Measuring the Electron’s Electric Dipole Moment using zero-g-factor paramagnetic molecules
APS March Meeting, 2006

Neil Shafer-Ray, The University of Oklahoma

Funding sources for preliminary research:

National Research Council (US)

NATO SfP (for field measurement.)

OU Office of the Vice President
for Research

Current funding:

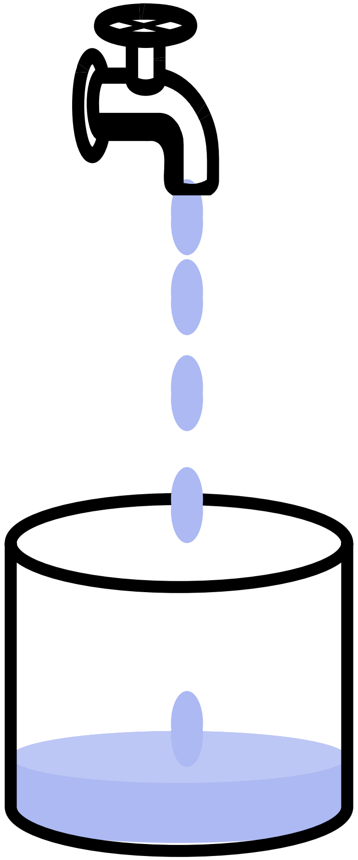
National Science Foundation

DOE EPSCoR Laboratory-State
Partnership

To all,

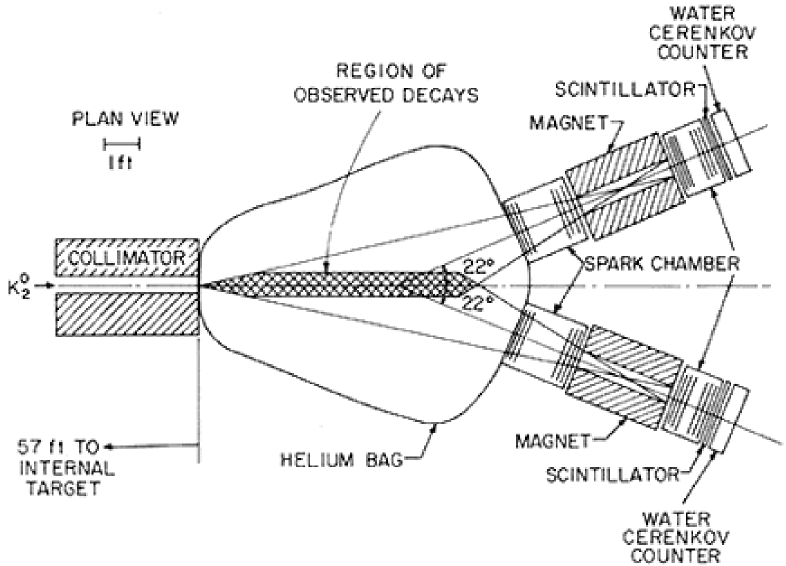
I am very sorry that I was not able to deliver this talk.
My grandmother has passed away a few hours ago
and I must return to the United States.

Sunday, October 8, 11:30pm
Neil Shafer-Ray

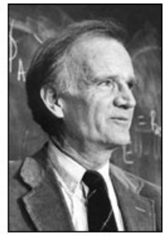


CP
(time reversal) violation

K-zero-long decay



James Cronin



Val Fitch

http://www.bnl.gov/bnlweb/history/**nobel**/nobel_80.asp

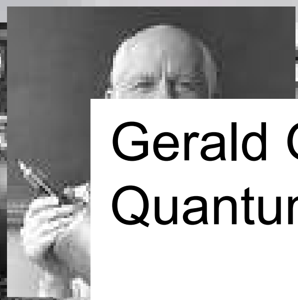
A completely different place to look for CP violation is in the interaction of fundamental particles with external fields.

The study of the magnetic moment of the electron is an integral part of some of the most compelling experiments of the last 100 years.

$$U = \mu_B (g\ \vec{B} \cdot \vec{S}) \qquad \mu_B = 1.39962458\ \mathrm{Hz}/\mu\mathrm{G}$$

2.0023193043617 [redacted]6[redacted]

Hans lt



Gerald Gabrielse
Quantum nondistructive measurement
of the quantum structure of
a single electron in a magnetic trap

STANDARD OF MASS?

ıgle ance

TIME

HEMISTRY

An EDM proportional to spin would also give C̸P

$$U = \mu_B (g\ \vec{B}\cdot\vec{S} + g_{edm}\ \vec{E}\cdot\vec{S})$$

$$\mu_B = 1.39962458\ \mathrm{Hz}/\mu\mathrm{G}$$
$$= 1.93080\times 10^{-11}\ \mathrm{e}\cdot\mathrm{cm}$$

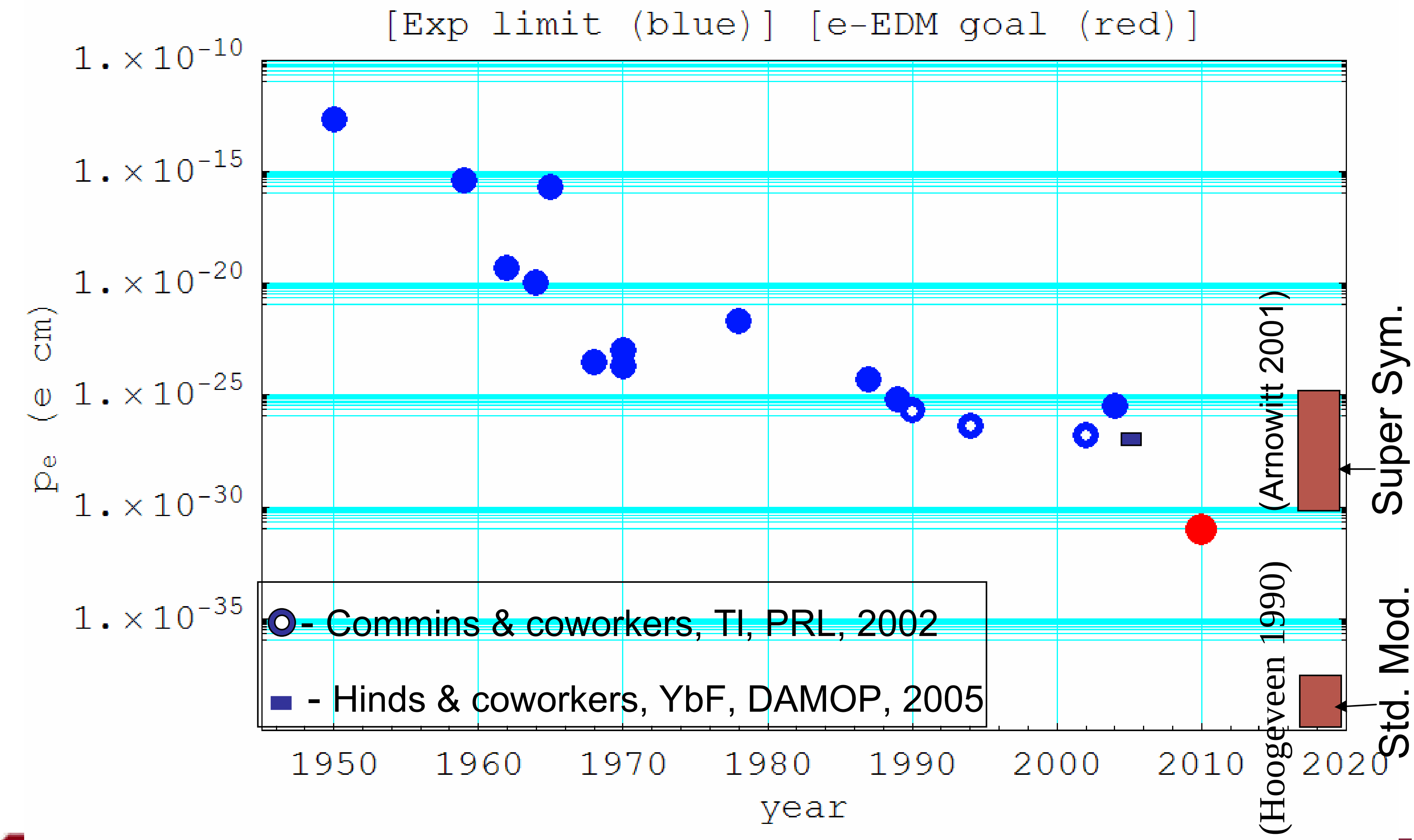
g = 2.0023193043617(16)

Gabrielse,PRL 2006

g_{edm} = 0.0000000000000000(5)

Commins, PRL, 2004

An EDM proportional to spin would also give CP



Outline

I. Introduction

How was the current experimental limit on the magnitude of the e-EDM obtained?

