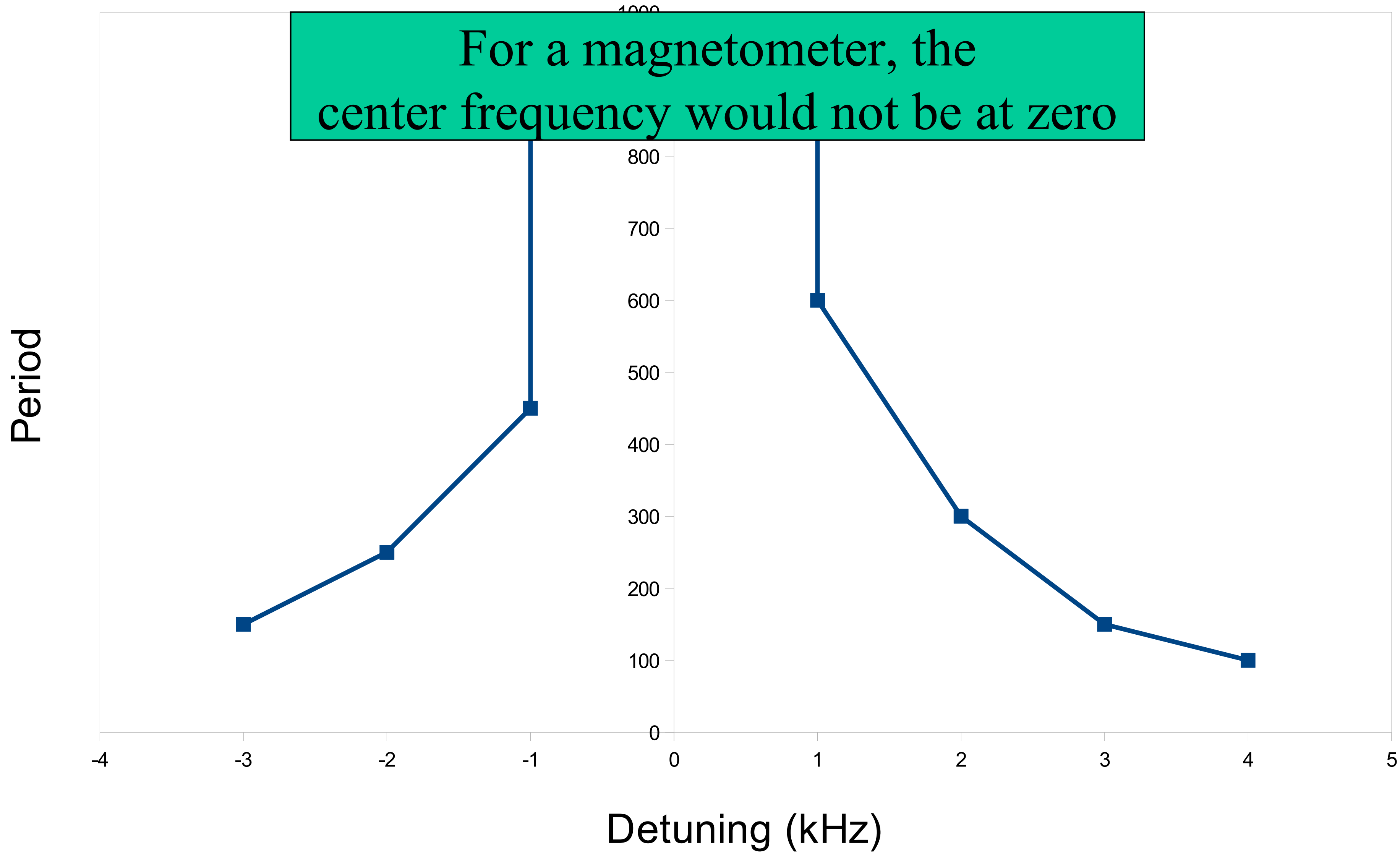
# f=1.517870 GHz



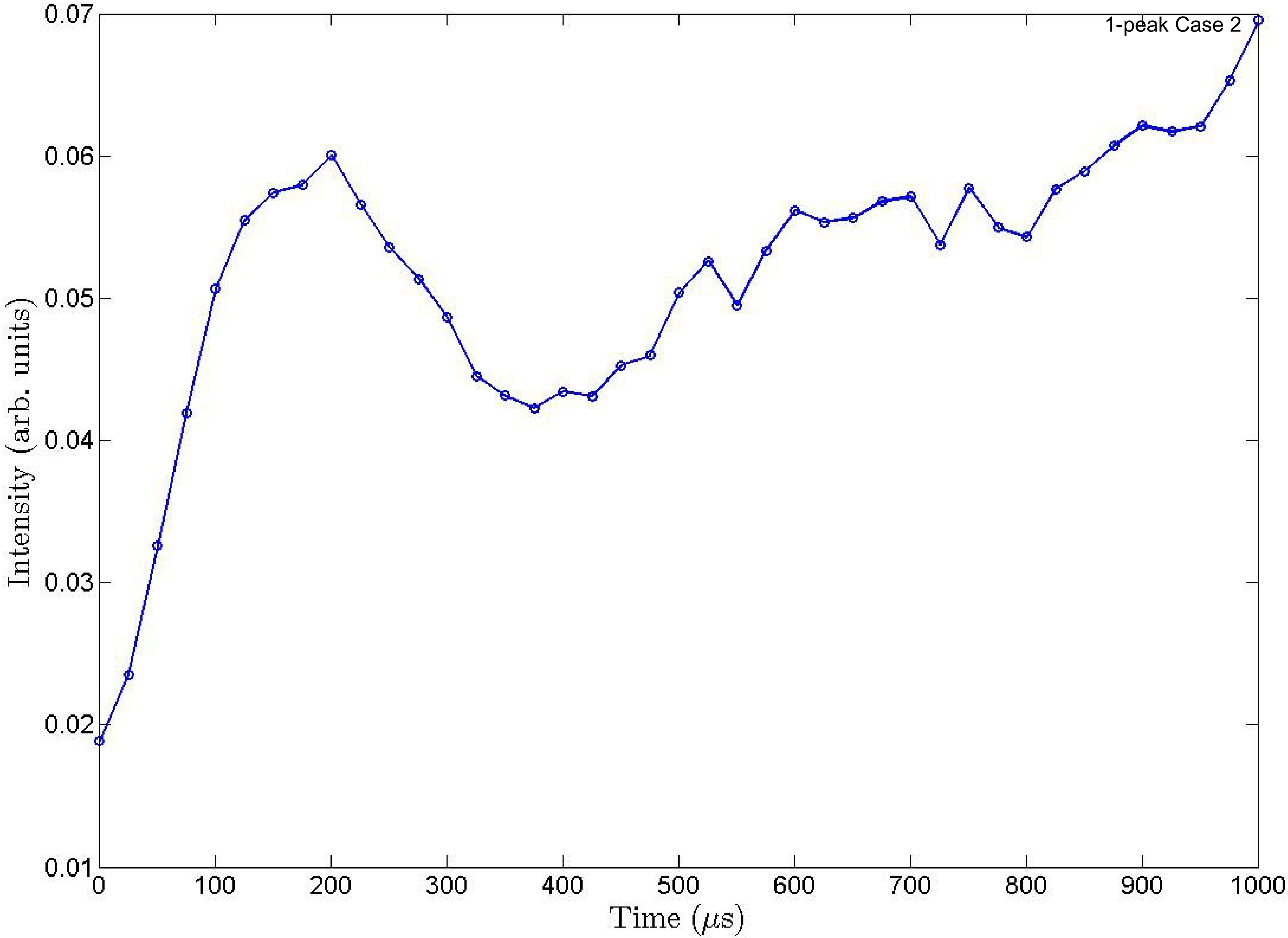

T=delay time between pulses

# Period vs frequency

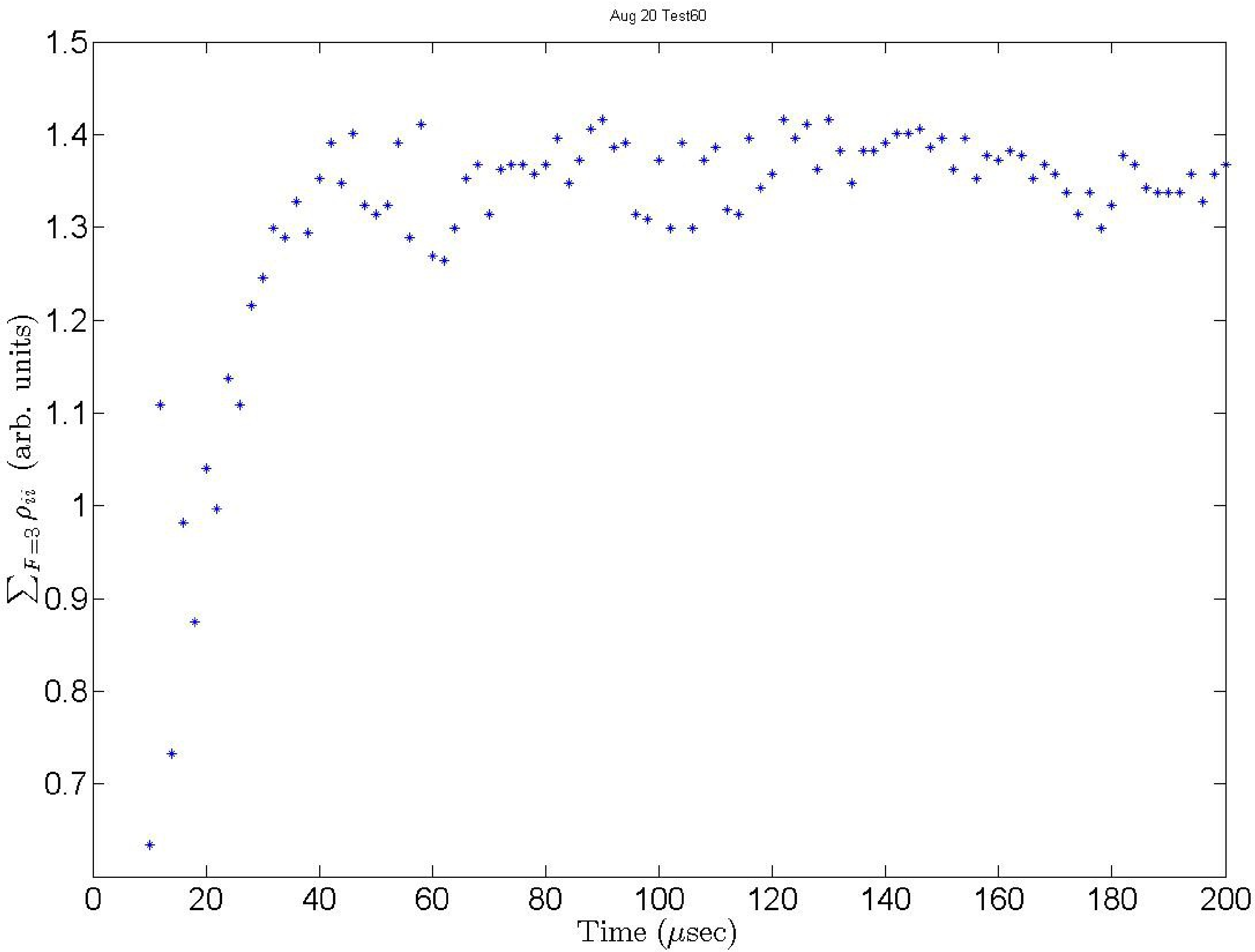
NAVAIR



# Rabi Cycling: +1 Peak (Expt.)

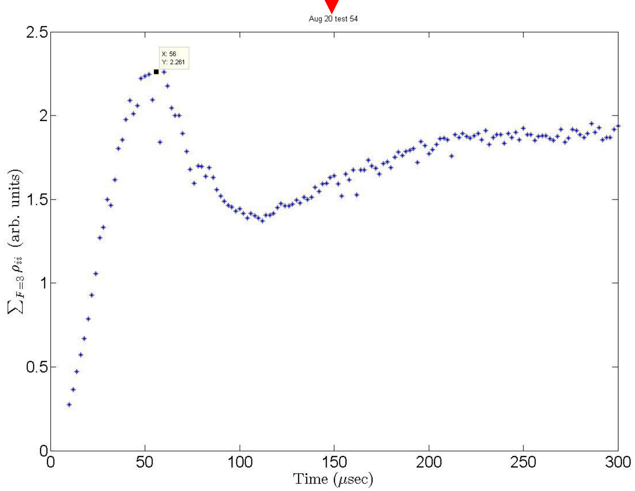


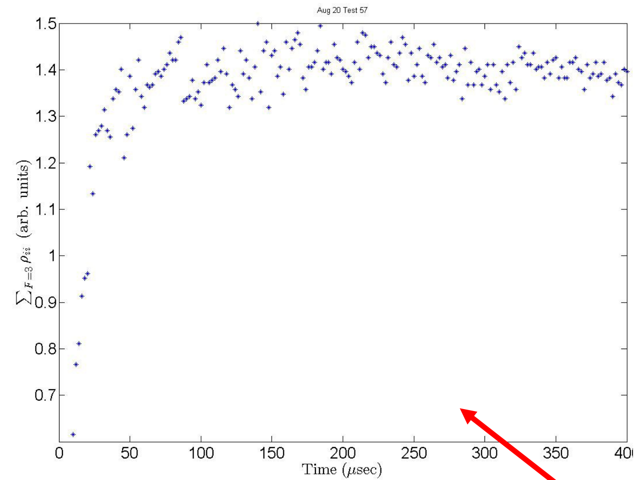
# Double Pulse on magnetic transition

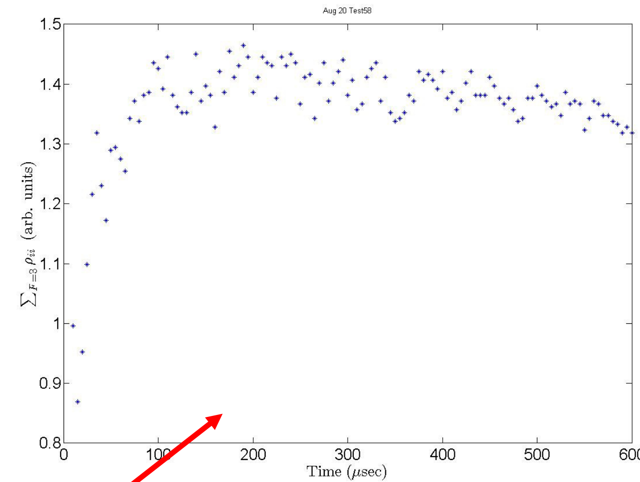



UVa
Nov 12, 2012

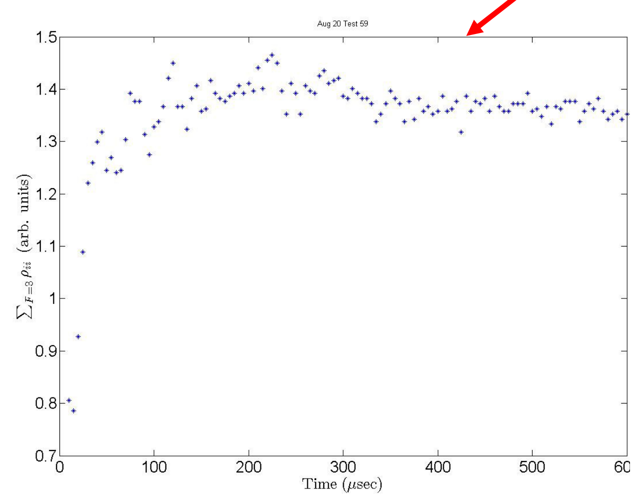
# Single Pulse

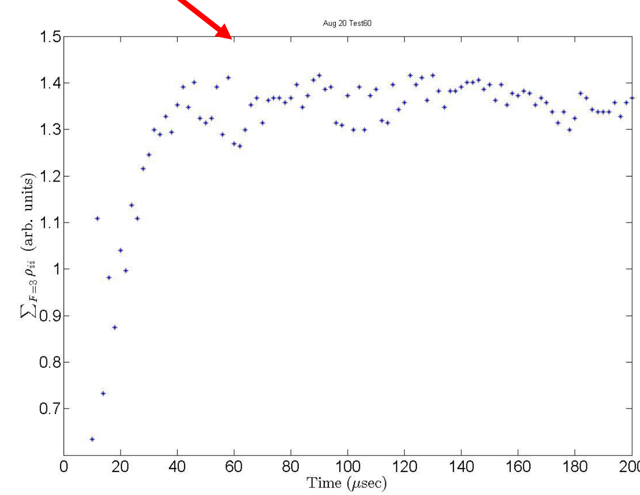


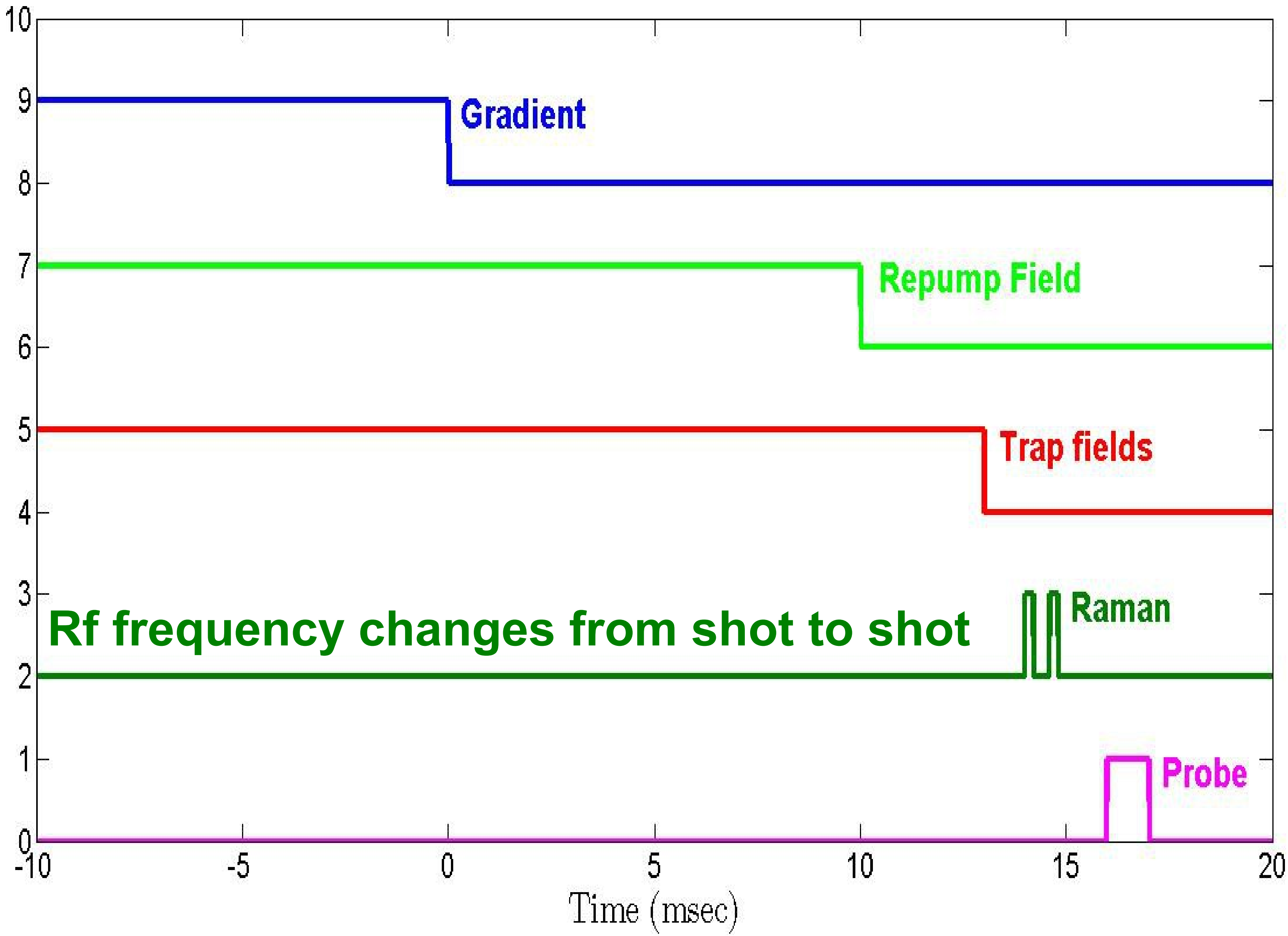