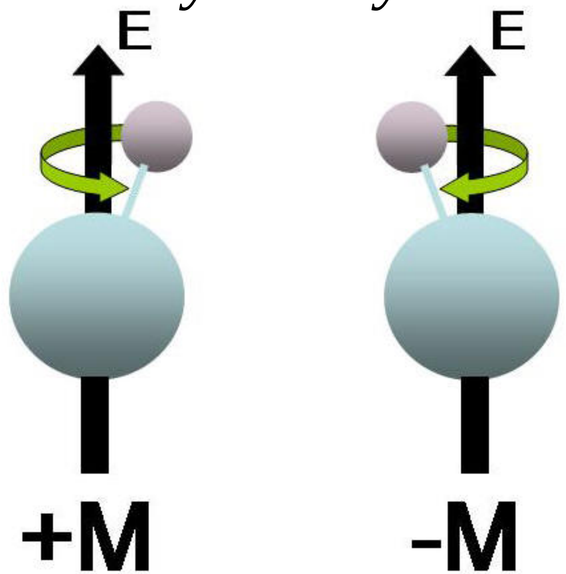
What are some of the current experiments being carried out to measure the e-edm

What is the OU group up to?

How the current limit on electron EDM is known

Symmetry leads to a ±M degeneracy of any molecule or atom that is not broken by an electric field along the quantization axis.
The existence of an electron electric dipole moment would break this symmetry.

To search for an e-EDM we will look for
$\Delta U = U_{+M} - U_{-M}$
in a strong E field.



Major Difficulty: A background magnetic field mimics an EDM.

The Commins Experiment with $^2P_{1/2}$ (F=1, M=±1) Tl

For an isolated electron,

$$U = \mu_B (g\ \vec{B}\cdot\vec{S} + g_{edm}\ \vec{E}\cdot\vec{S})$$

For an atom or molecule in a strong electric field,

$$U \approx \mu_B (g_z^{sys}\ B_z F_z + g_{edm}^{sys}\ E_z F_z).$$

$g_{edm}^{sys} = 0$ for diamagnetic atoms

$g_{edm}^{sys} << g_{edm}$ for light atoms/molecules (Schiff's theorem.)

$g_{edm}^{sys} >> g_{edm}$ for relativistic (heavy atoms/molecules.)

We want to use heavy paramagnetic atoms or molecues.

The Commins Experiment with $^2P_{1/2}$ (F=1, M=±1) Tl

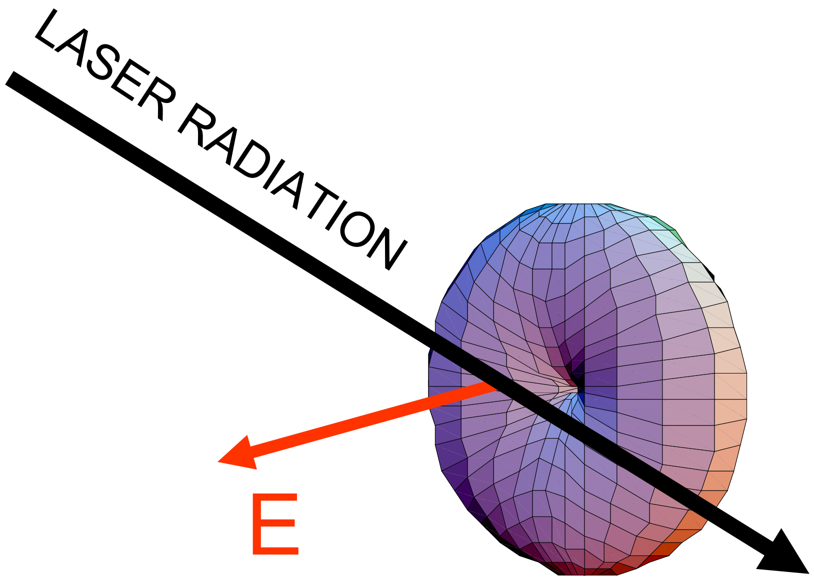
$$\frac{\Delta U_{Tl}}{h} = 2\left[(-585)(-0.77)\frac{d_e}{h}E_z - (0.34)\frac{\mu_B}{h}B_z\right]$$

enhancement factor

geometric factors

$$\frac{\Delta U_{Tl}}{h} = 0.022mHz\left(\frac{d_e}{10^{-27}e\cdot cm}\left(\frac{E_z}{10^5 volt/cm}\right)-\left(\frac{B_z}{24pG}\right)\right)$$

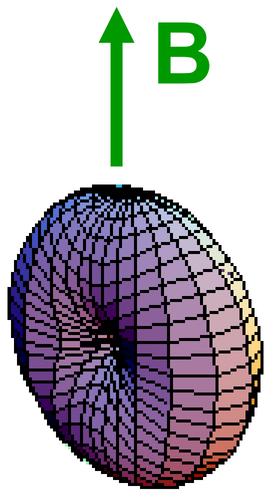
Graphical Description of the Commins e-EDM Experiment



P(θ,ϕ) = probability of finding the system In the state M=F when quantization axis is in the direction of θ,ϕ.

Tl($^2P_{1/2}$ F=1),
|1,1> + |1,-1>

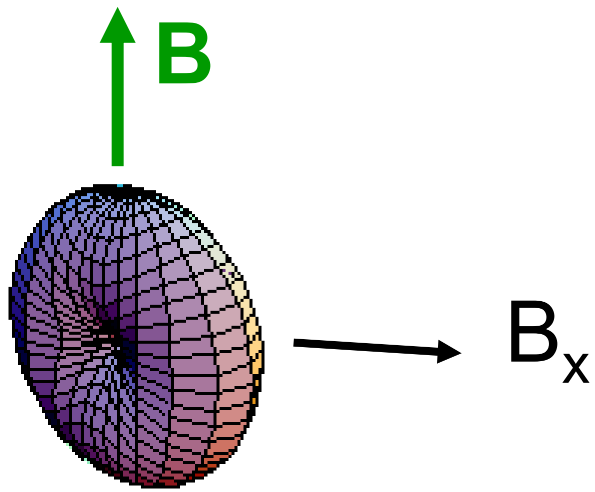
EFFECT OF MAGNETIC FIELDS ON THE DISTRIBUTION OF ANGULAR MOMENTUM



$$\text{Tl}(^2P_{1/2}\ F{=}1),$$

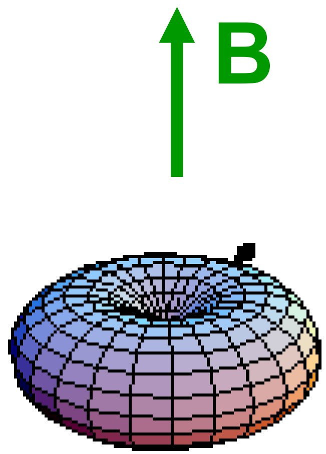
$$|1,1\rangle + \text{Exp}[i\,\Delta U\ t/\hbar]\ \ |1,-1\rangle$$

EFFECT OF MAGNETIC FIELDS ON THE DISTRIBUTION OF ANGULAR MOMENTUM



A small constant field B_x along an axis perpendicular to B has little effect.

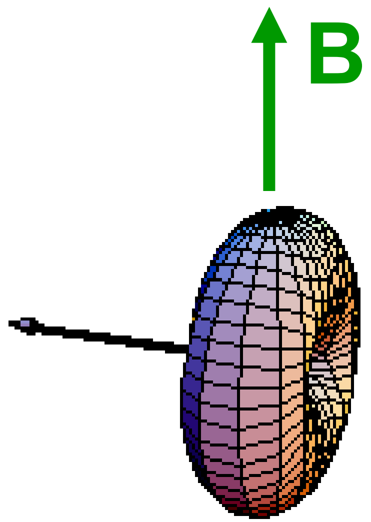
EFFECT OF MAGNETIC FIELDS ON THE DISTRIBUTION OF ANGULAR MOMENTUM



B_{rot}

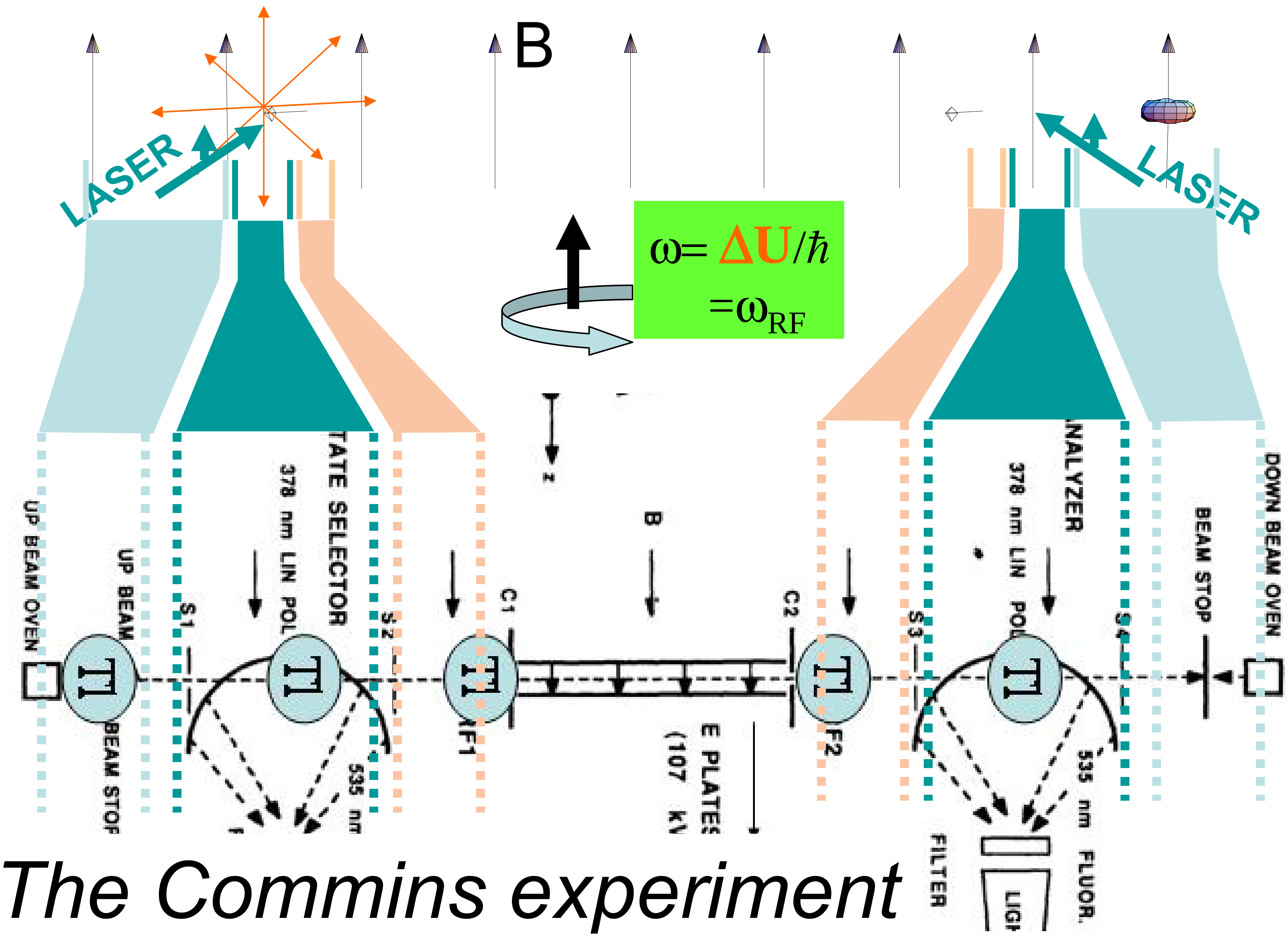
A small field B_x along an axis perpendicular to B that rotates with the distribution *may* have a dramatic effect.

EFFECT OF A MAGNETIC FIELD ON OF ANGULAR MOMENTUM ORIENTATION



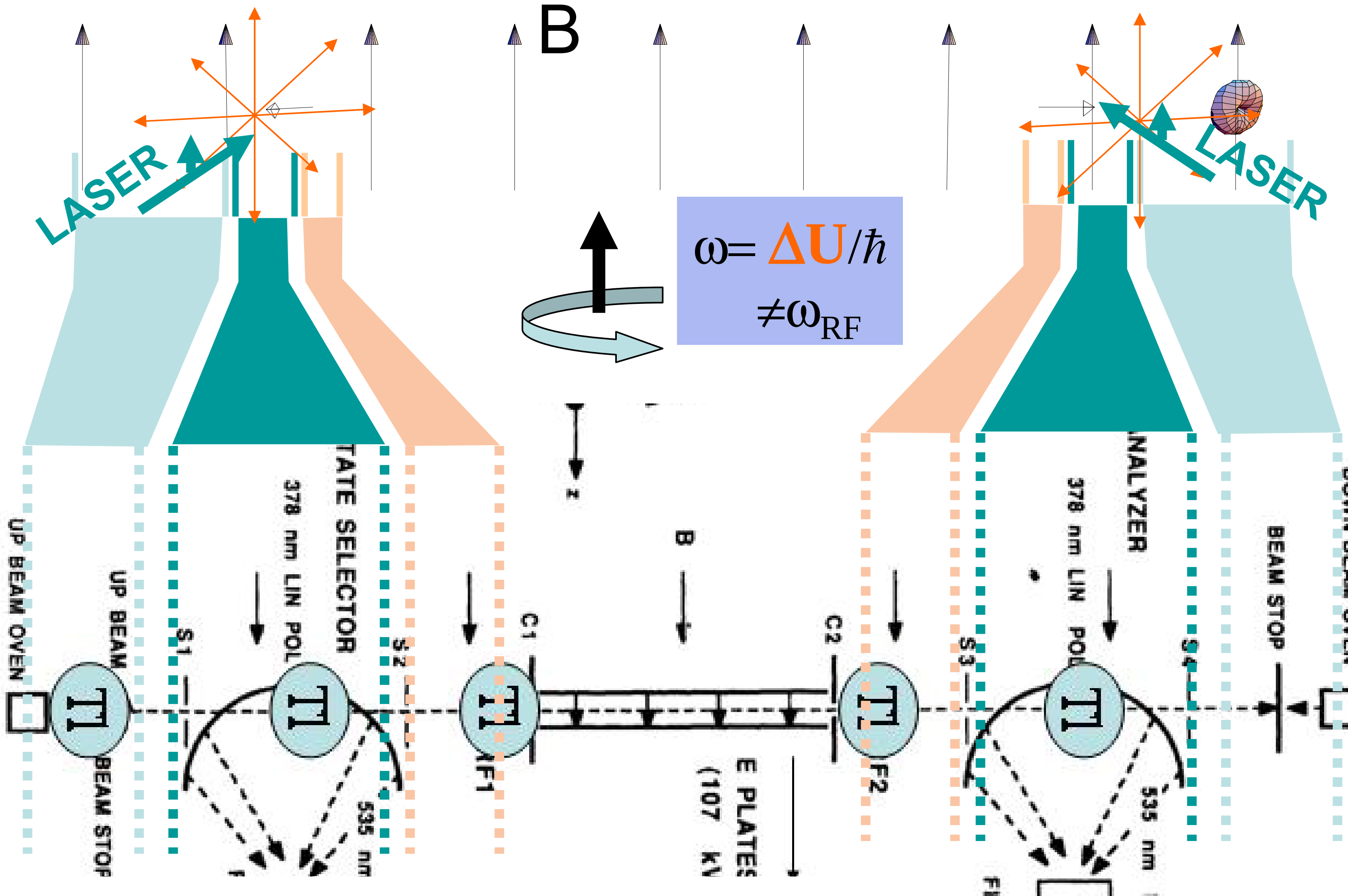
A small field B_x along an axis perpendicular to B that rotates with the distribution *may* have a dramatic effect.

The Ramsey beam resonance technique takes advantage of this dependence of the Rabi rotation on the phase of the rotating field.