# Double Pulse



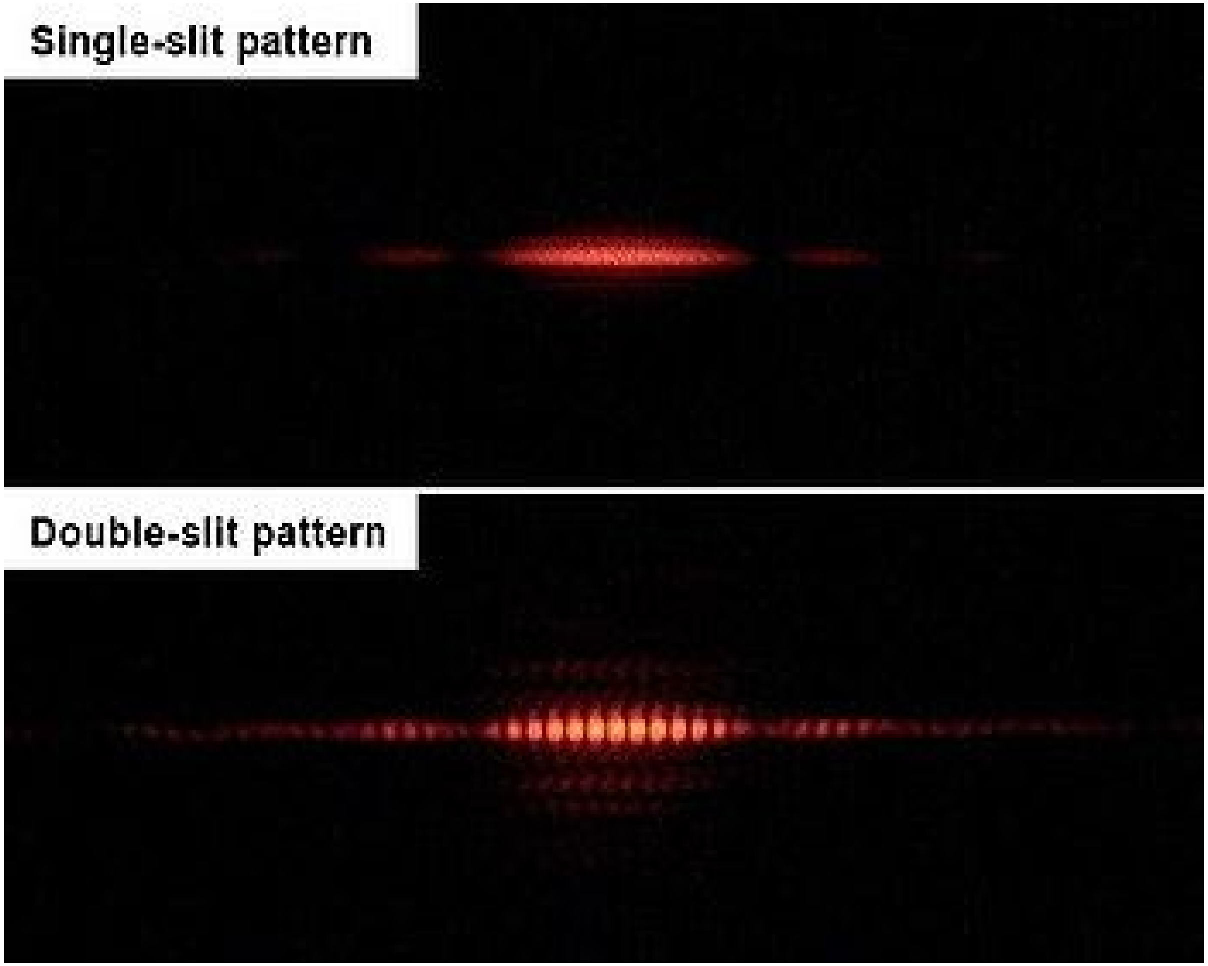



# Double Pulse Experiment (Ramsey) Frequency Domain

# Timing sequence

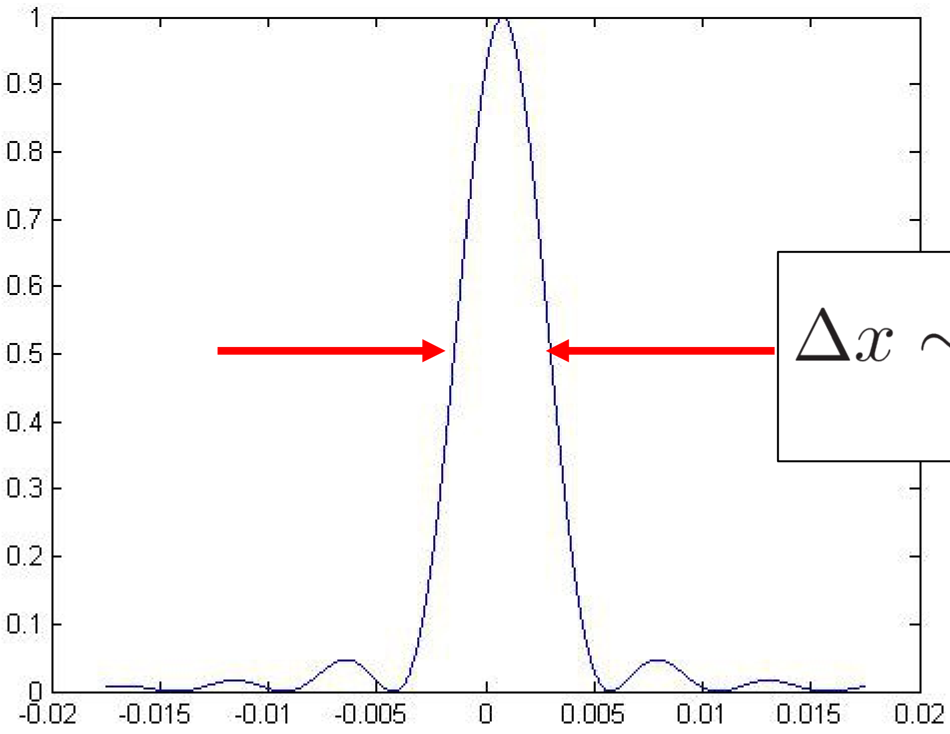


# Inspiration from optics/clocks



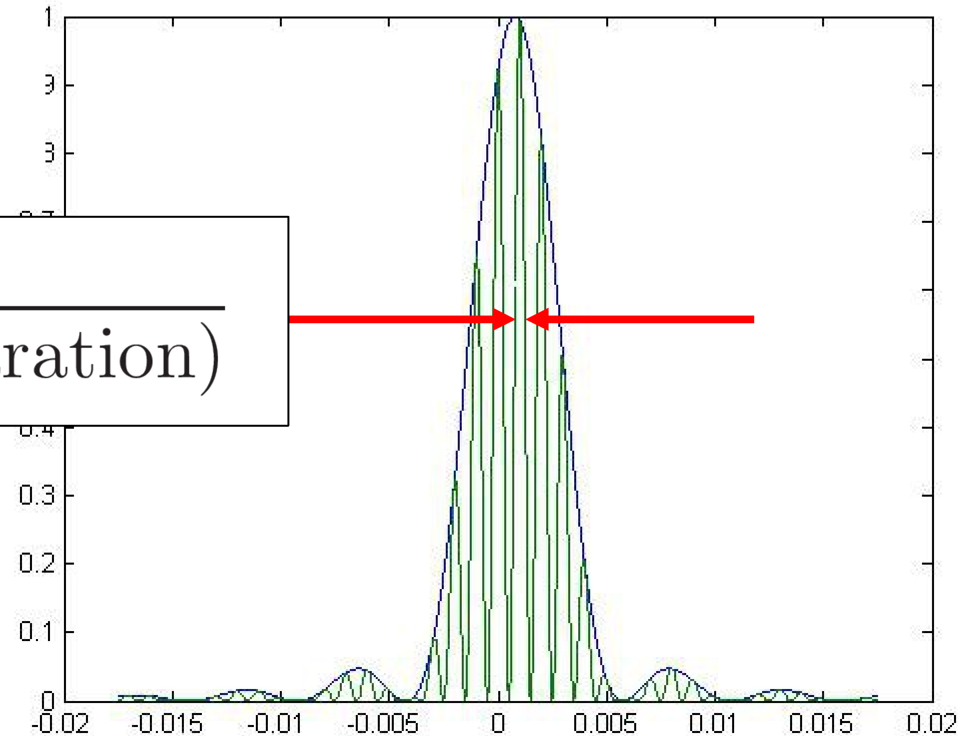

http://en.wikipedia.org/wiki/Double-slit_experiment

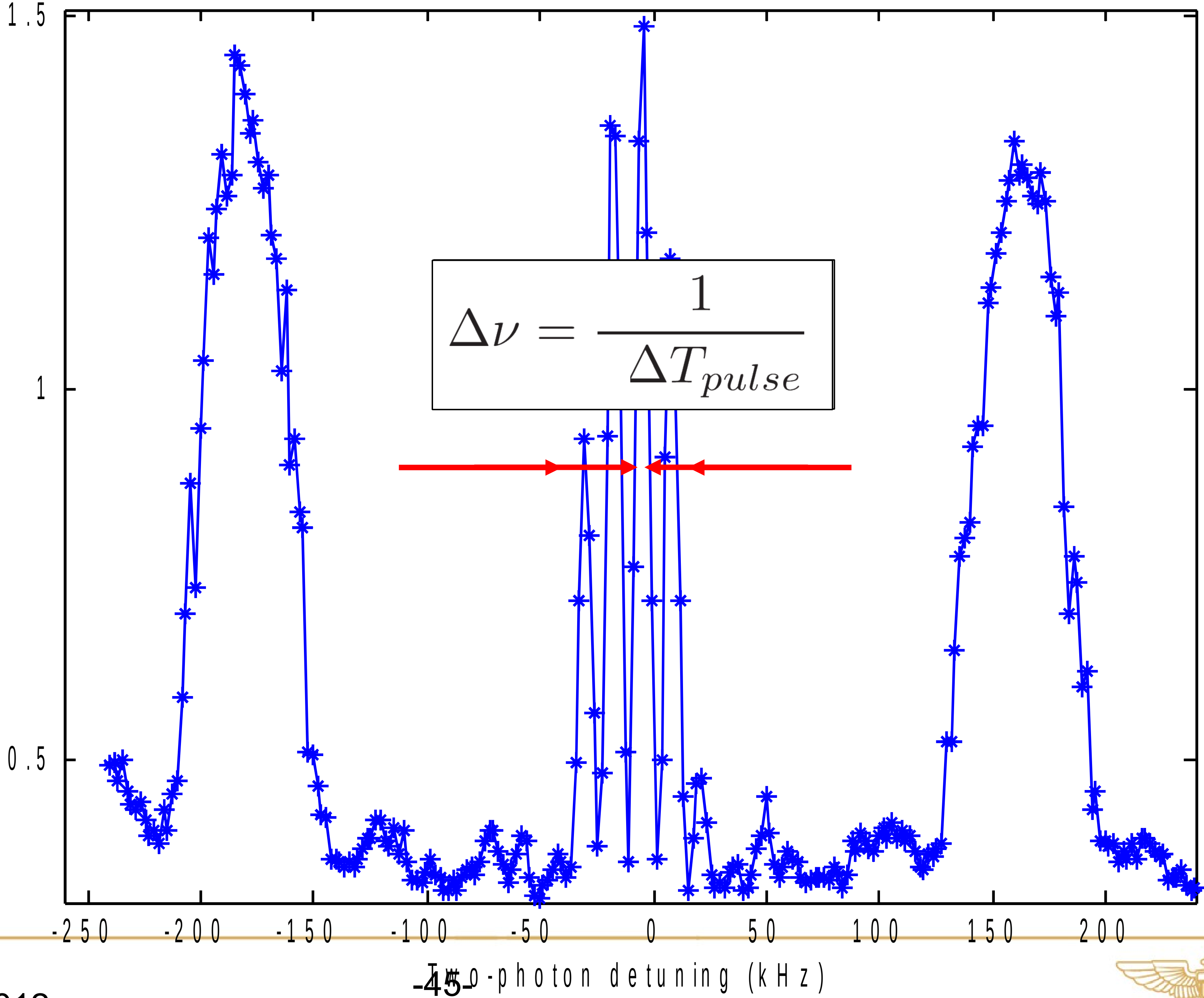
# Intensity profile

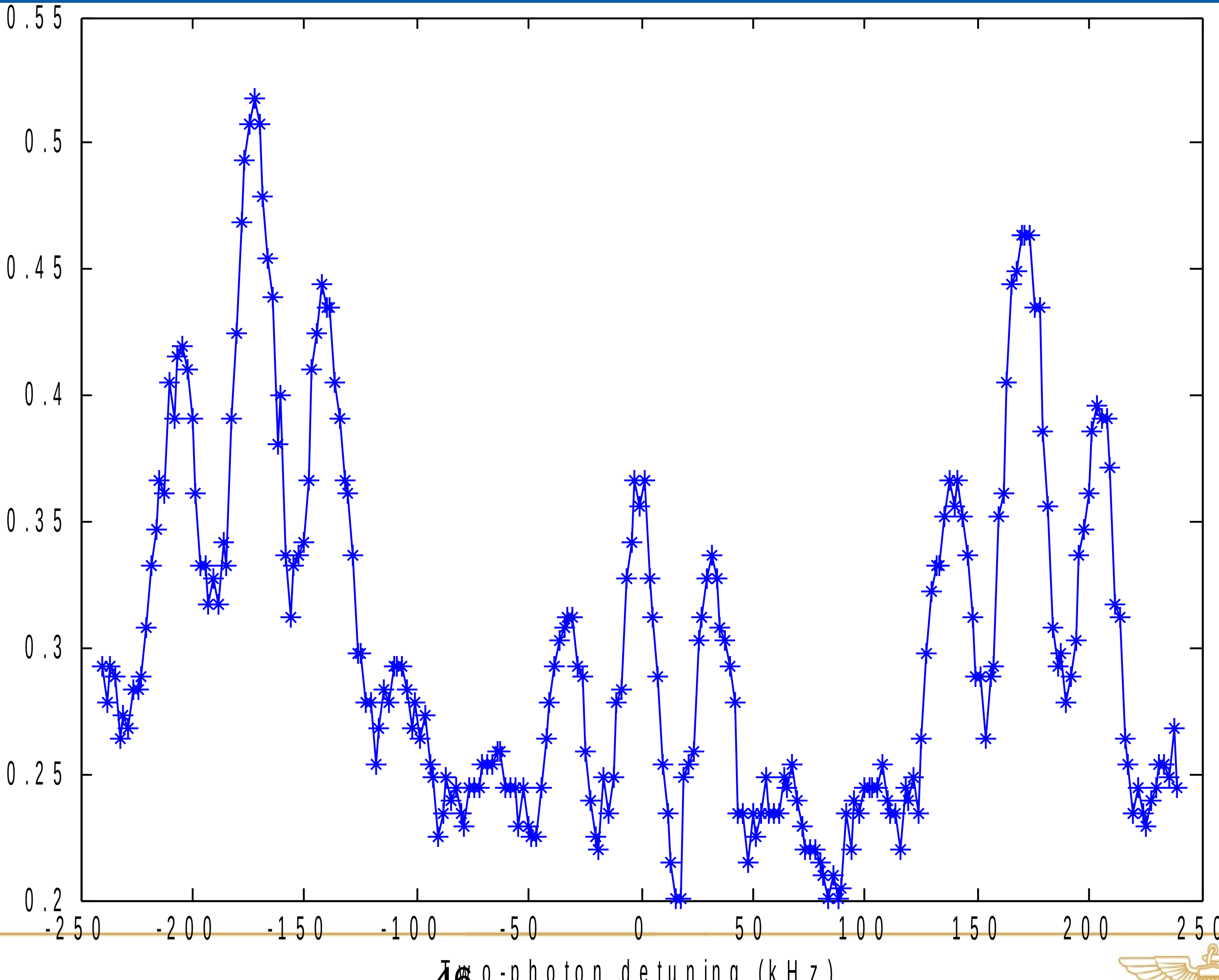


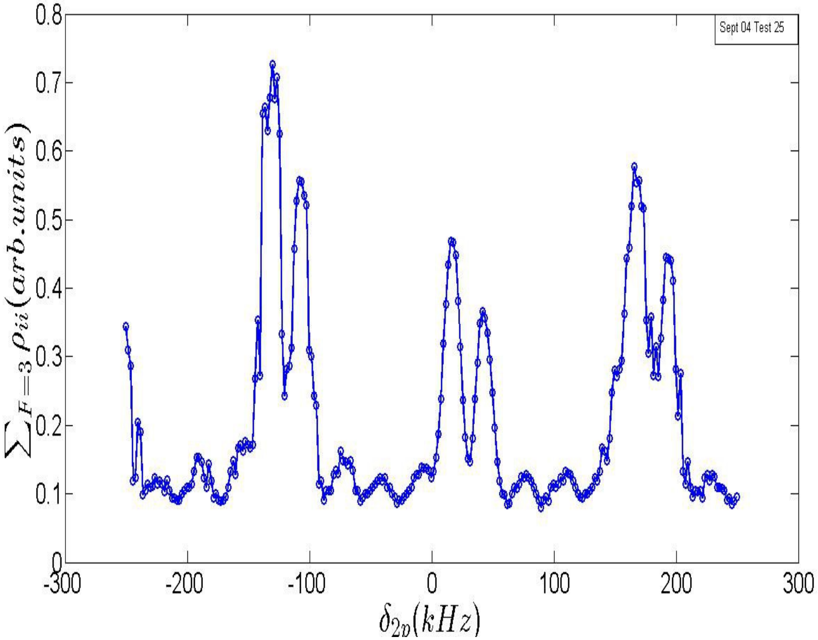

$$\Delta x \sim \frac{1}{2(\text{slit width})}$$

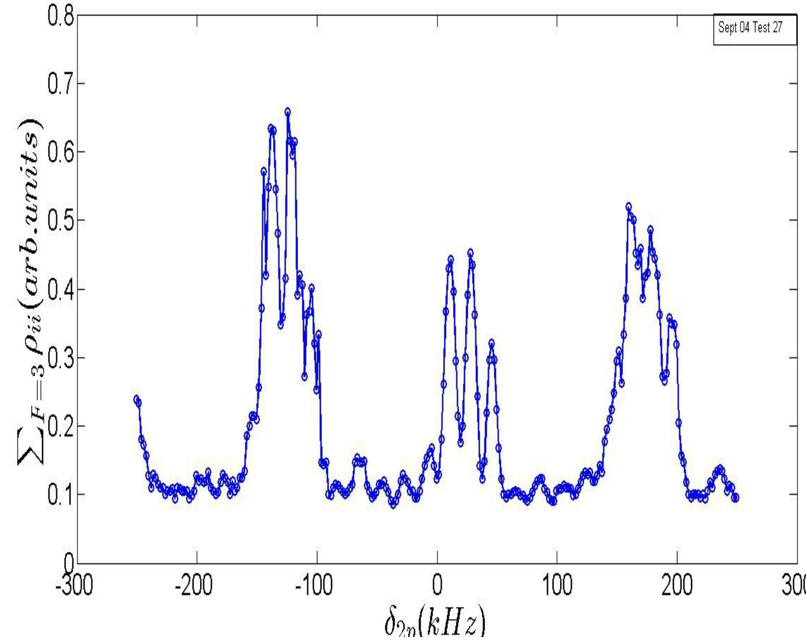
$$\Delta x \sim \frac{1}{2(\text{slit separation})}$$