The Commins experiment

Commins et al, PRL **88**, 71805, 2002



The Commins experiment

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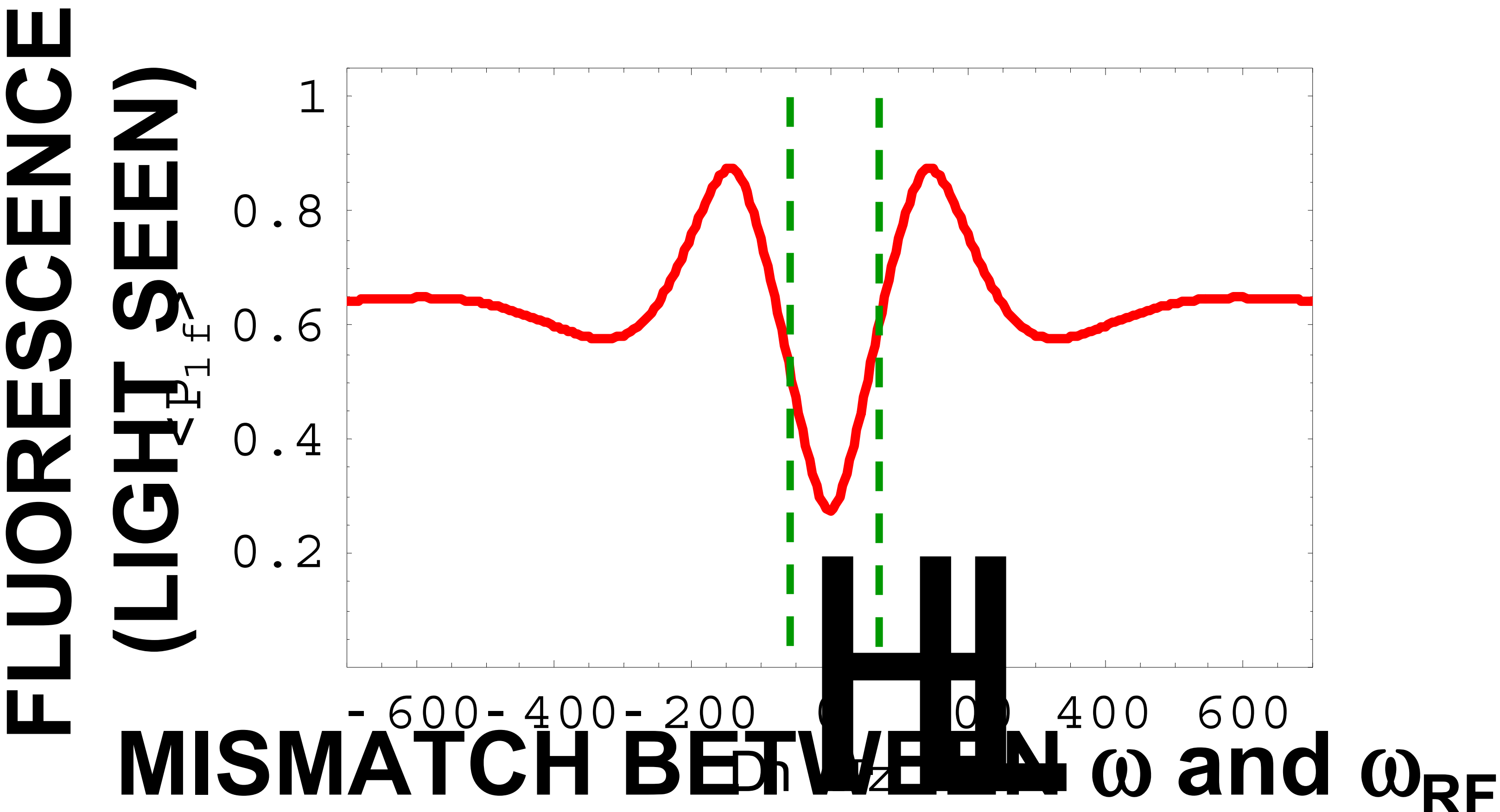
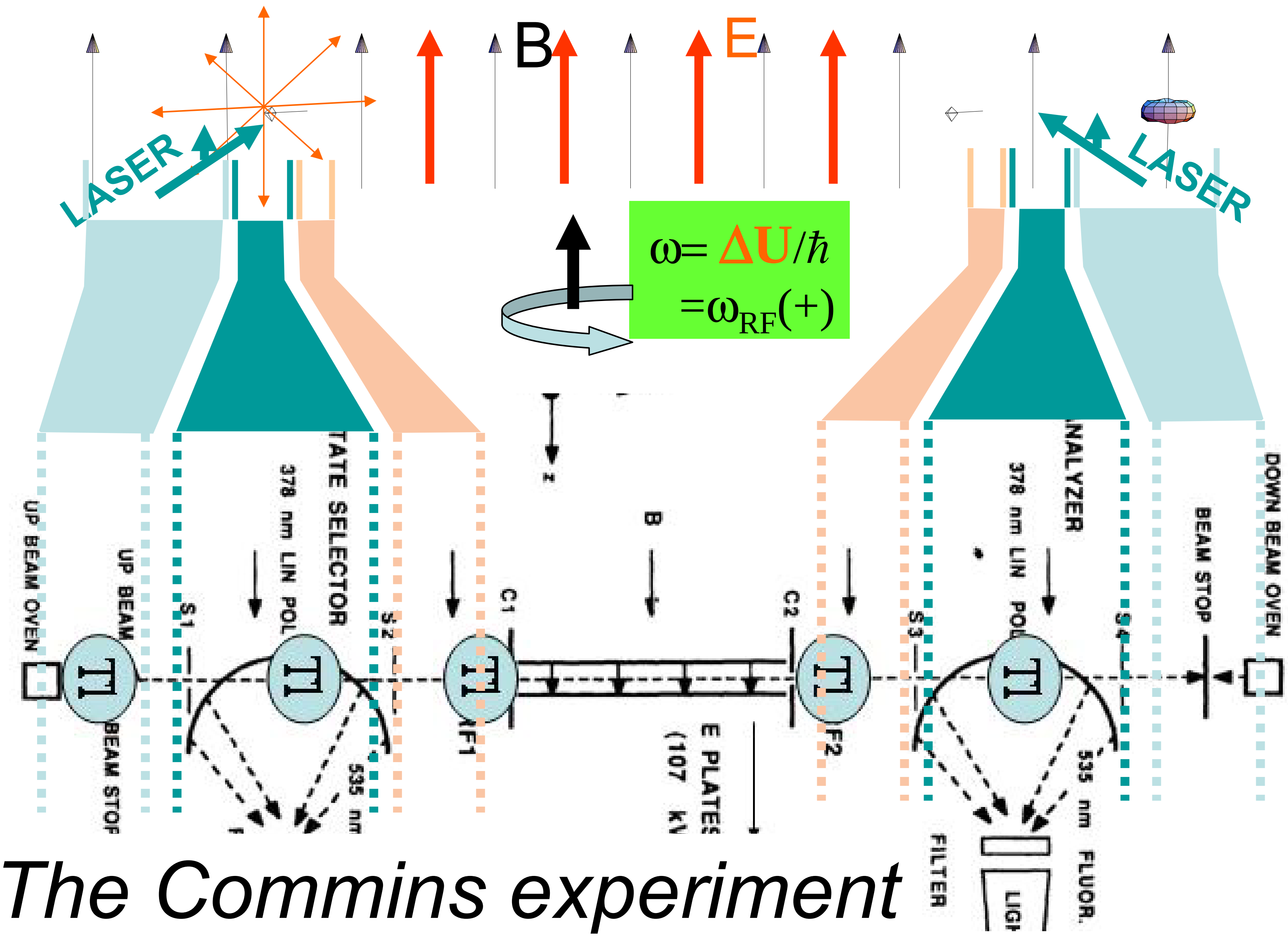