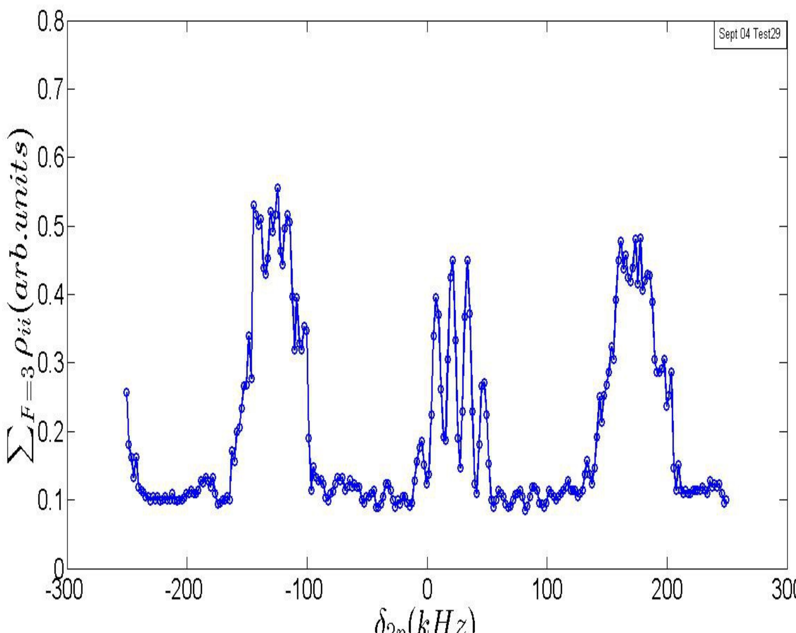


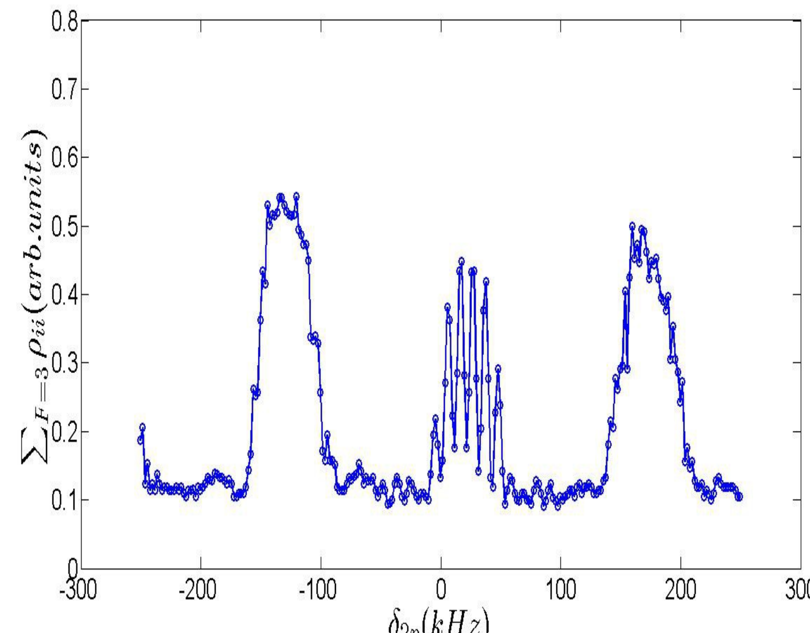

1.5
1
0.5
-250
-200
-150
-100
-50
0
50
100
150
200
Two-photon detuning (kHz)
$\Delta\nu = \dfrac{1}{\Delta T_{pulse}}$

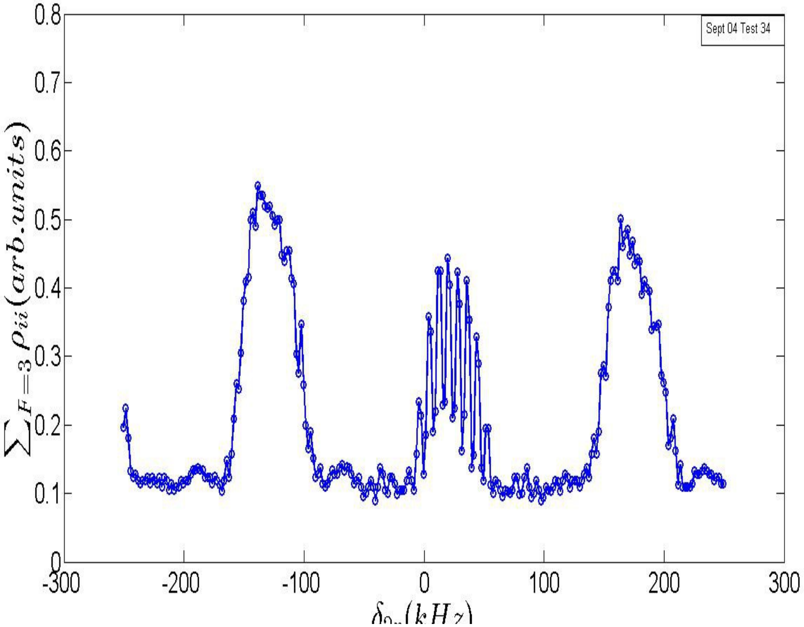

0.55
0.5
0.45
0.4
0.35
0.3
0.25
0.2
-250
-200
-150
-100
-50
0
50
100
150
200
250
Two-photon detuning (kHz)

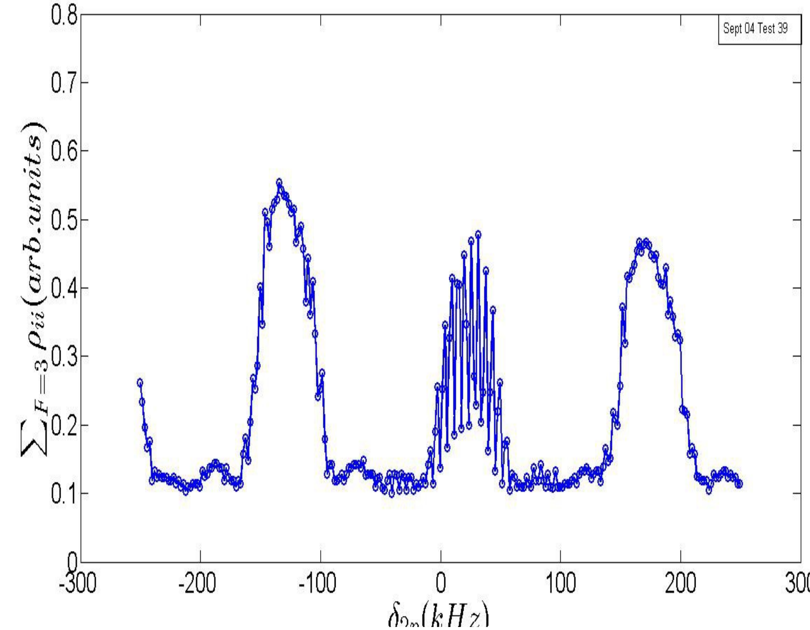

Sept 04 Test 25
$\sum_{F=3}\rho_{ii}(arb.units)$
$\delta_{2p}(kHz)$

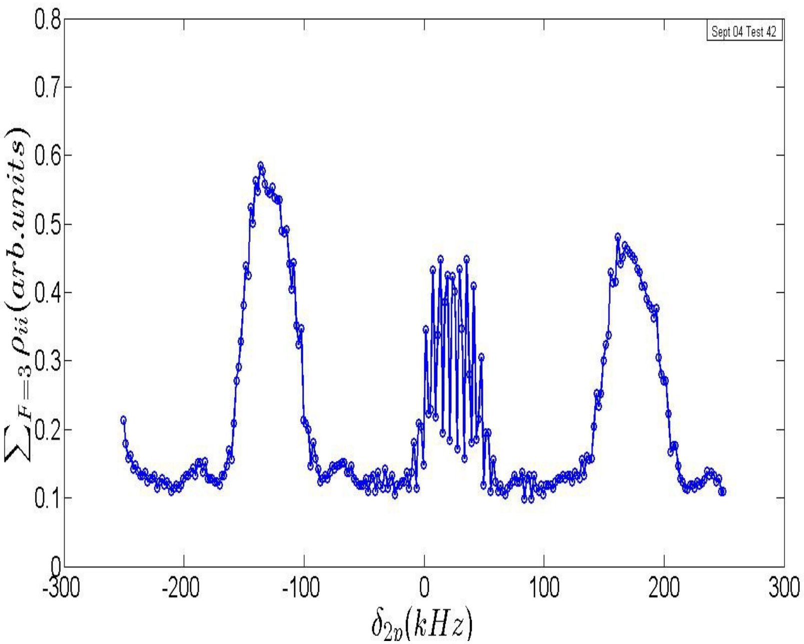

Sept 04 Test 27
$\sum_{F=3}\rho_{ii}(arb.units)$
$\delta_{2p}(kHz)$

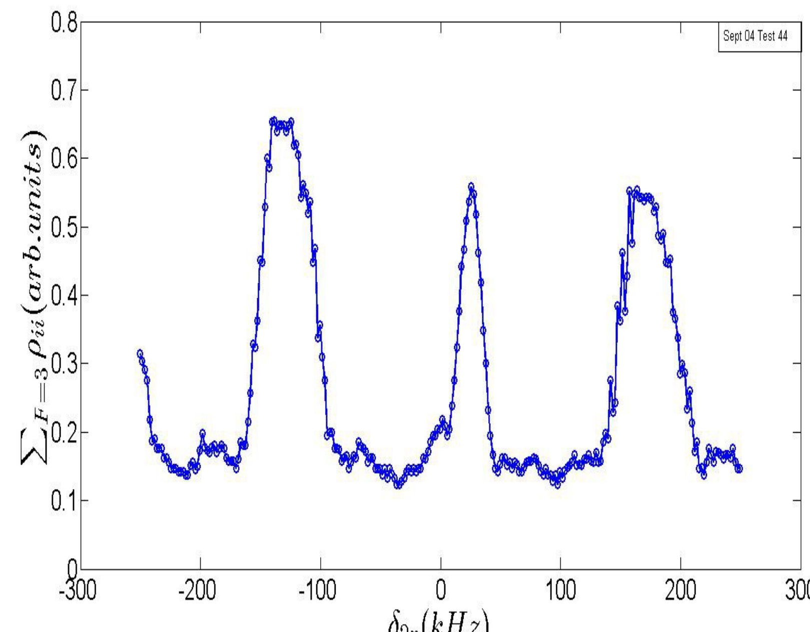

Sept 04 Test29
$\sum_{F=3}\rho_{ii}(arb.units)$
$\delta_{2p}(kHz)$


$\sum_{F=3}\rho_{ii}(arb.units)$
$\delta_{2p}(kHz)$


Sept 04 Test 34
$\sum_{F=3} \rho_{ii}(arb.units)$
$\delta_{2v}(kHz)$
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
-300
-200
-100
0
100
200
300

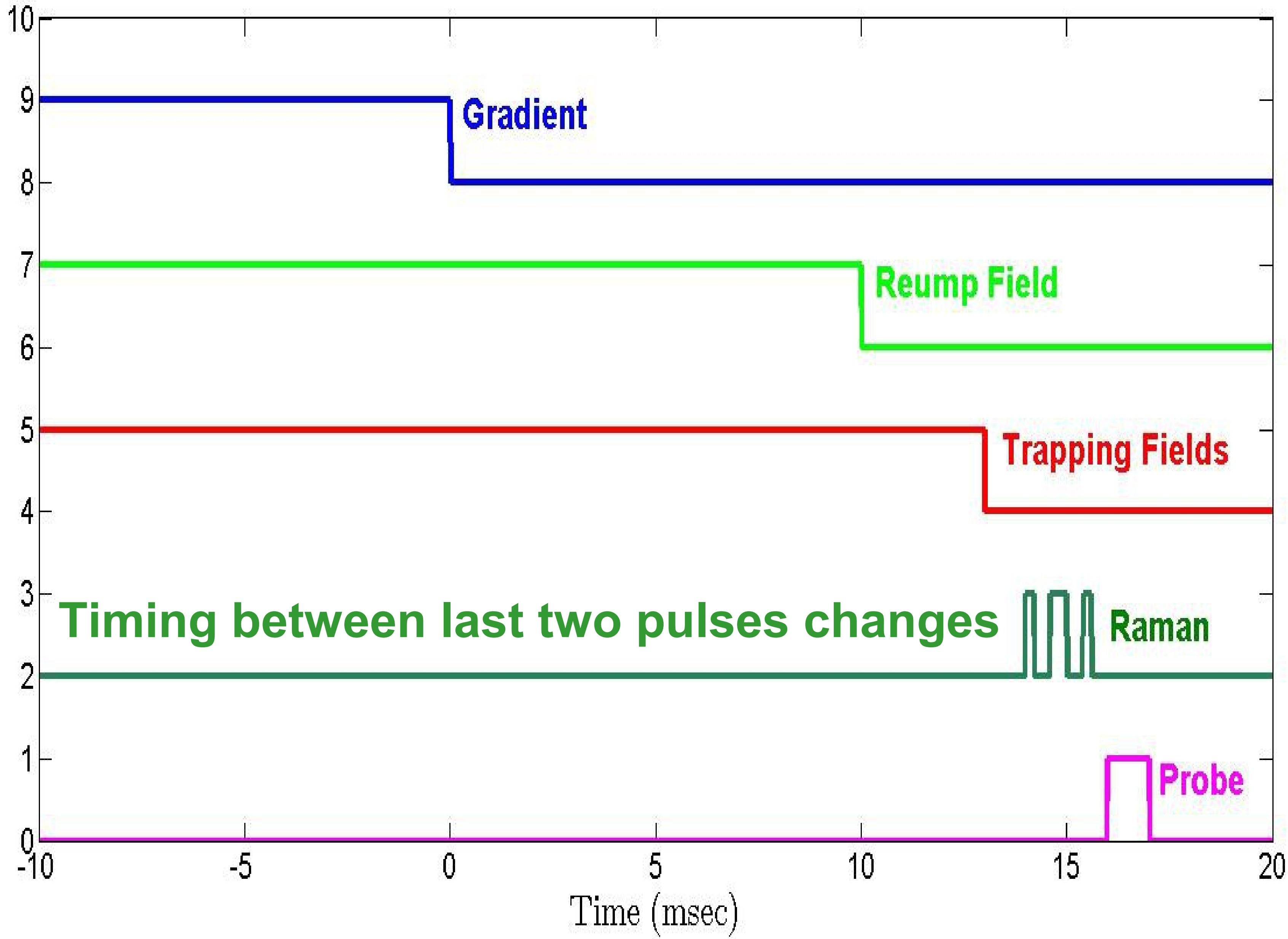

Sept 04 Test 39
$\sum_{F=3} \rho_{ii}(arb.units)$
$\delta_{2v}(kHz)$
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
-300
-200
-100
0
100
200
300

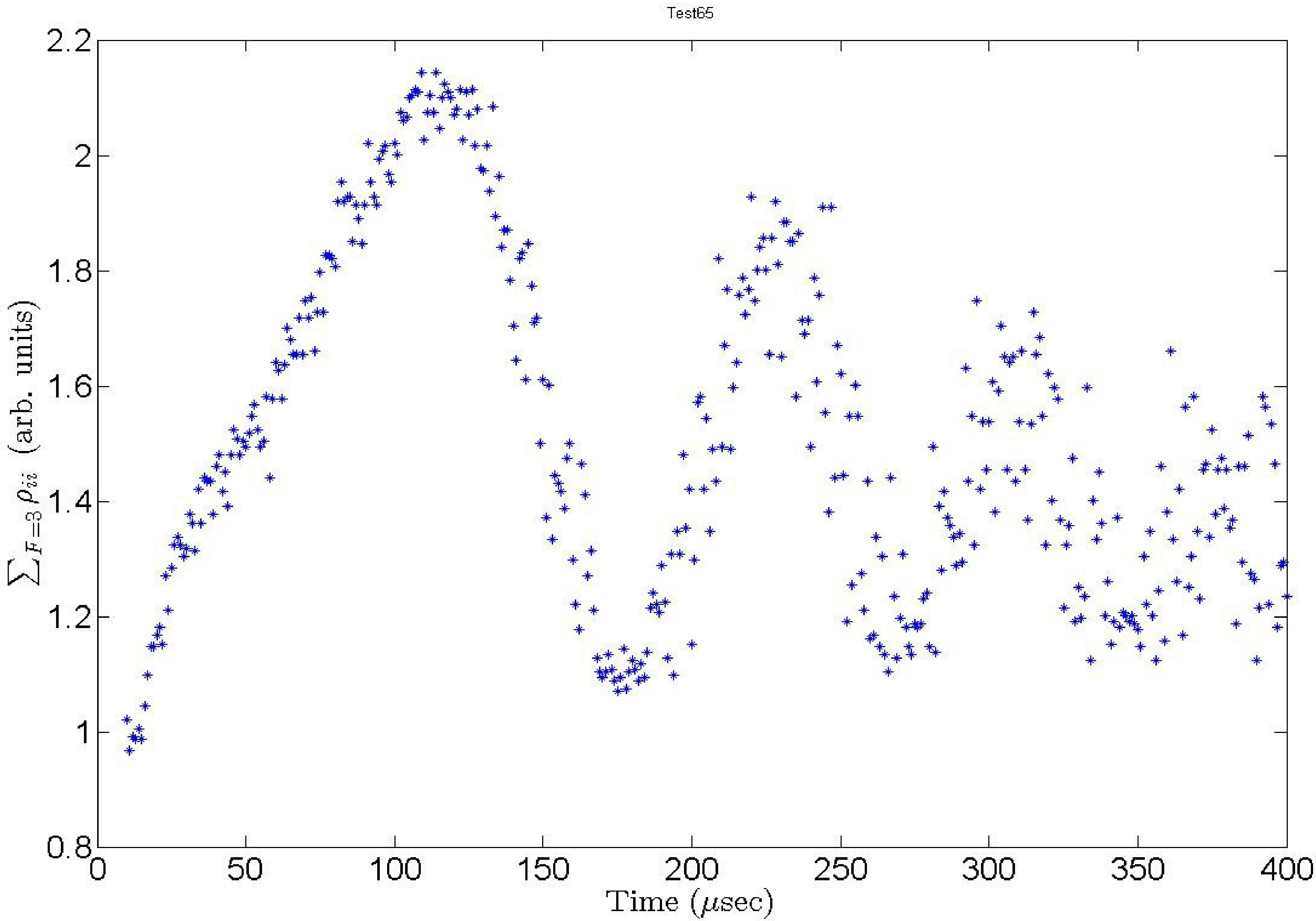

Sept 04 Test 42
$\sum_{F=3} \rho_{ii}(arb.units)$
$\delta_{2v}(kHz)$
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
-300
-200
-100
0
100
200
300


Sept 04 Test 44
$\sum_{F=3} \rho_{ii}(arb.units)$
$\delta_{2v}(kHz)$
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
-300
-200
-100
0
100
200
300

Triple Pulse Experiment
Time Domain

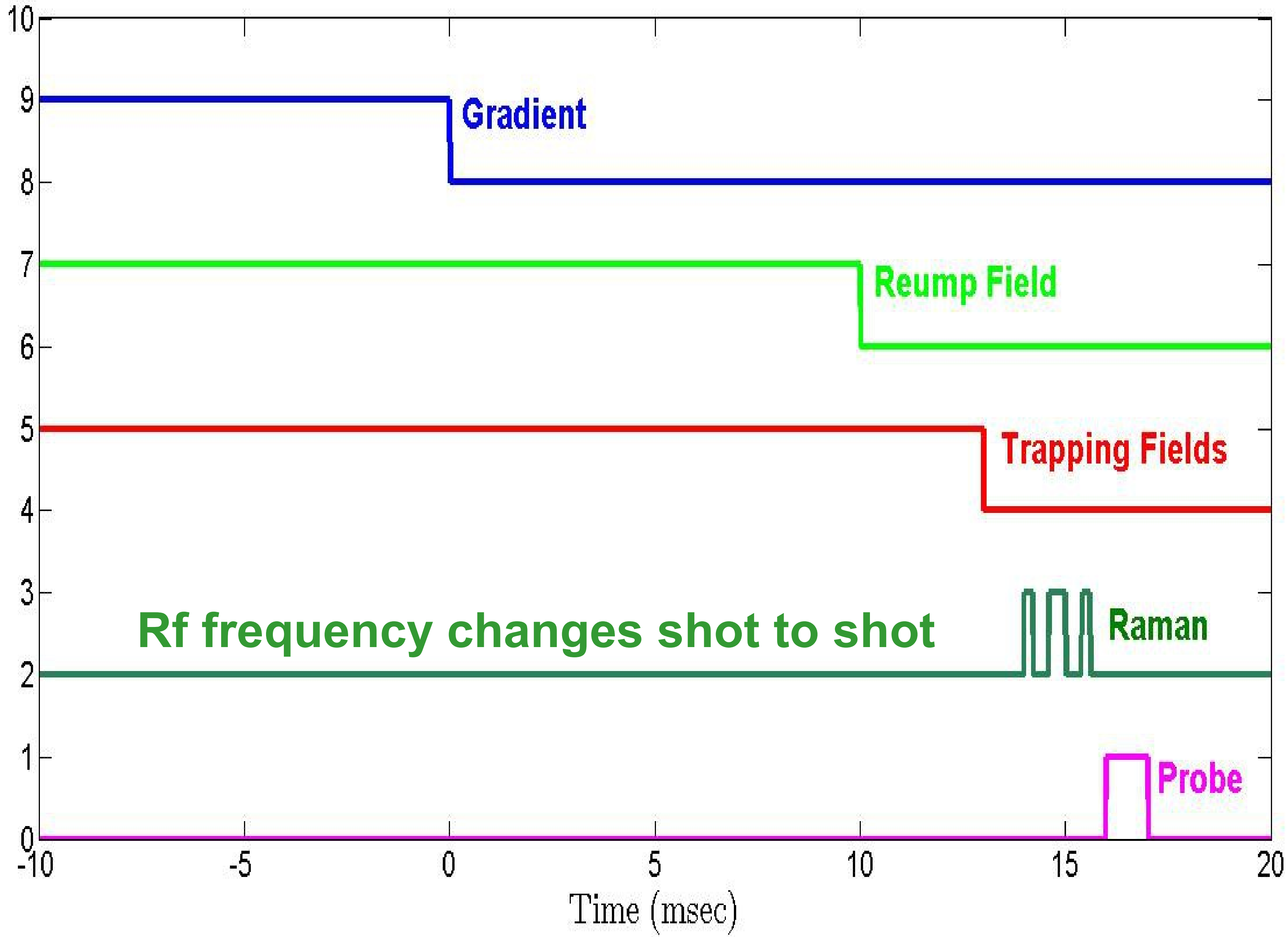
# Timing sequence

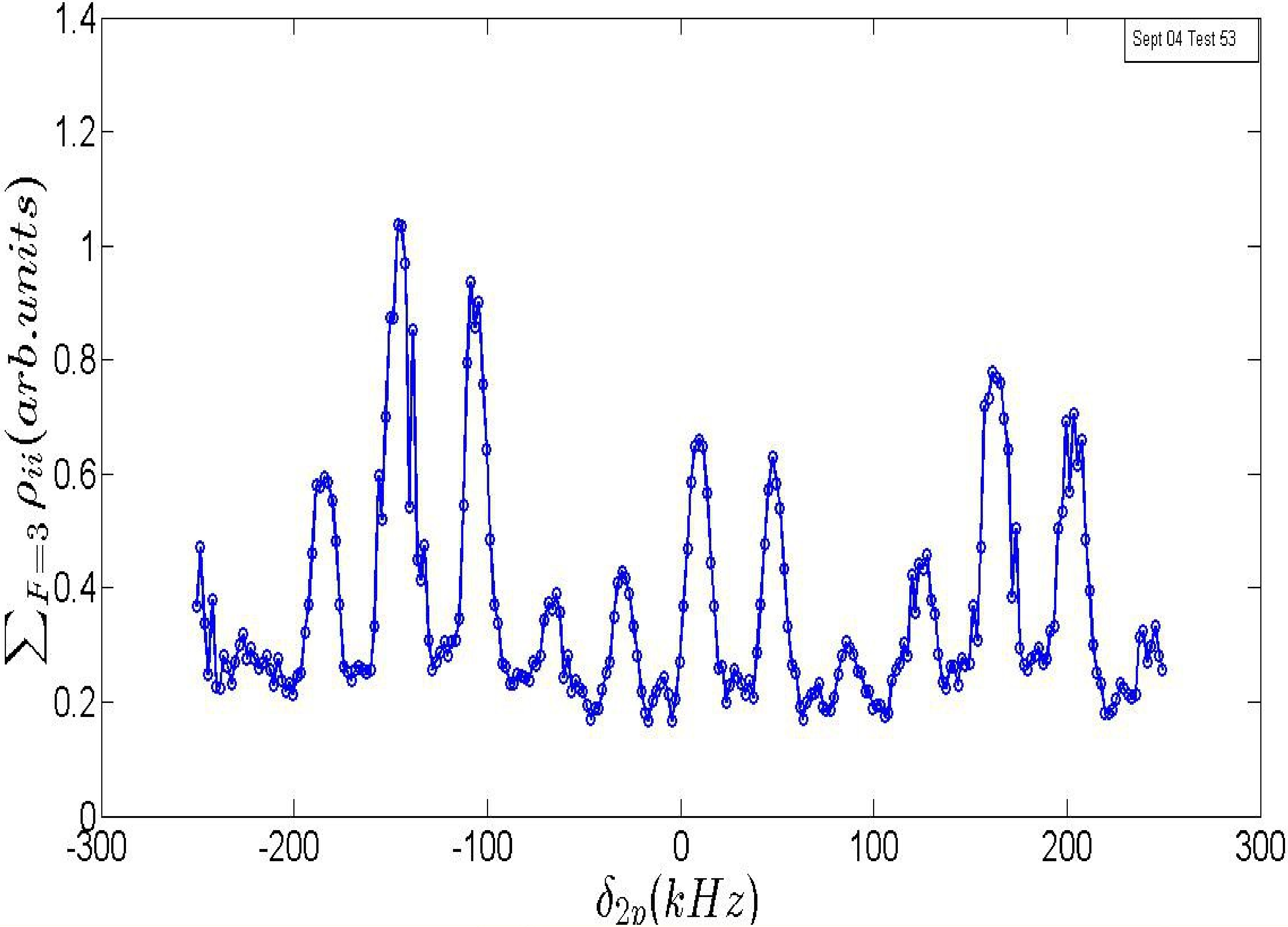



Test65
2.2
2
1.8
1.6
1.4
1.2
1
0.8
0
50
100
150
200
250
300
350
400
Time ($\mu$sec)
$\sum_{F=3} \rho_{ii}$ (arb. units)