Expected Ramsey resonance signal for

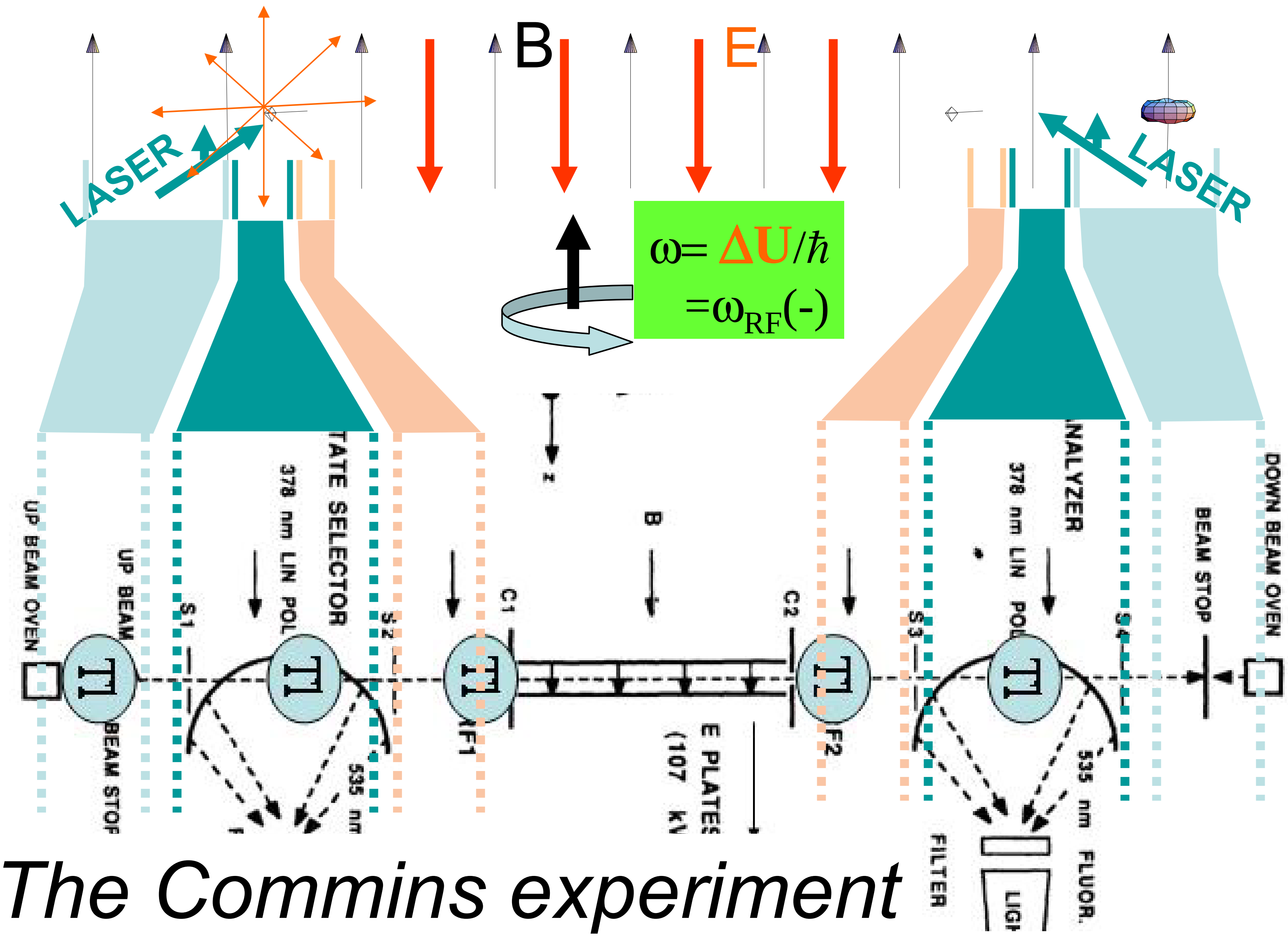
$\nu_T = (2kT/m)^{1/2} / 2L = 140$ Hz

(m=100 amu , T=500K, and interaction length L= 1000mm)



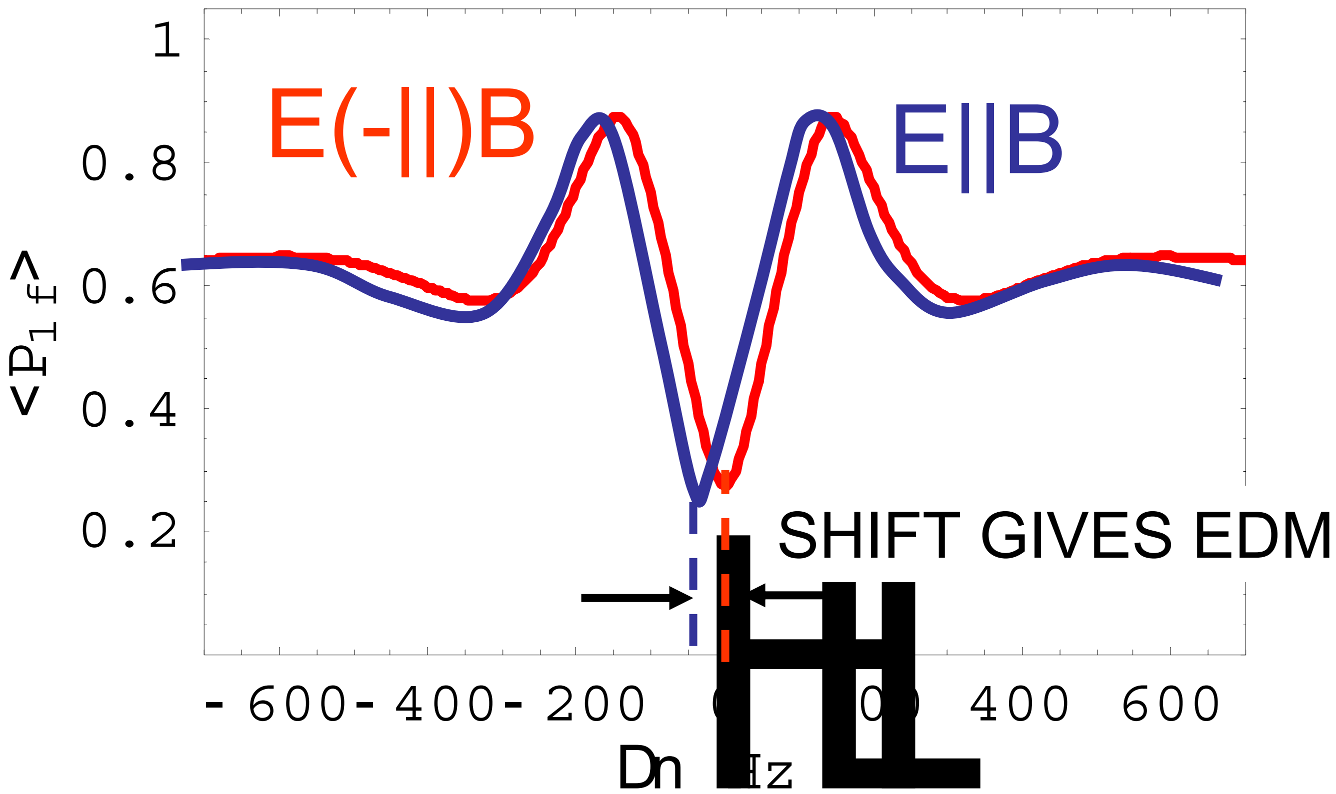
The Commins experiment

Commins et al, PRL **88**, 71805, 2002



The Commins experiment

Commins et al, PRL **88**, 71805, 2002



SHIFT SHOWN TO BE ~ 10^{-7} OF THE WIDTH!!!

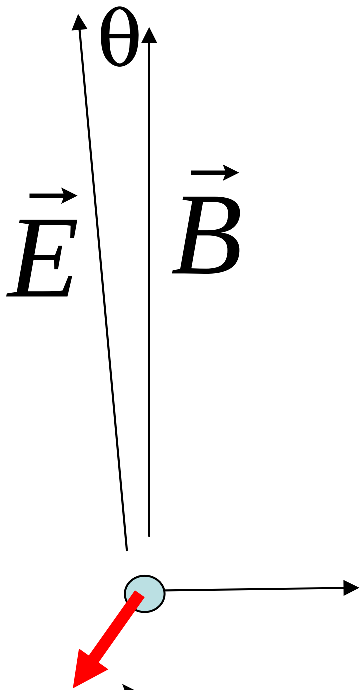
GREAT STATISTICS!

limiting systematic error

$$|\vec{B}+\vec{B}'_{up}|-|\vec{B}+\vec{B}'_{down}|=2vE\sin\theta/c^2$$

$$\text{splitting of } \approx (100Hz)\sin\theta$$

$\sin\theta \approx 10^{-6}$



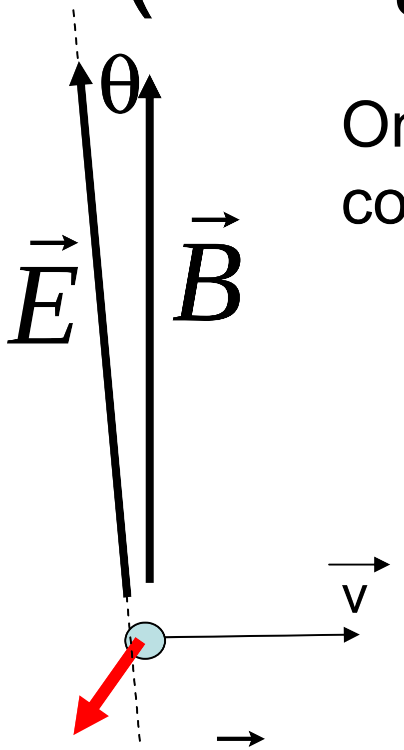
$$\vec{B}'=\vec{v}\times\vec{E}/c^2$$

Measurement of the e-EDM using paramagnetic molecules

System (state)		E-field (kV/cm)	split @ 10^{-27}e cm (mHz)	B @ 10^{-27}e cm (nG)	$t_{coherence}$ (ms)	d_{limit} (10^{-27}e cm)
Tl ($^2P_{1/2}$ F=1)	Commins	100	0.02	0.024	3	1.3
YbF ($X^2\Sigma$,F=1)	Hinds	10.	13	5	3	-

1) Effective electric field is the internal field of the molecule.
2) Idea by Saunders (Atomic Phys, 14 1975,71).
3) Calculation of shift by N.S. Mosyagin, M.G. Kozlov, A.V. Titov, (J Phys B, 31, L763)

Effect of the large tensor split (energy dependence on |M|)



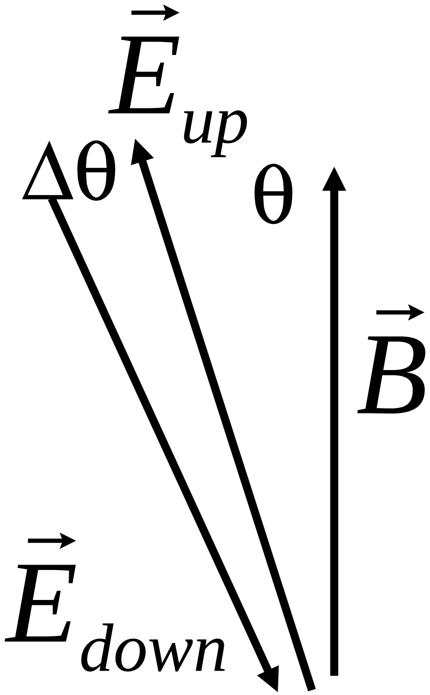
$$\vec{B}' = \vec{v} \times \vec{E} / c^2$$

Only the projection of $\vec{B}$ on the $\vec{E}$ axis contributes to the energy between ±M levels:

$$(B_z + B'_{z,up}) - (B_z + B'_{z,down}) = 0$$

$\vec{v} \times \vec{E} / c^2$ systematic goes away!

Effect of the large tensor split (energy dependence on |M|)



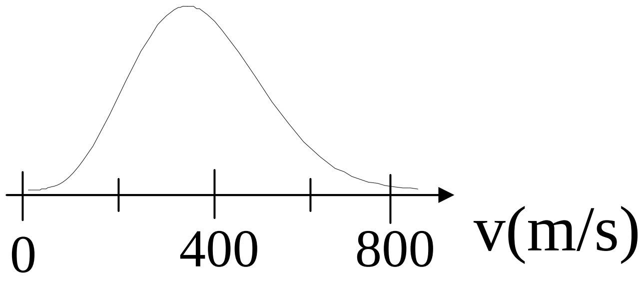
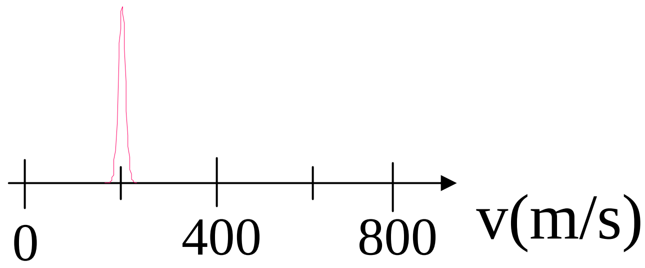
Only the projection of $\vec{B}$ on the $\vec{E}$ axis contributes to the energy between ±M levels:

$$B_{z,up} - B_{z,down} = 2B\Delta\theta\sin\theta$$

$$\text{splitting of } \approx (1Hz)\frac{B}{Gauss}\frac{\sin\theta}{10^{-6}}\Delta\theta$$

A much less severe problem then the vxE/c² effect.

Differences between an atomic beam and a beam of paramagnetic molecules

Beam	Expected Flux	Speed Distribution
Tl(F=1,|M|=1) (from oven)	8×10^{15}/str/sec	
YbF(J=1/2, F=1,|M|=1) (from supersonic expansion)	6×10^{10}/str/sec	

Easy to lose in statistics what one gains in intrinsic sensitivity.

System (state)		E-field (kV/cm)	shift @ 10^{-27}e cm (mHz)	B @ 10^{-27}e cm (nG)	$t_{coherence}$ (ms)	d_{limit} (10^{-27}e cm)
Tl ($^2P_{1/2}$ F=1)	Commins	100	0.02	0.024	3	1.3
YbF ($X^2\Sigma$,F=1)	Hinds (Hinds)	10.	13	5	3	30 (1?)
Cs ($^2P_{1/2}$ F=3)	Hunter	4	0.00016	0.00025	15	60
	(Weiss)	100?	0.004	0.005	2×10^3	-
	(Gould)	?	0.004	0.005	$\sim10^3$	-
PbF ($X^2\Pi_{1/2}$, F=1)	(Shafer-Ray)	60-100	12	**500 to 10^7**	**10^3 to 3**	-
HfF^+ ($^3\Delta_1$)	(Cornell)	~1 volt RF ion trap	~10	~200	$\sim10^3$	-
PbO ($a^3\Sigma$,F=1)	(DeMille)	.01	2.9	1	0.1	-

Cs Atomic Fountain (Provided by Harvey Gould)

LBNL Cesium Fountain Electron EDM Experiment*

Harvey Gould, Charles T. Munger Jr.[1], & Jason Amini[2]

Details: http://homepage.mac.com/gould137/index.html

Sensitivity ≥ 2 x 10^{-50} C-m (10^{-29} e-cm)

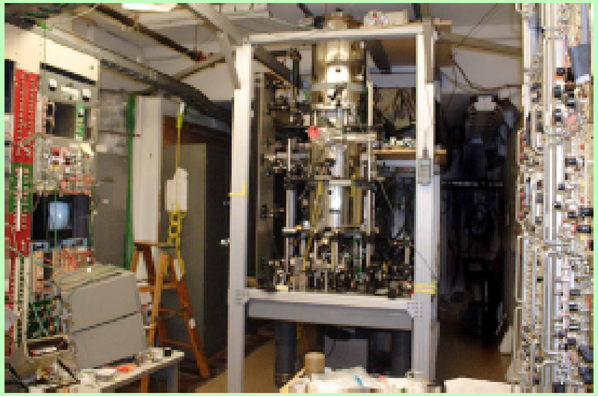
- linewidth narrowed 7-quantum transition
- electrostatic focusing through plates

Systematics < 5 x 10^{-52} C-m (2 x10^{-31} e-cm)

- electric-field quantization suppresses vXE
  - cancel incomplete E reversal with ± m_F

$m_F = +4 \rightarrow m_F = -3$
$m_F = -4 \rightarrow m_F = +3$

Demonstration cesium fountain electron EDM experiment



Status:

Demonstration experiment completed http://arxiv.org/physics/0602011 and seeking funding for full-scale experiment

* Demonstration experiment supported by NASA and NIST
1 SLAC
2. Now at NIST, Boulder CO.