# Triple Pulse Experiment
# Frequency Domain

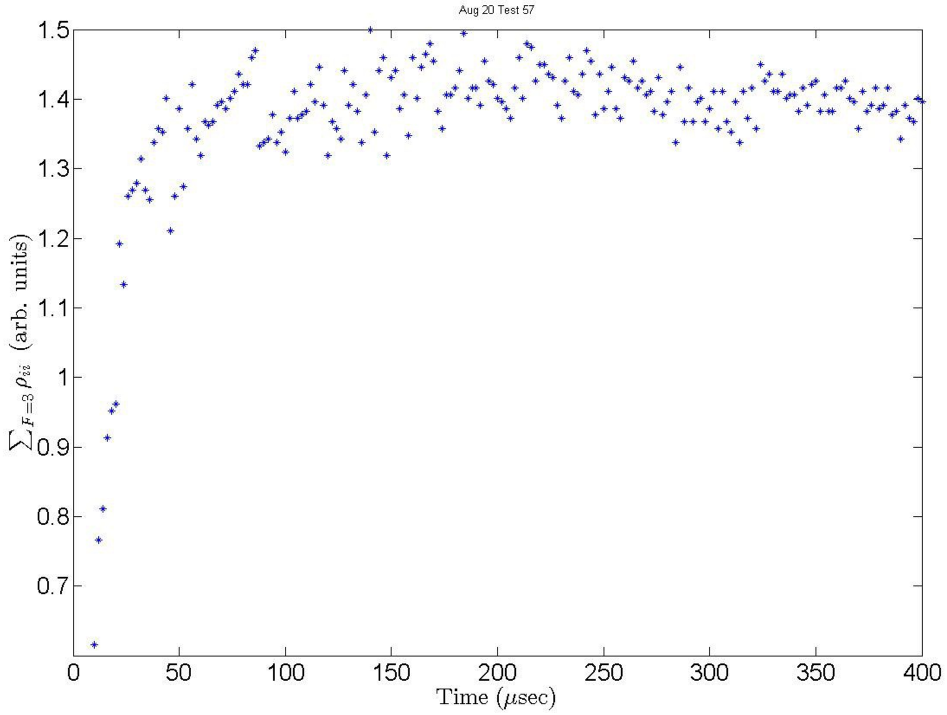
# Timing sequence

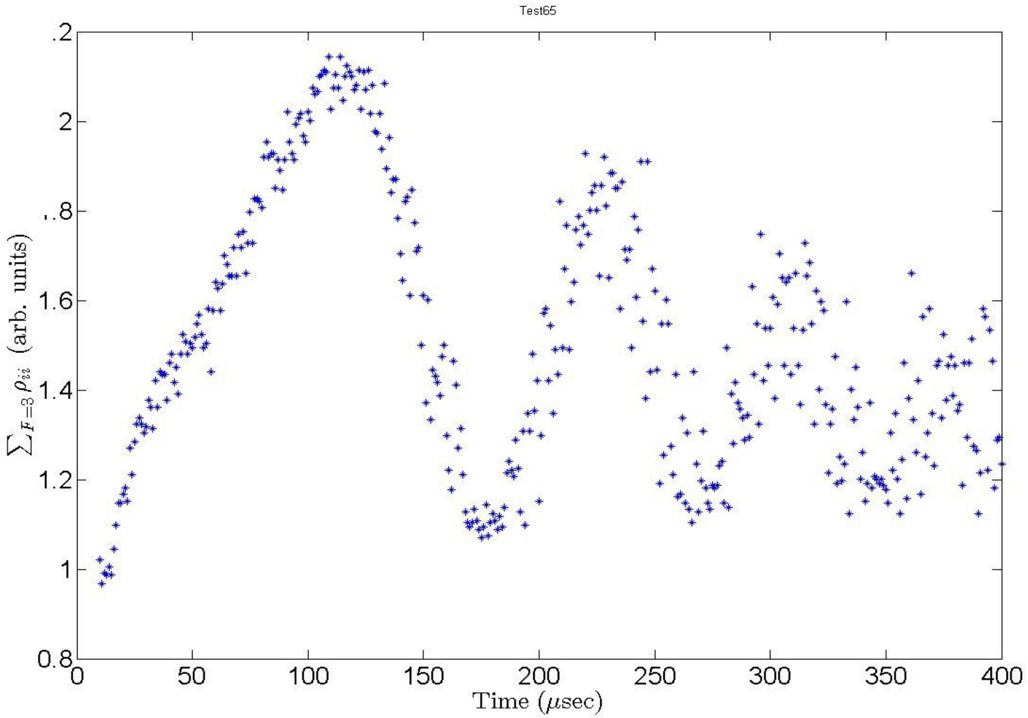




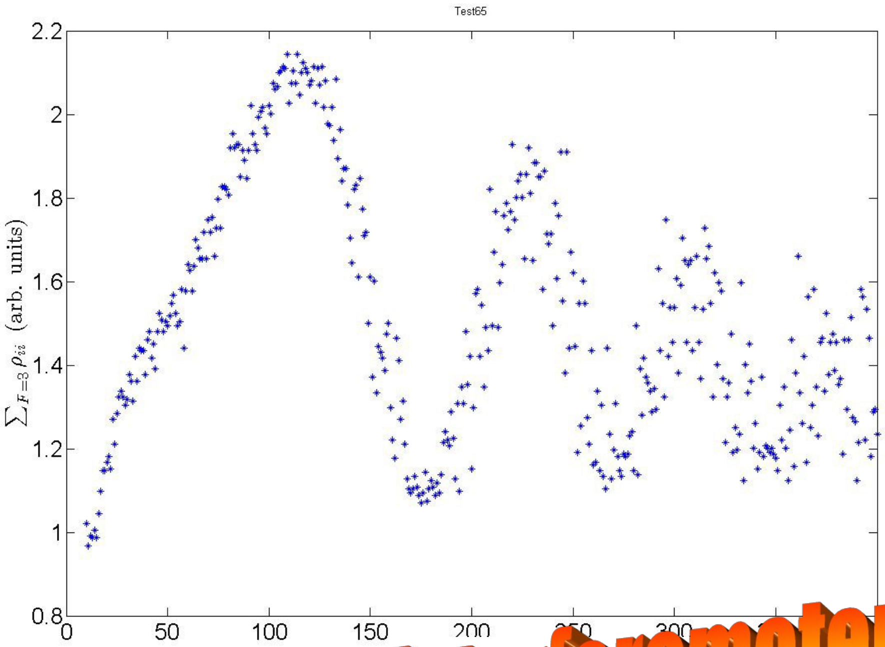

UVa
Nov 12, 2012

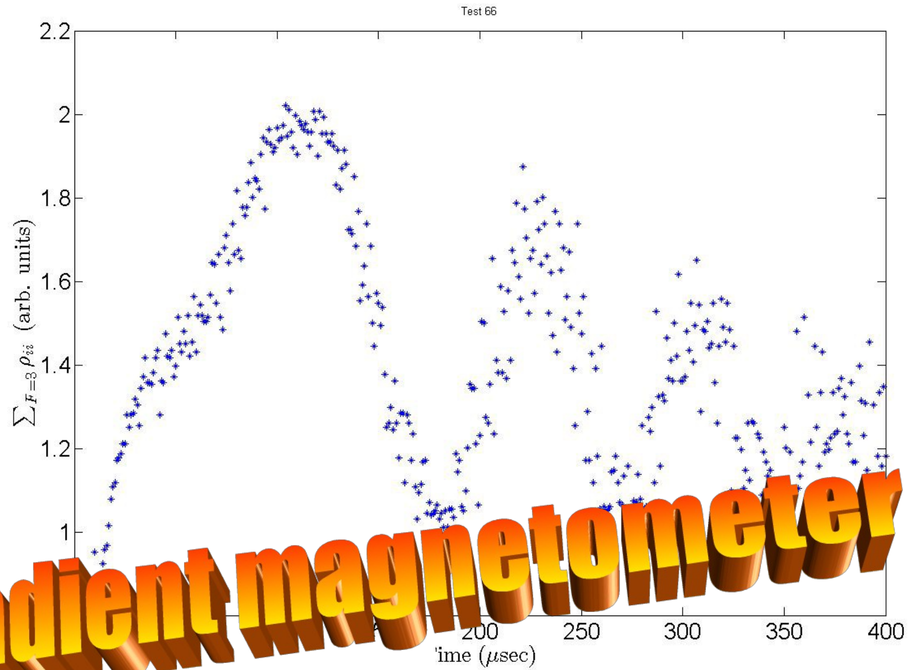
# Evidence of gradiometer



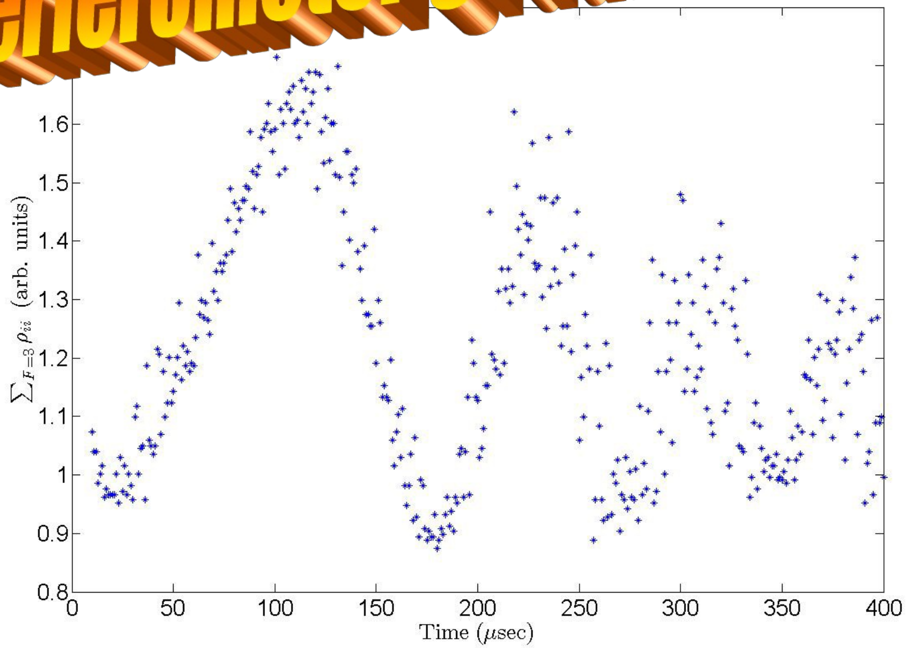



# Similar Bfield –changing spatial gradient

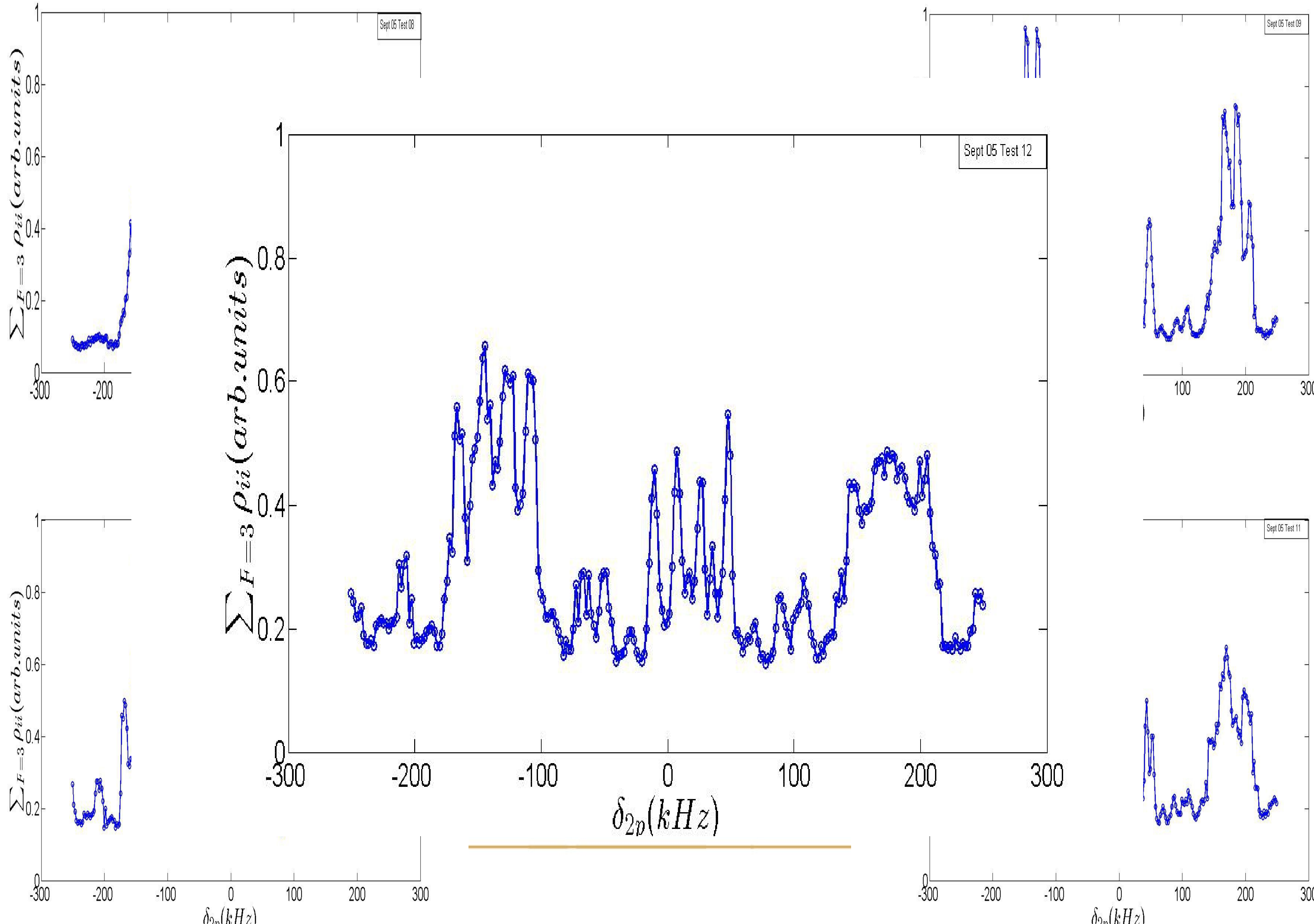



An atom interferometer gradient magnetometer



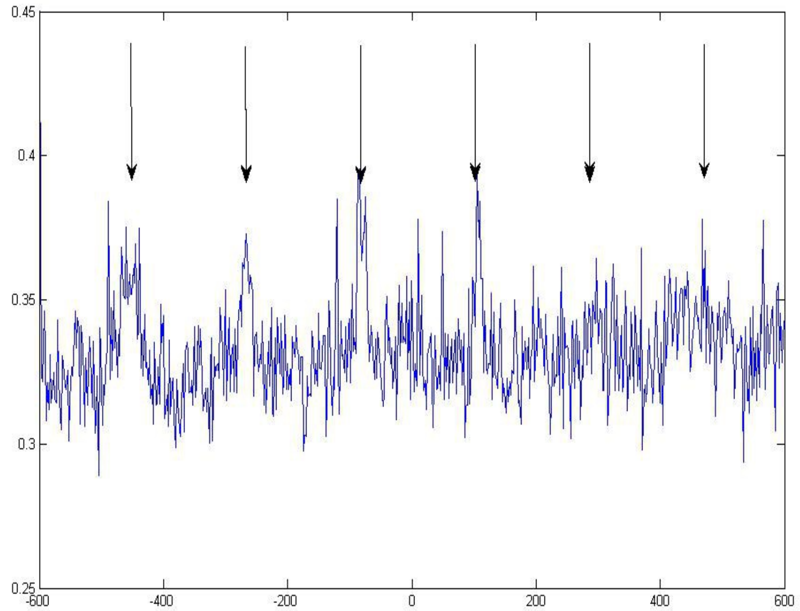
# Just for fun…..

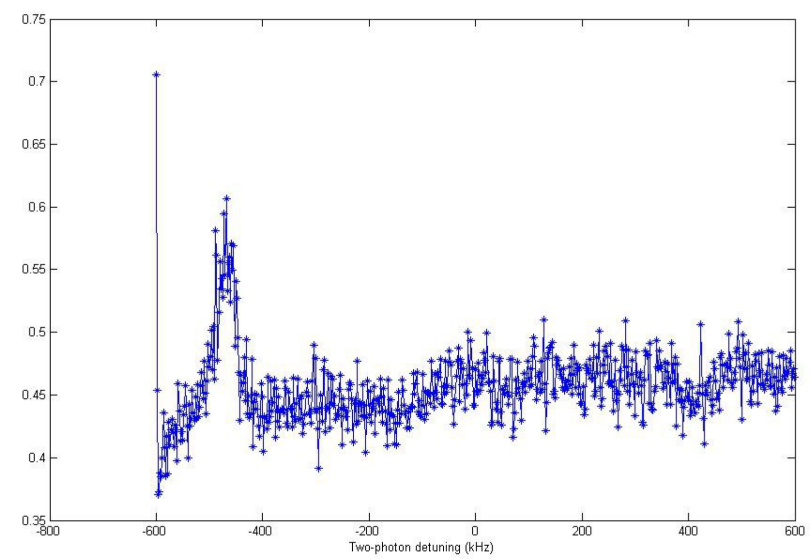

Sept 05 Test 08
Sept 05 Test 09
Sept 05 Test 11
Sept 05 Test 12
$\sum_{F=3} \rho_{ii}(arb.units)$
$\delta_{2p}(kHz)$
0
0.2
0.4
0.6
0.8
1
-300
-200
-100
0
100
200
300

# Work to be done….

- Systematic measurement of output vs.
  - Magnetic field
  - Gradient magnetic field
- Atom fountain arrangement
- Sensitivity

# Optical pumping



# Conclusions

- Single Pulse
  - Time Domain
  - Frequency Domain
- Double Pulse
  - Time Domain
  - Frequency Domain
- Triple Pulse
  - Time Domain
  - Frequency Domain

→ Single Slit

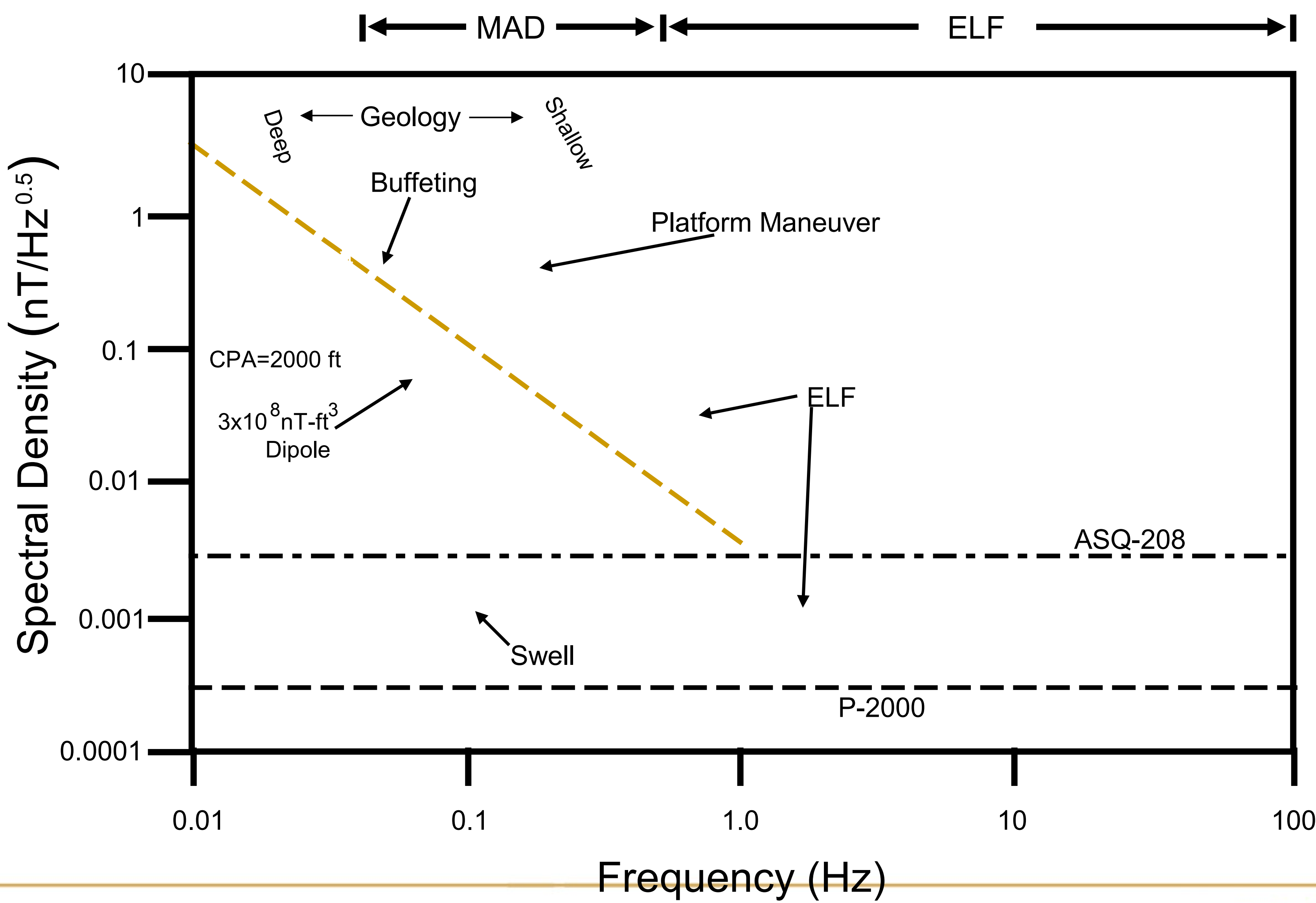
Double Slit

"Demonstration" of a gradient magnetometer atom interferometer

# Questions?

# Noises

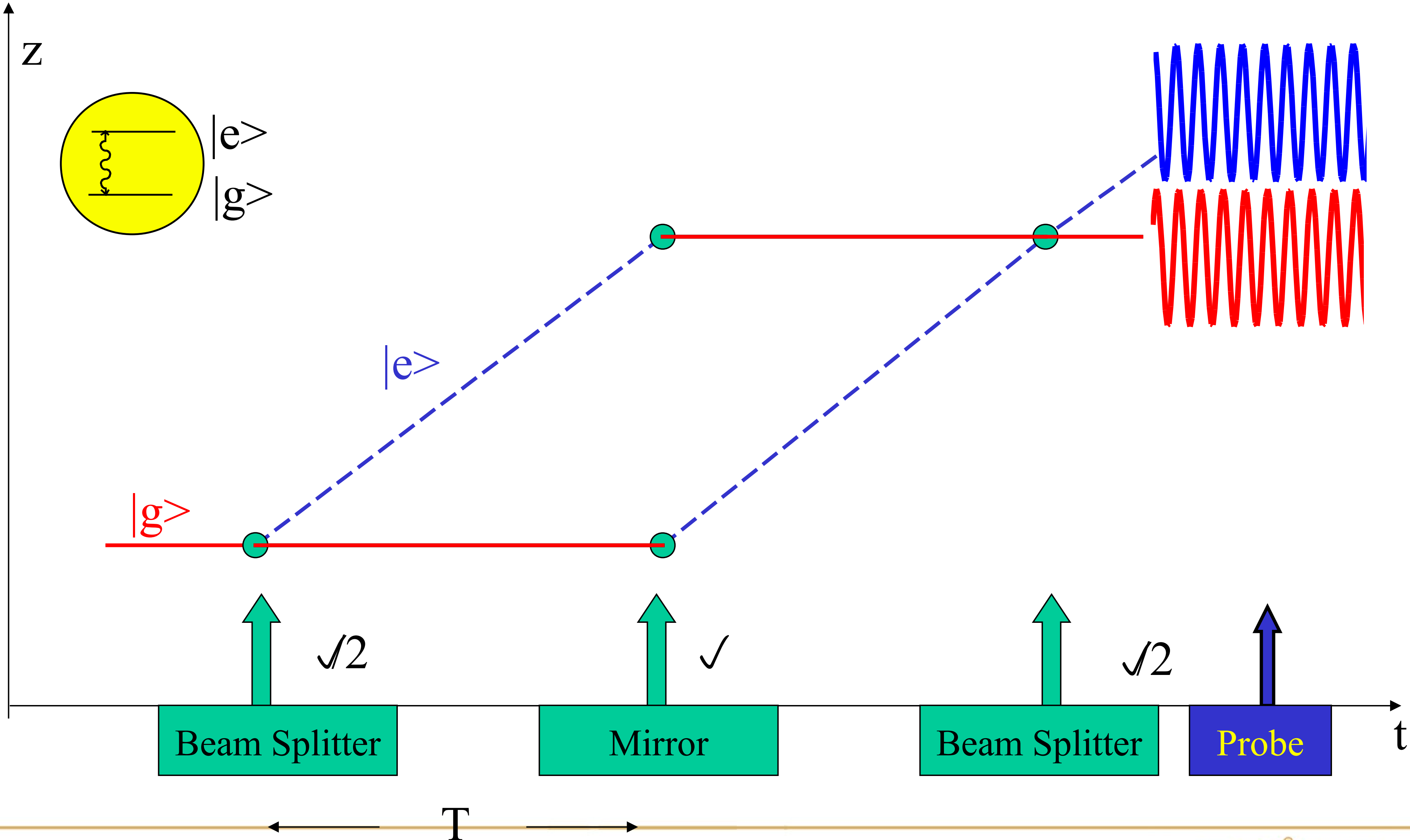
## Gradiometers can remove distant noise



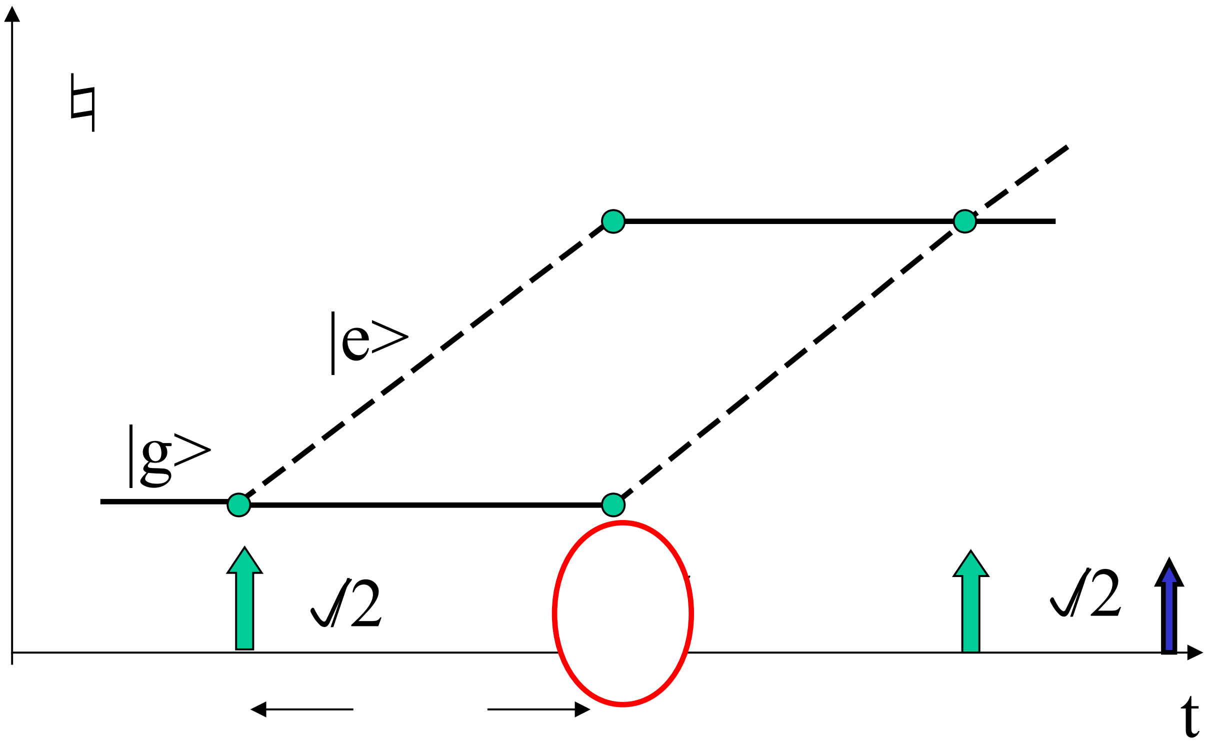

UVa
Nov 12, 2012

# Technical Overview of AI sensors

$$|c_{e,p+\hbar k}(2T+\tau)|^2 = \frac{1}{2}[1-\cos(\Delta\phi - \delta\tau/2)]$$



# State-space interferometer




- Co-propagating Raman beams for Doppler-free, acceleration free configuration
- Coherent superposition of magnetic sublevels