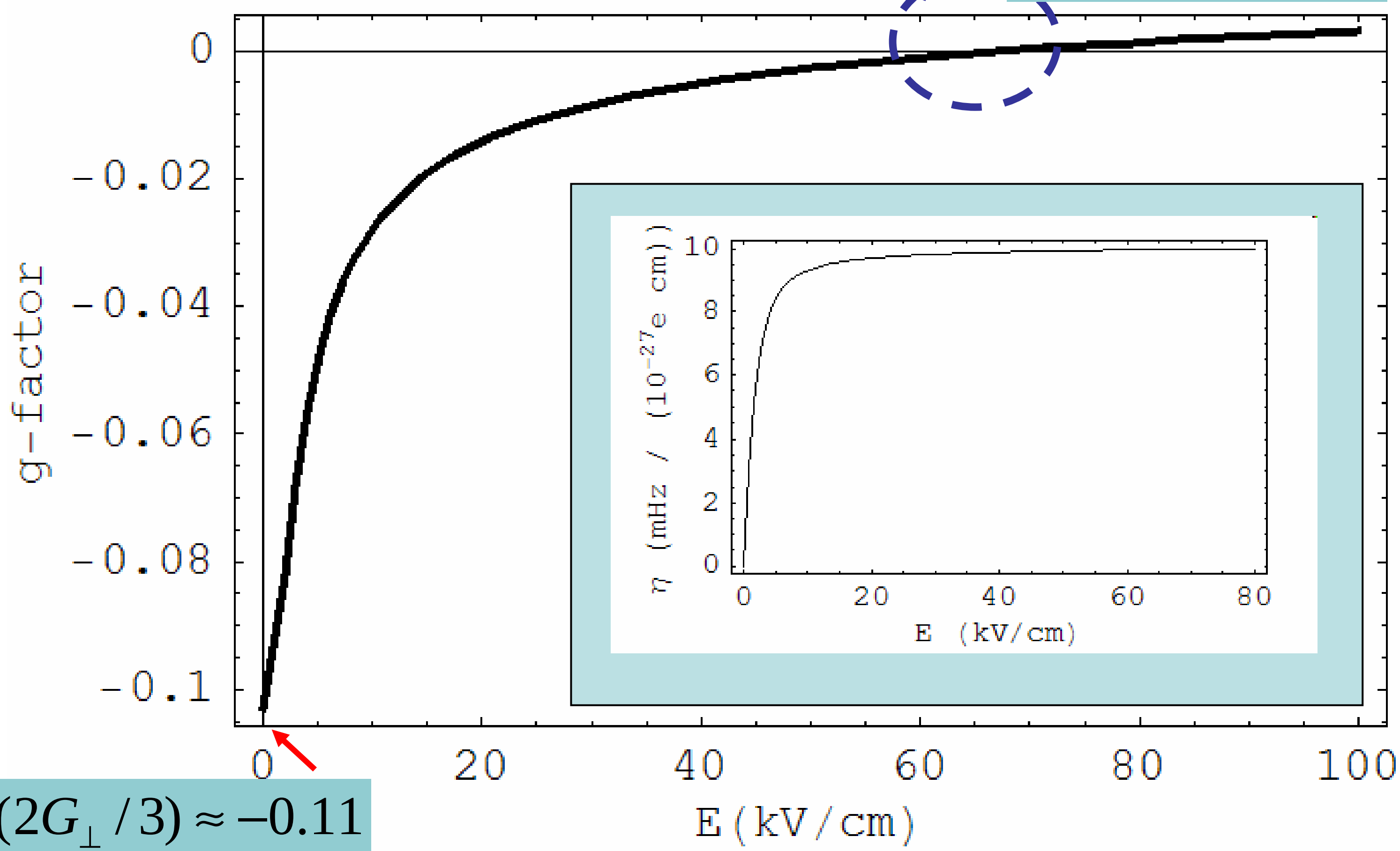
The OU PbF edm experiment

g factor of PbF F=1, $|M_F|$=1, high-field-seeking ground state:

Shafer-Ray, PRA,73, 34102

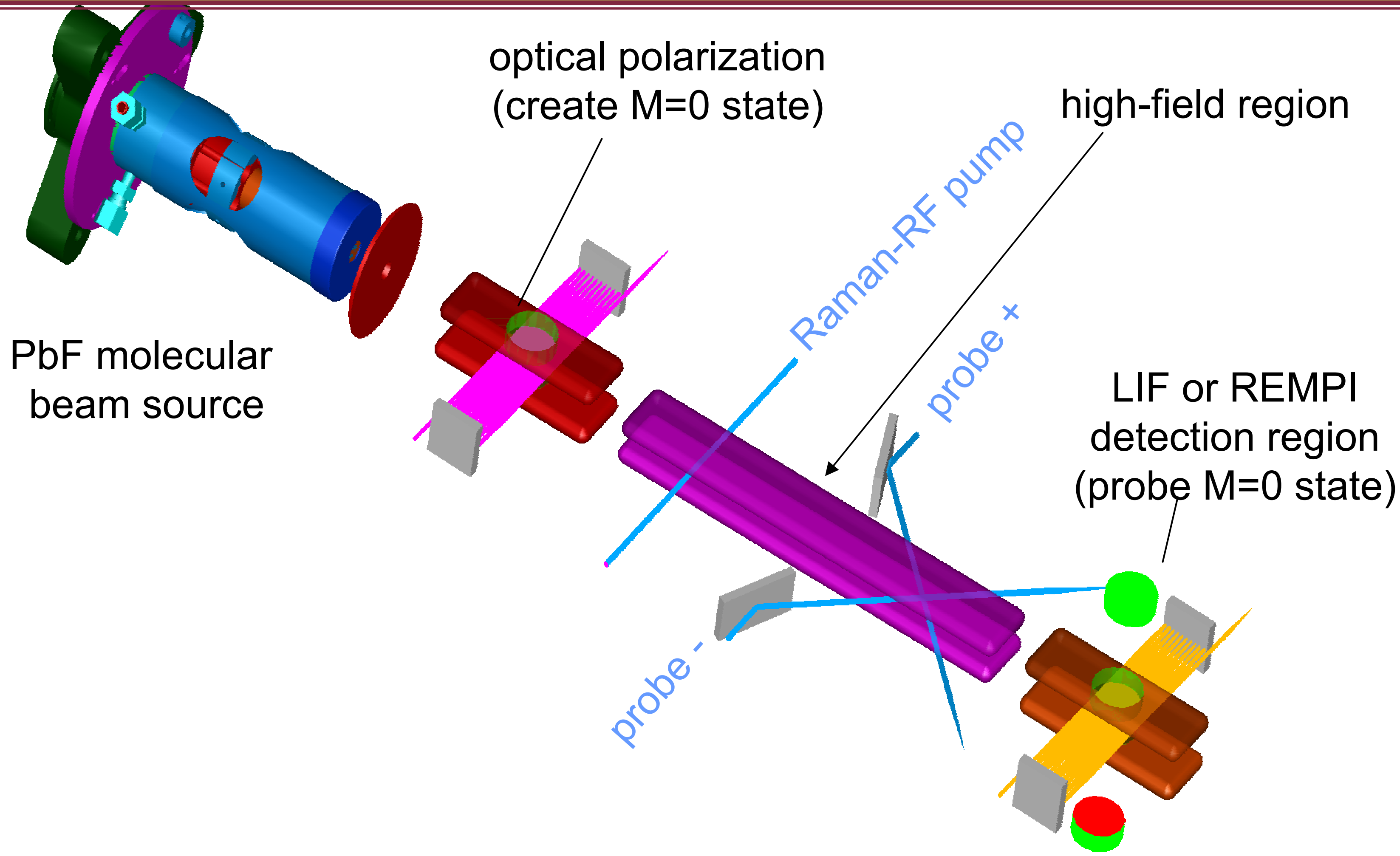
g-factor can be tuned to zero!