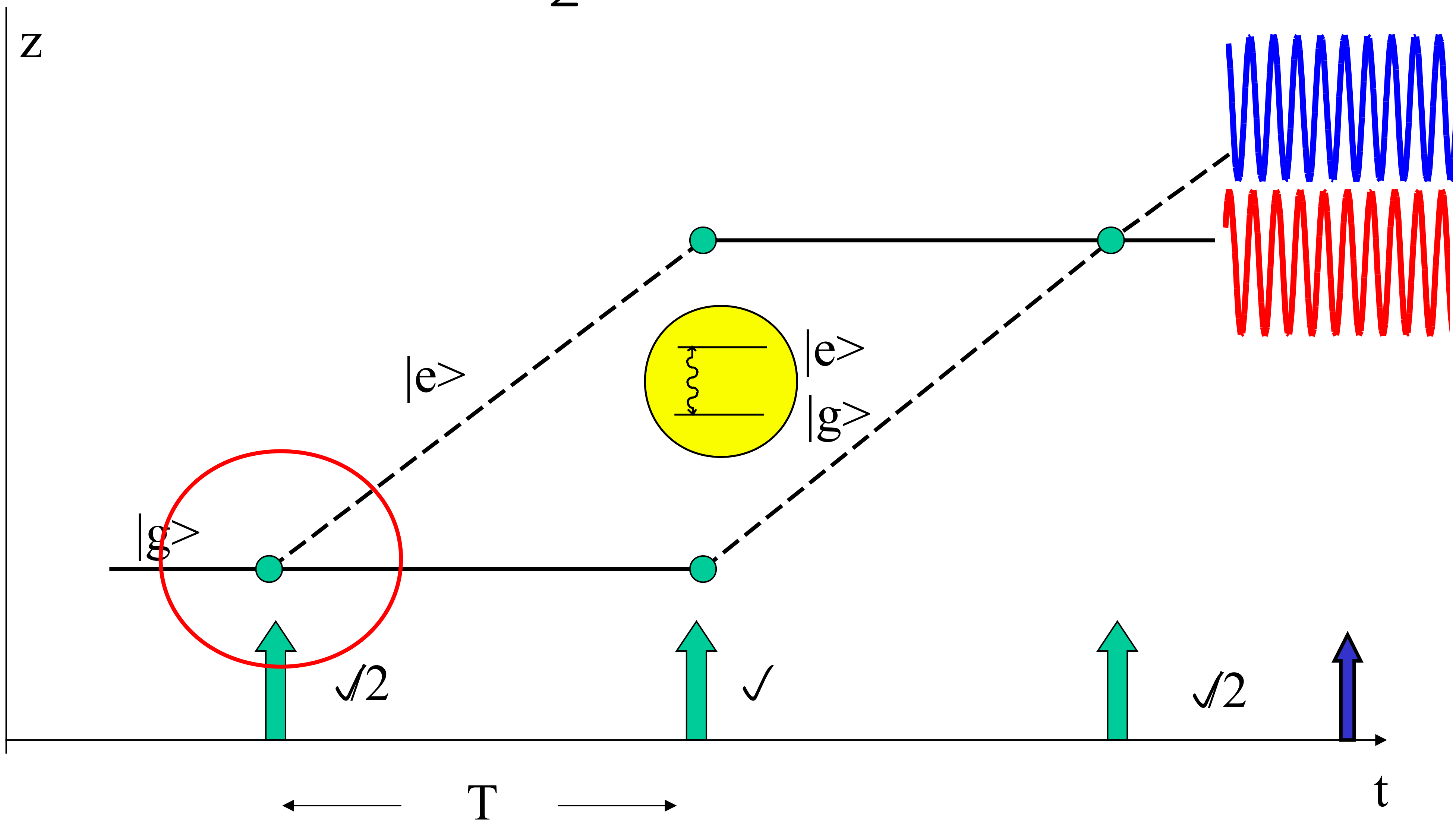
$$\Delta\phi = \frac{\Delta S}{\hbar} = \frac{\mu_B}{\hbar}\left(g_{F'}m_{F'} - g_F m_F\right)\left(\frac{\partial B}{\partial z}\right) v_o T^2$$

$$= \frac{\mu_B}{\hbar}\left(g_{F'}m_{F'} - g_F m_F\right)\left(\frac{\partial B}{\partial z}\right) \frac{\Delta z}{2} T$$

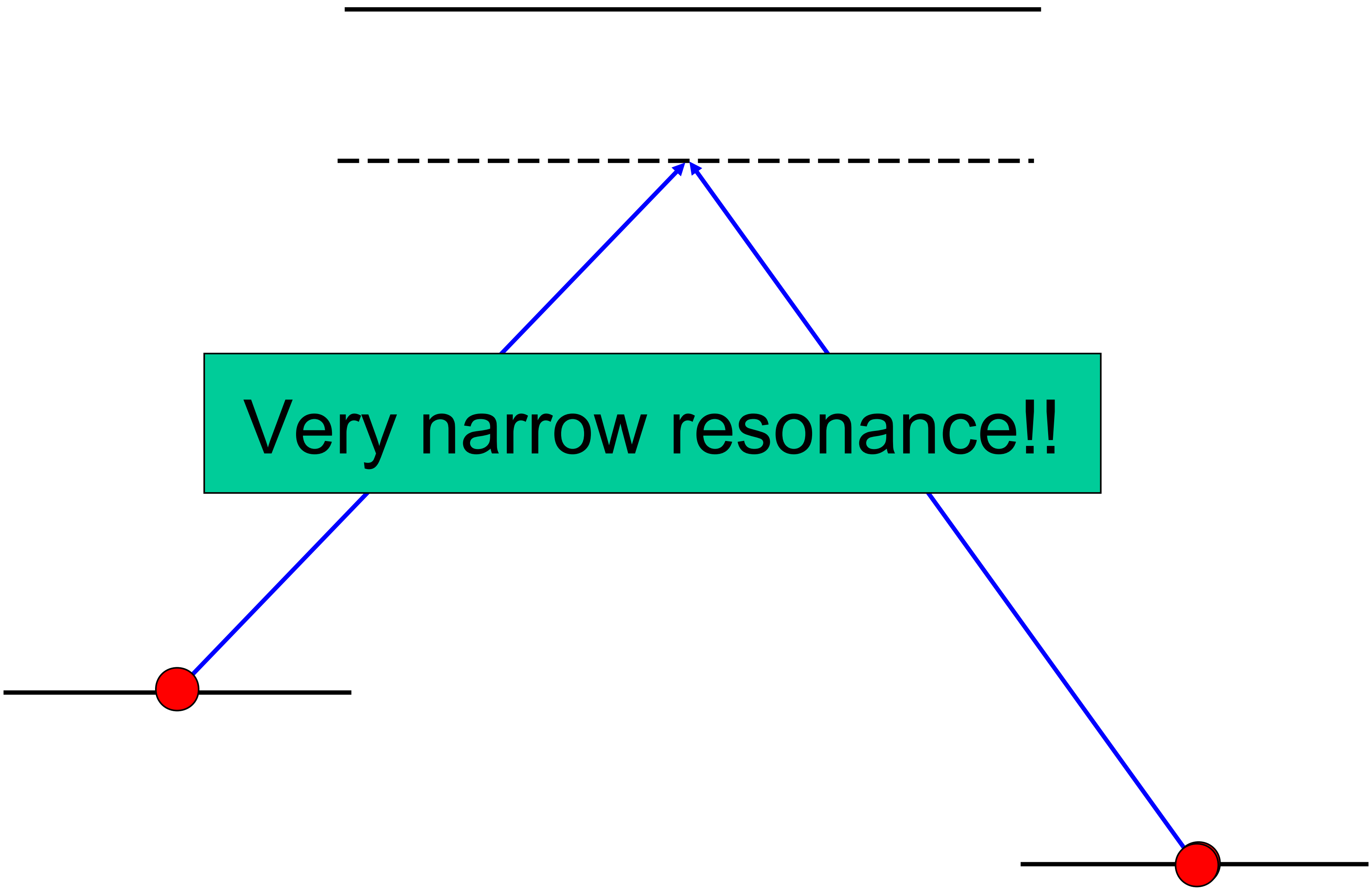
Same picture allows us to see how this runs as a magnetometer (possibly with stationary atoms)

# Components for the atom optics

$$|c_{e,p+\hbar k}(2T+\tau)|^2 = \frac{1}{2}[1 - \cos(\Delta\phi - \delta\tau/2)]$$



# Raman Transfer (3-level atom)

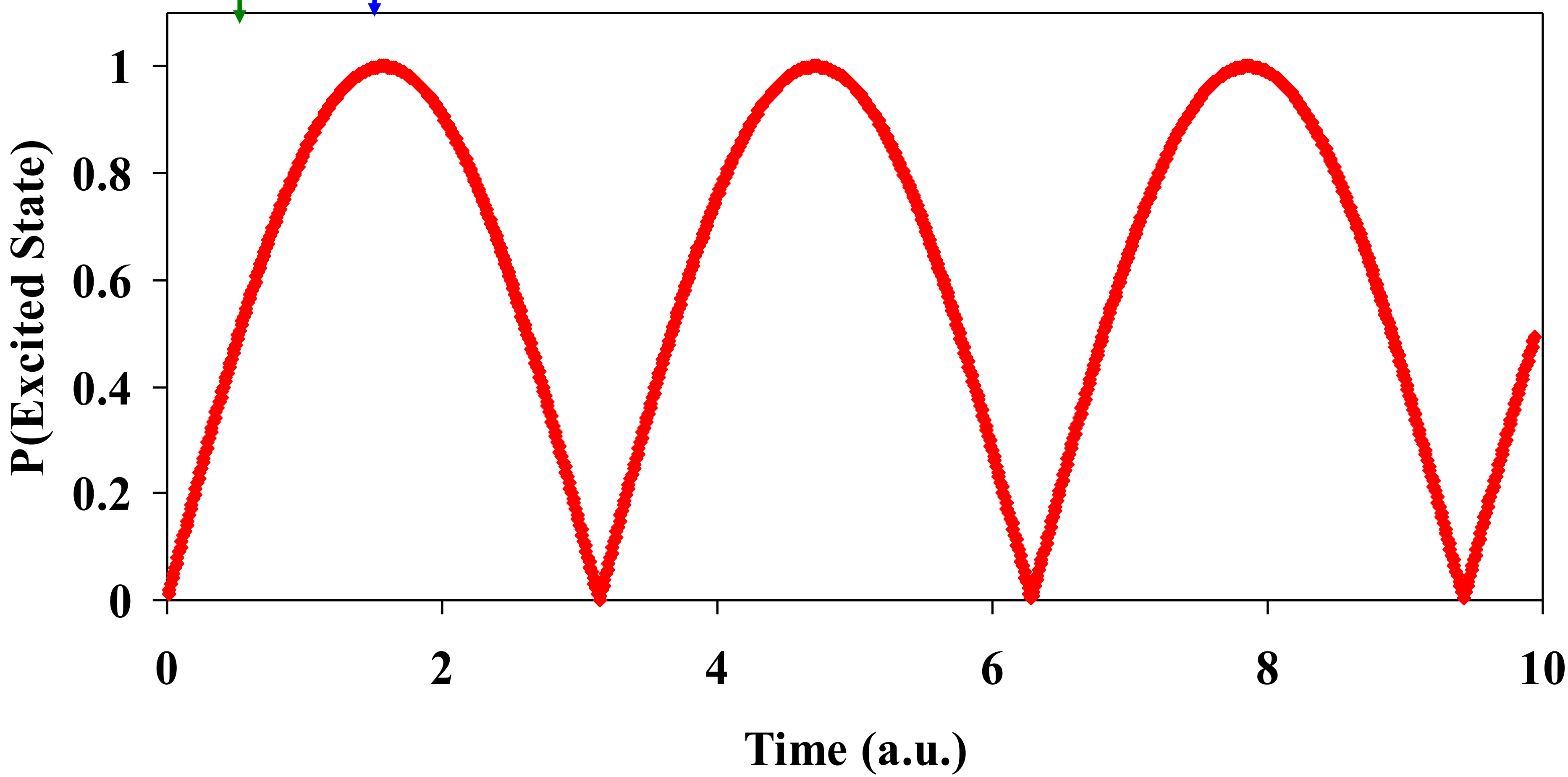


# Atom Beamsplitter

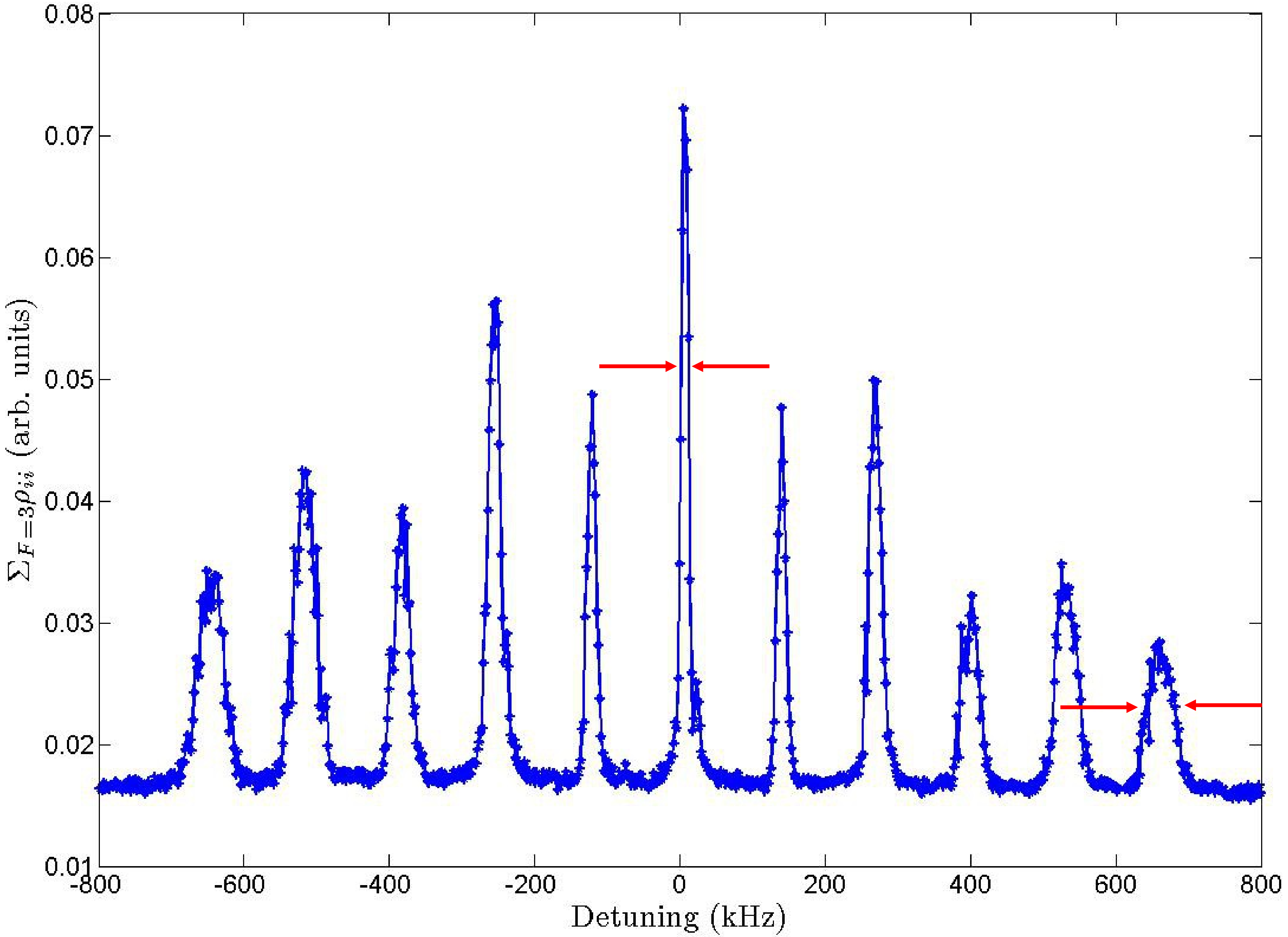


✓pulse-all the population is transferred

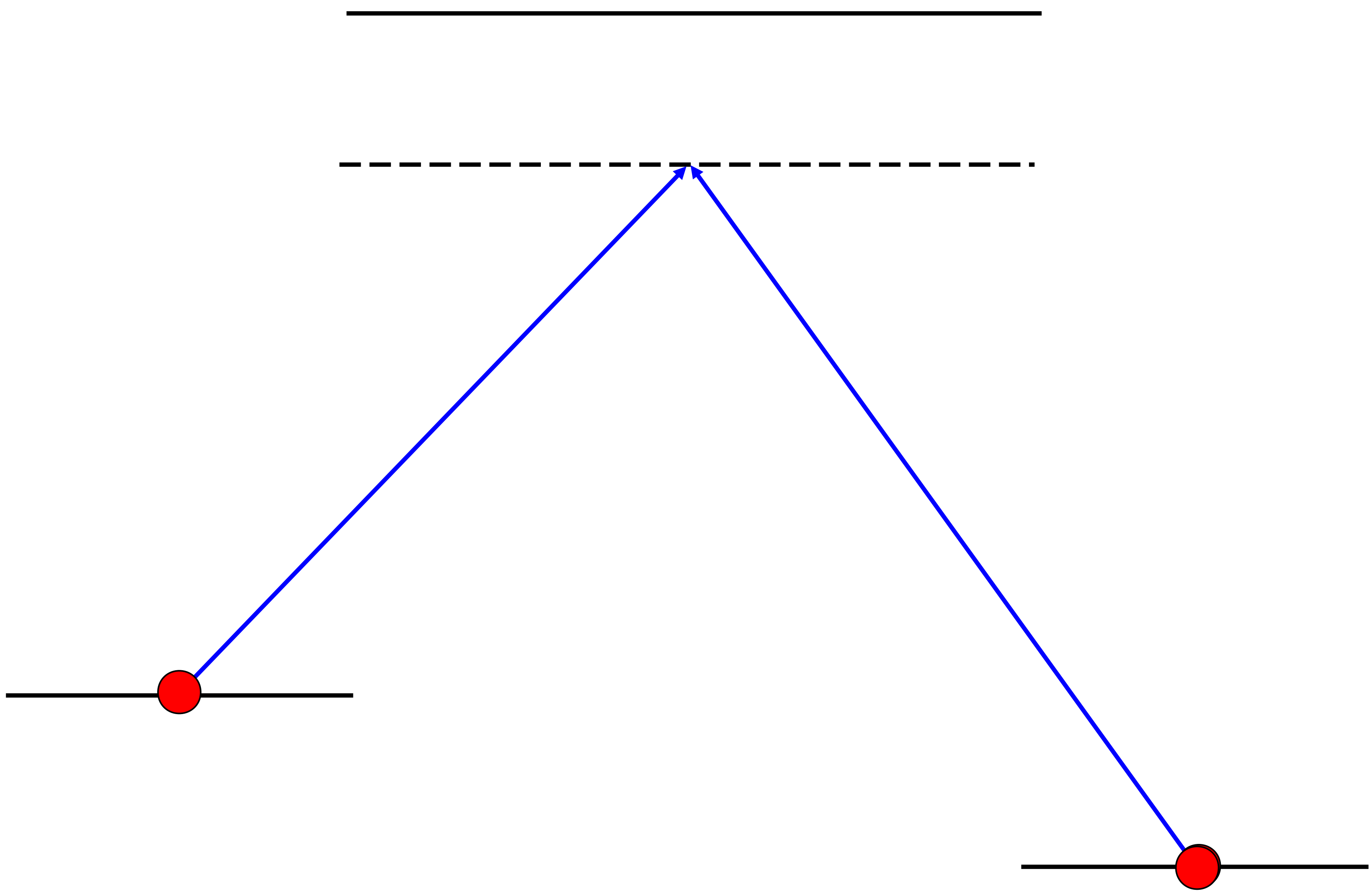
✓π pulse-half the population is transferred



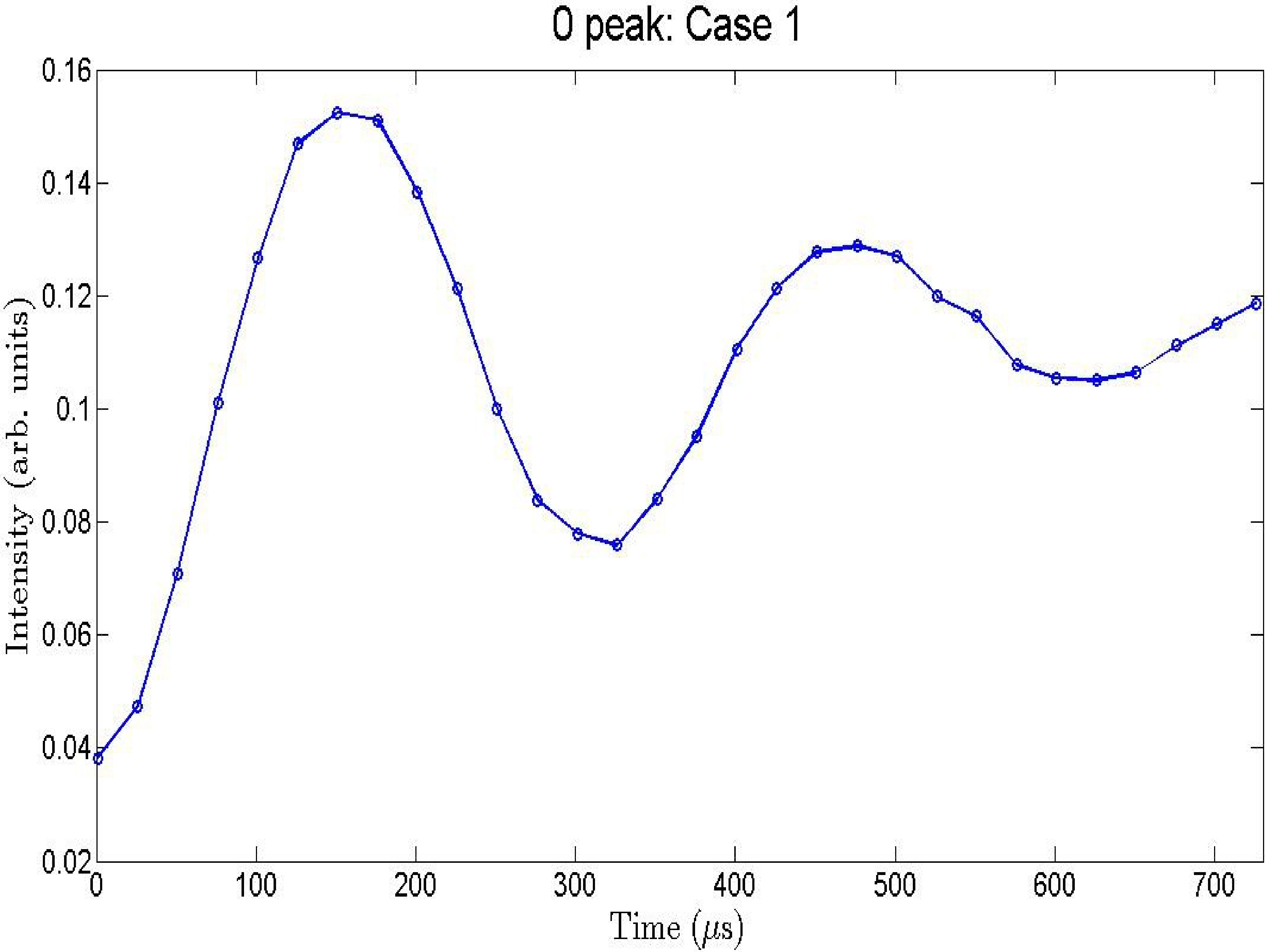
# Raman Spectra-Arbitrary Field



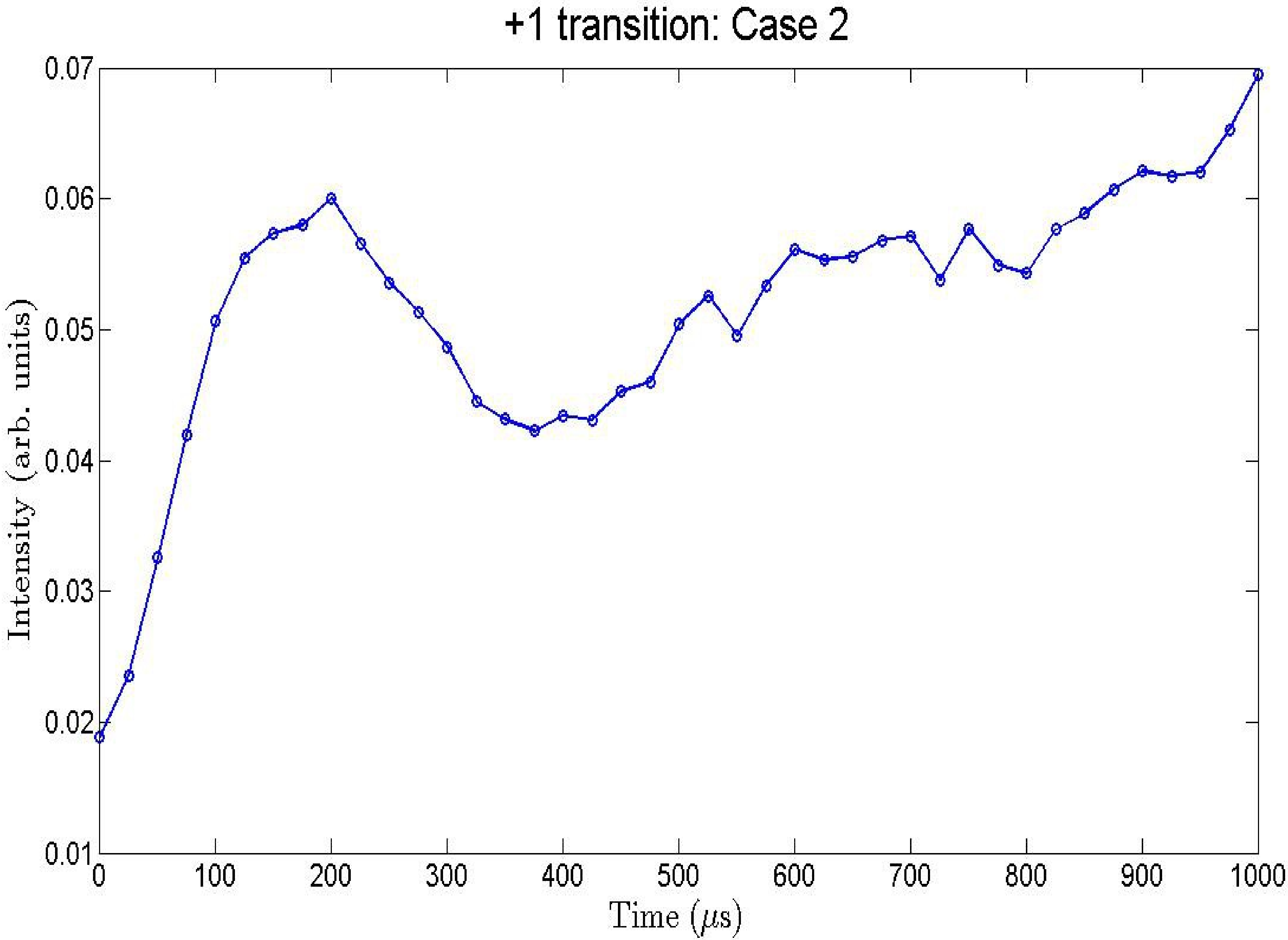
# Raman Transfer (Cycling)



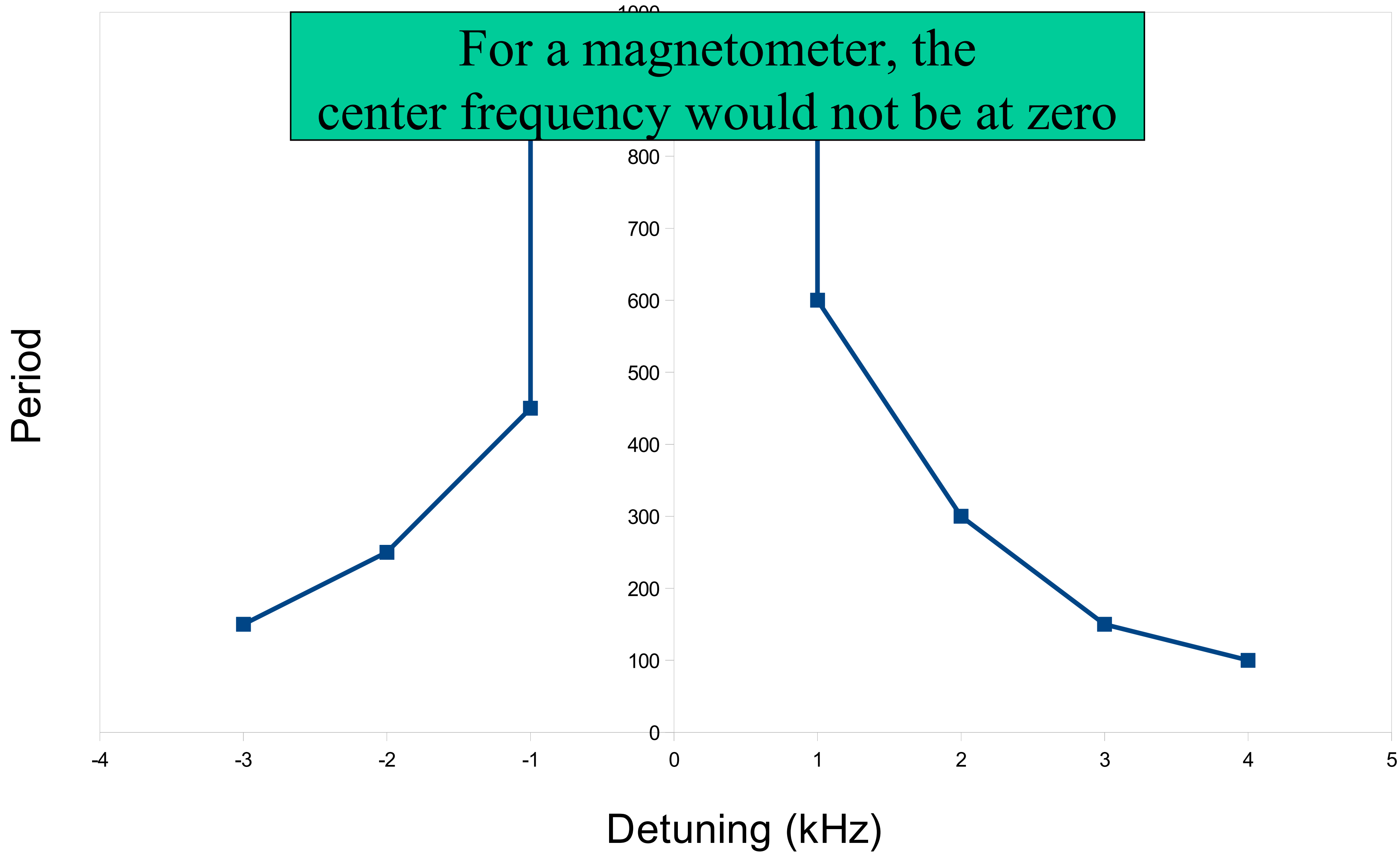
# Rabi cycling: 0 peak (Expt.)



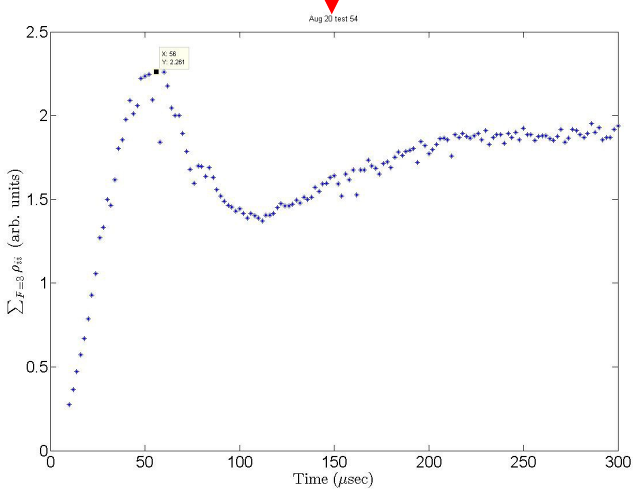
# Rabi Cycling: +1 Peak (Expt.)

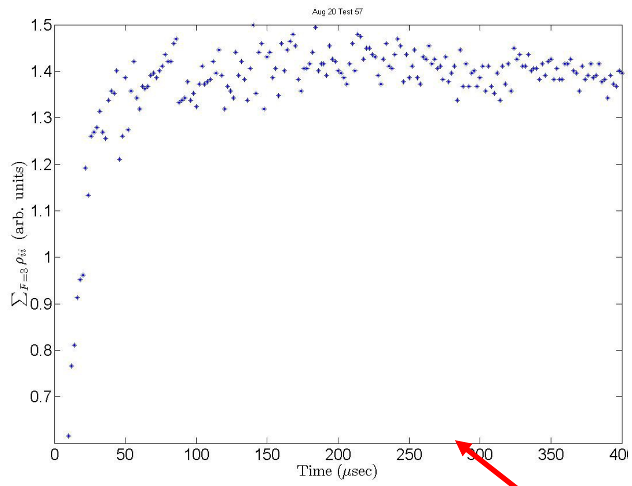


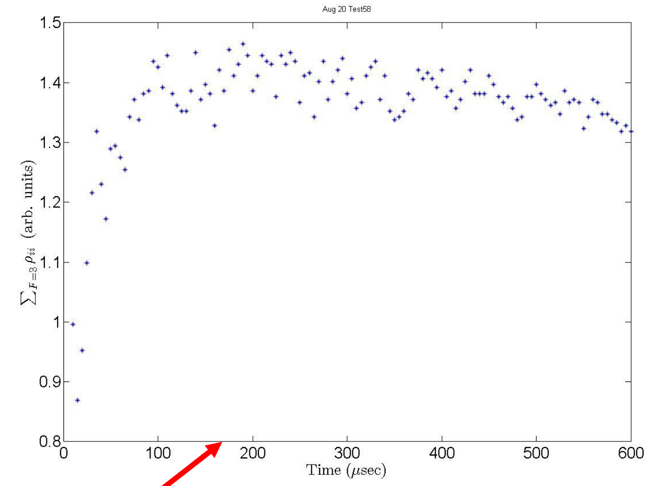
# Period vs frequency



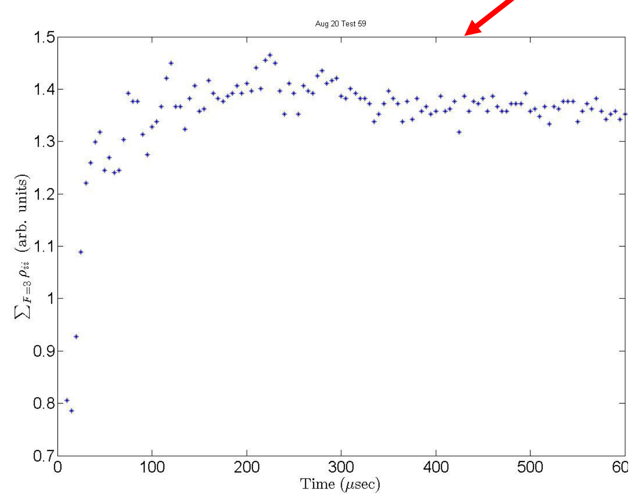
Single Pulse

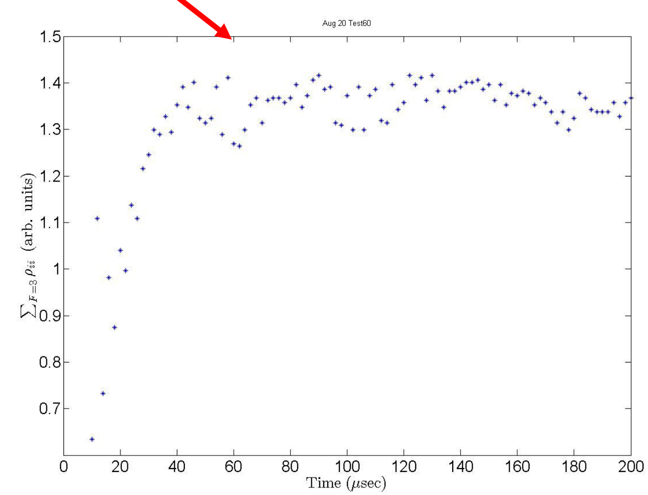


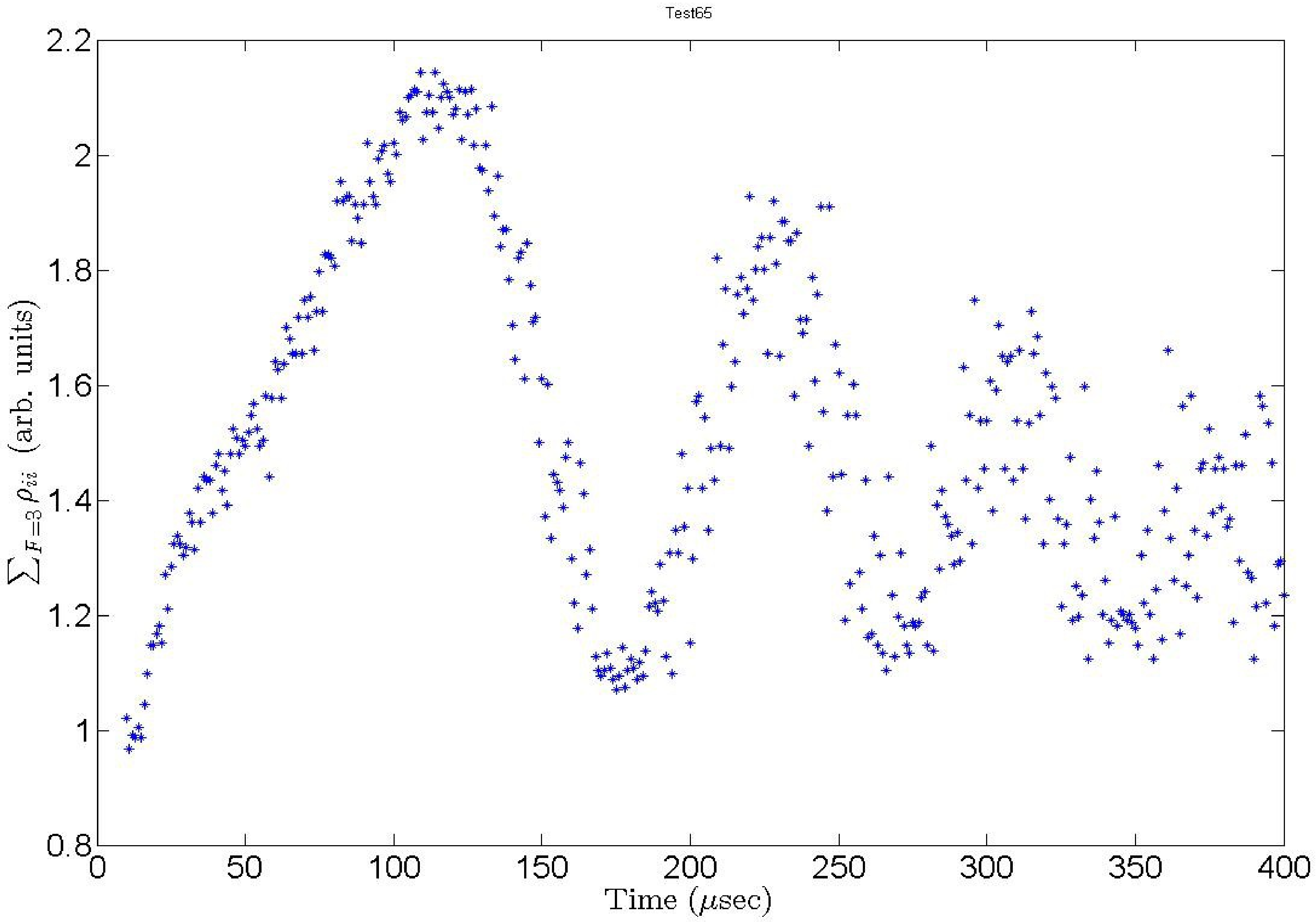




Double Pulse



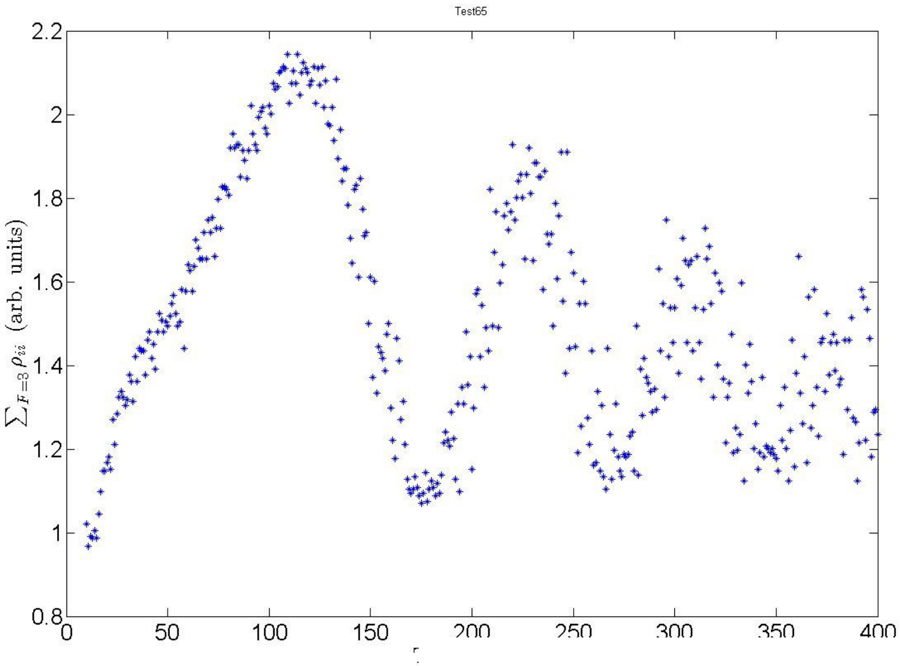



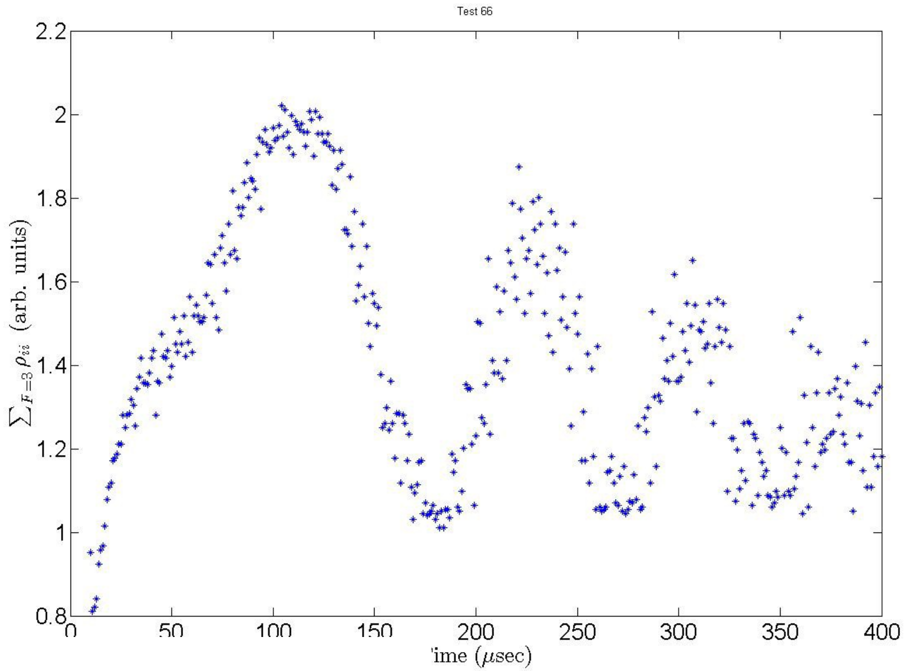
# Triple Pulse Experiment
# Time Domain

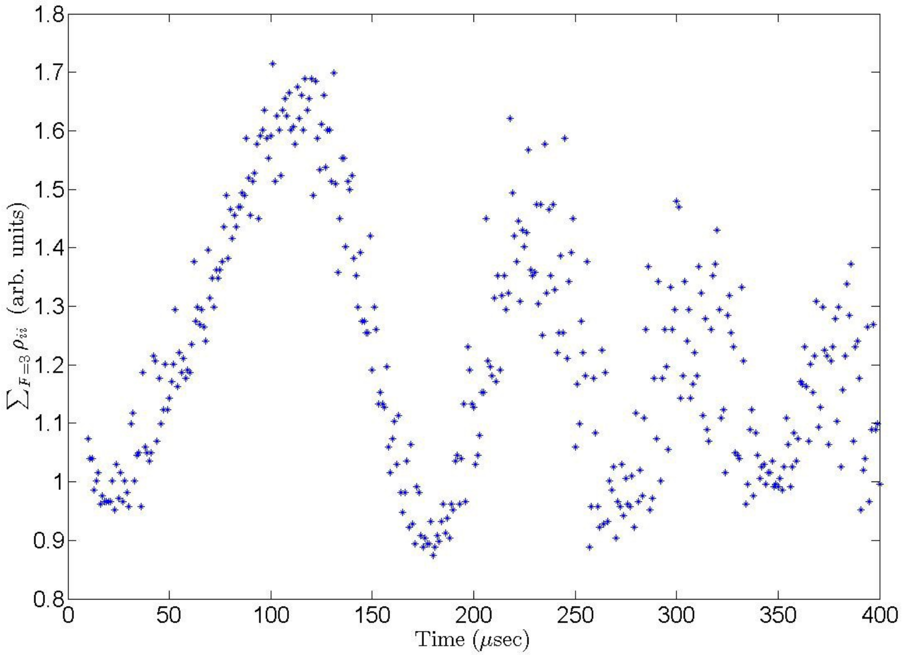


Test65
$\sum_{F=3}\rho_{ii}$ (arb. units)
2.2
2
1.8
1.6
1.4
1.2
1
0.8
0
50
100
150
200
250
300
350
400
Time ($\mu$sec)

# Similar Bfield –changing spatial gradient

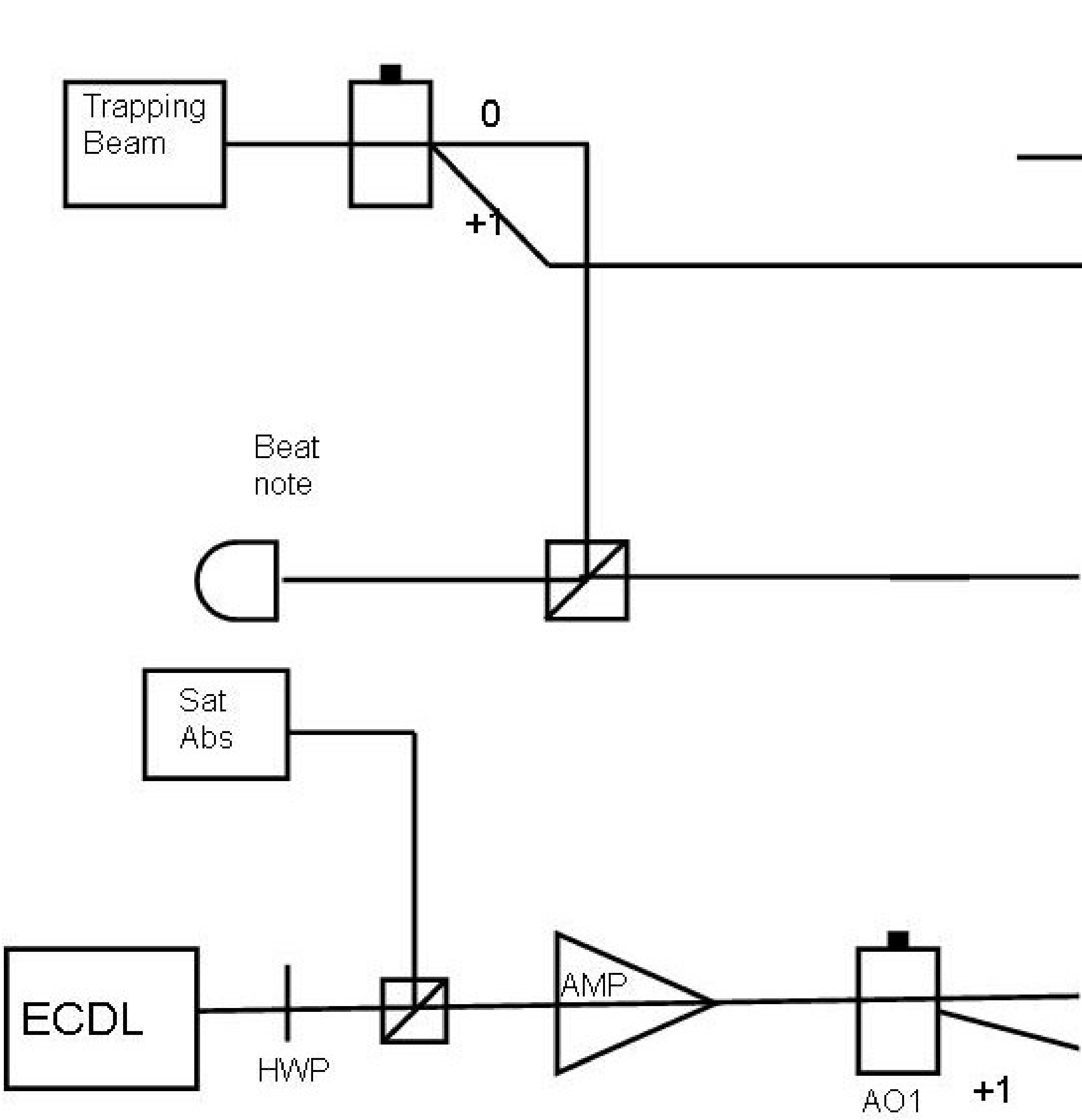


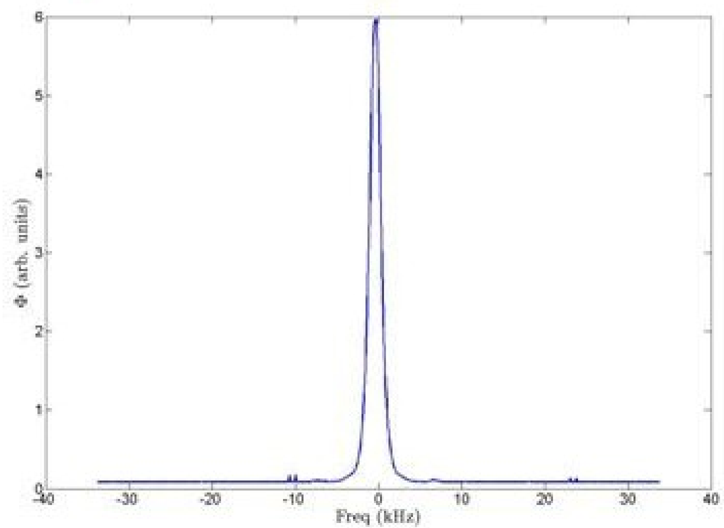



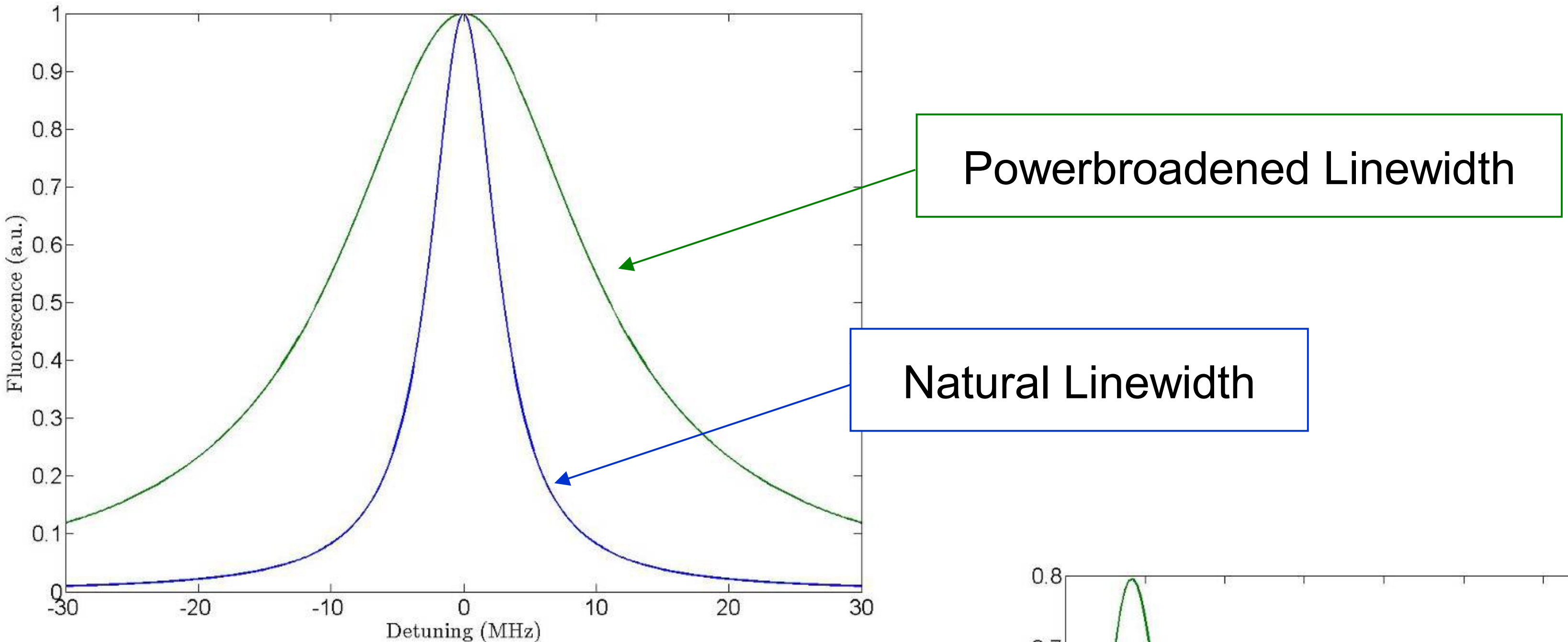
# Backups

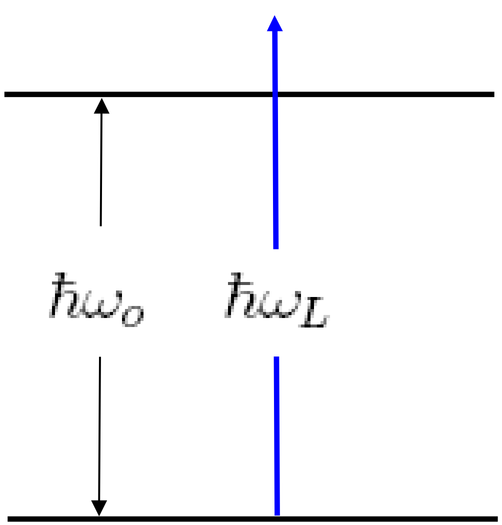
# Experimental Arrangement

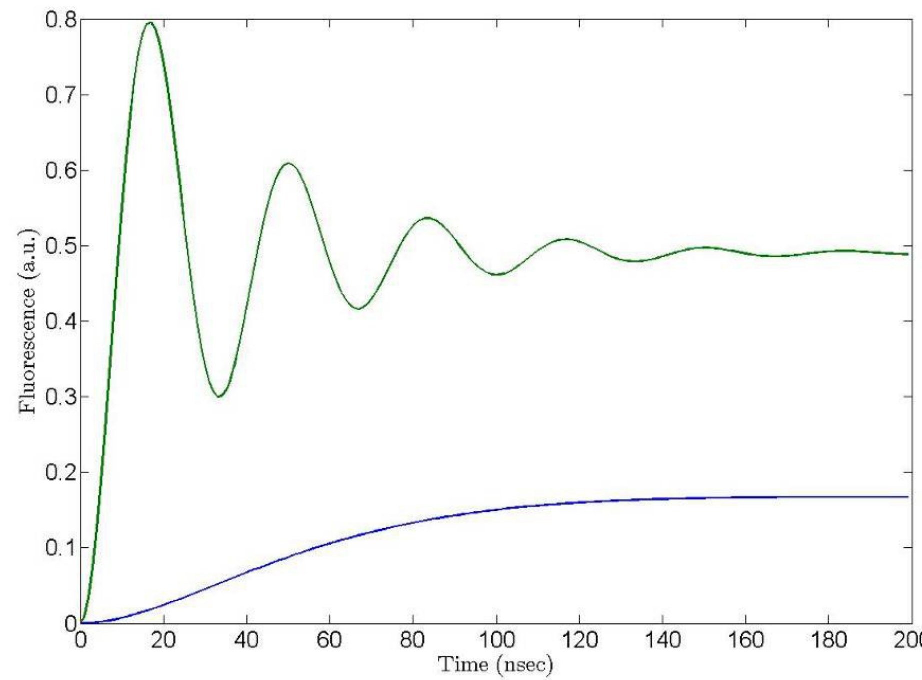


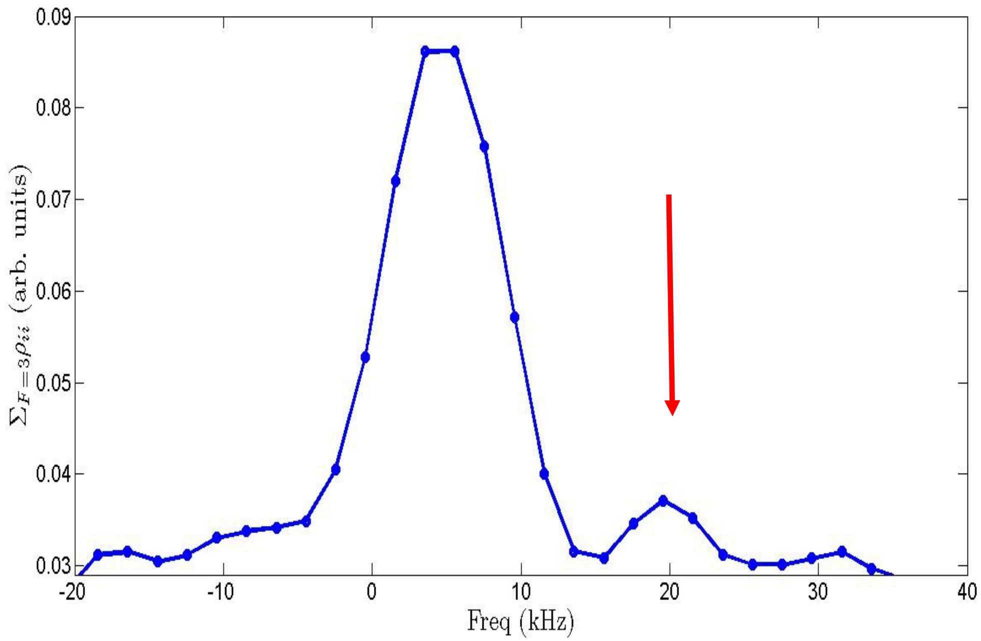
# •Two level atom reminder



# Square vs Gaussian Pulses




Square Pulse

Gaussian Pulse