$g \approx \frac{1}{2}(G_{\|}) \approx 0.017$

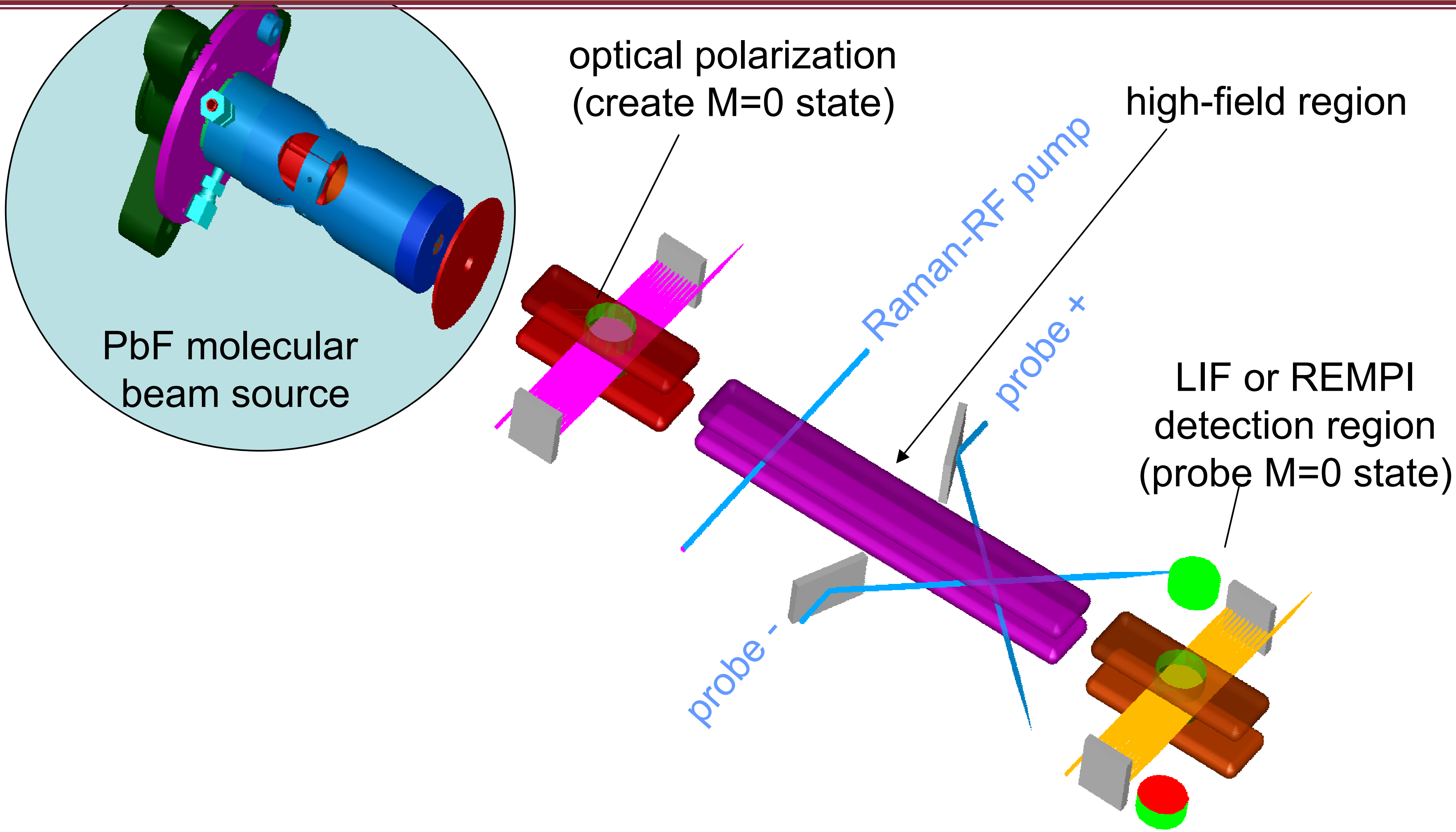


$g \approx -\frac{1}{2}(2G_{\perp}/3) \approx -0.11$

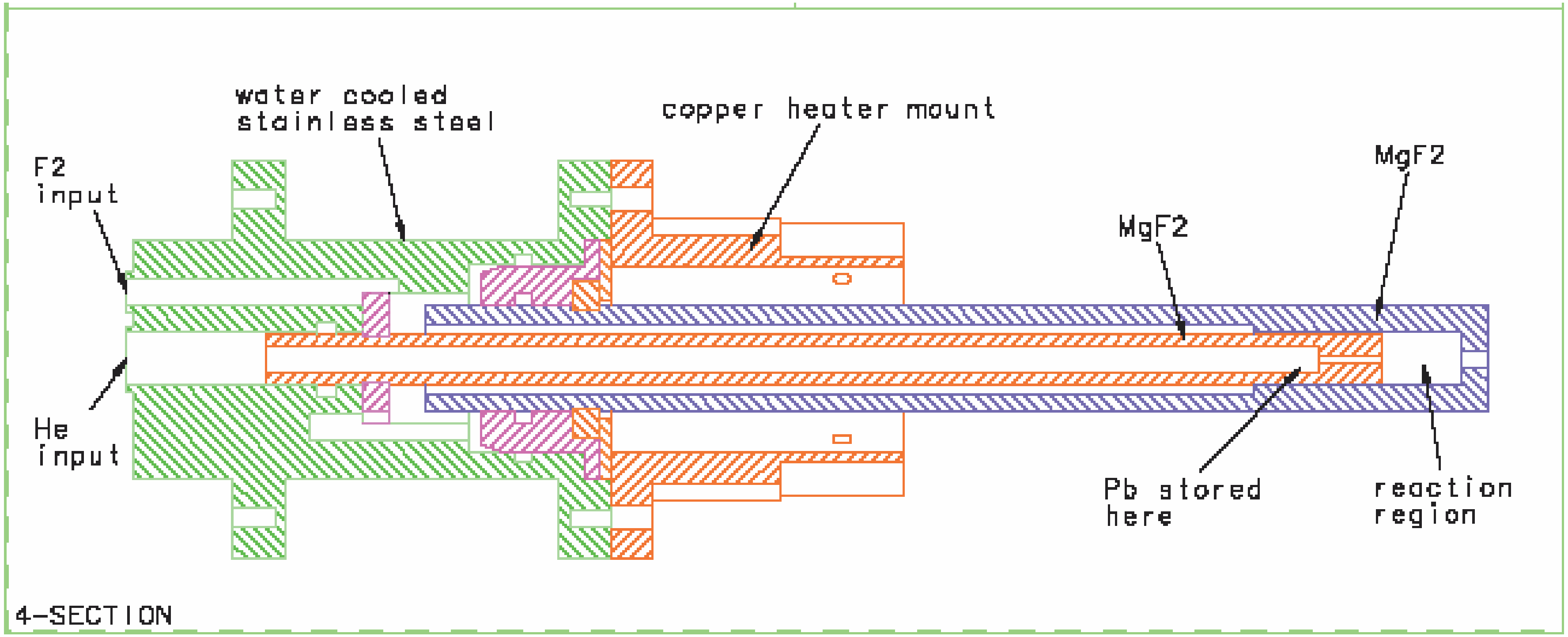
Schematic of PbF g=0 measurement



Schematic of PbF g=0 measurement



First things first: Production and detection of PbF

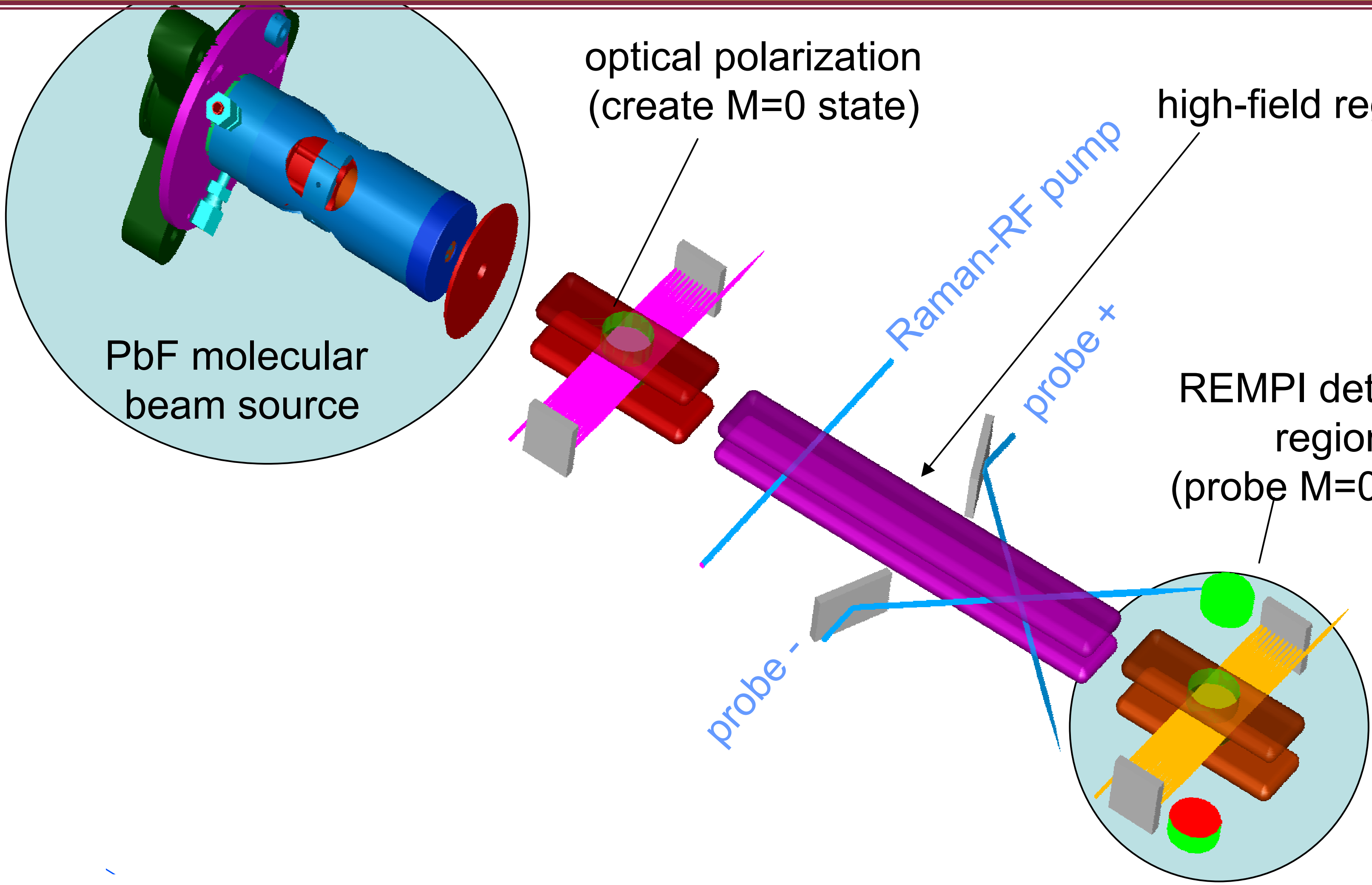


Pb / F_2 flow reactor: Operational Temperature 1200K

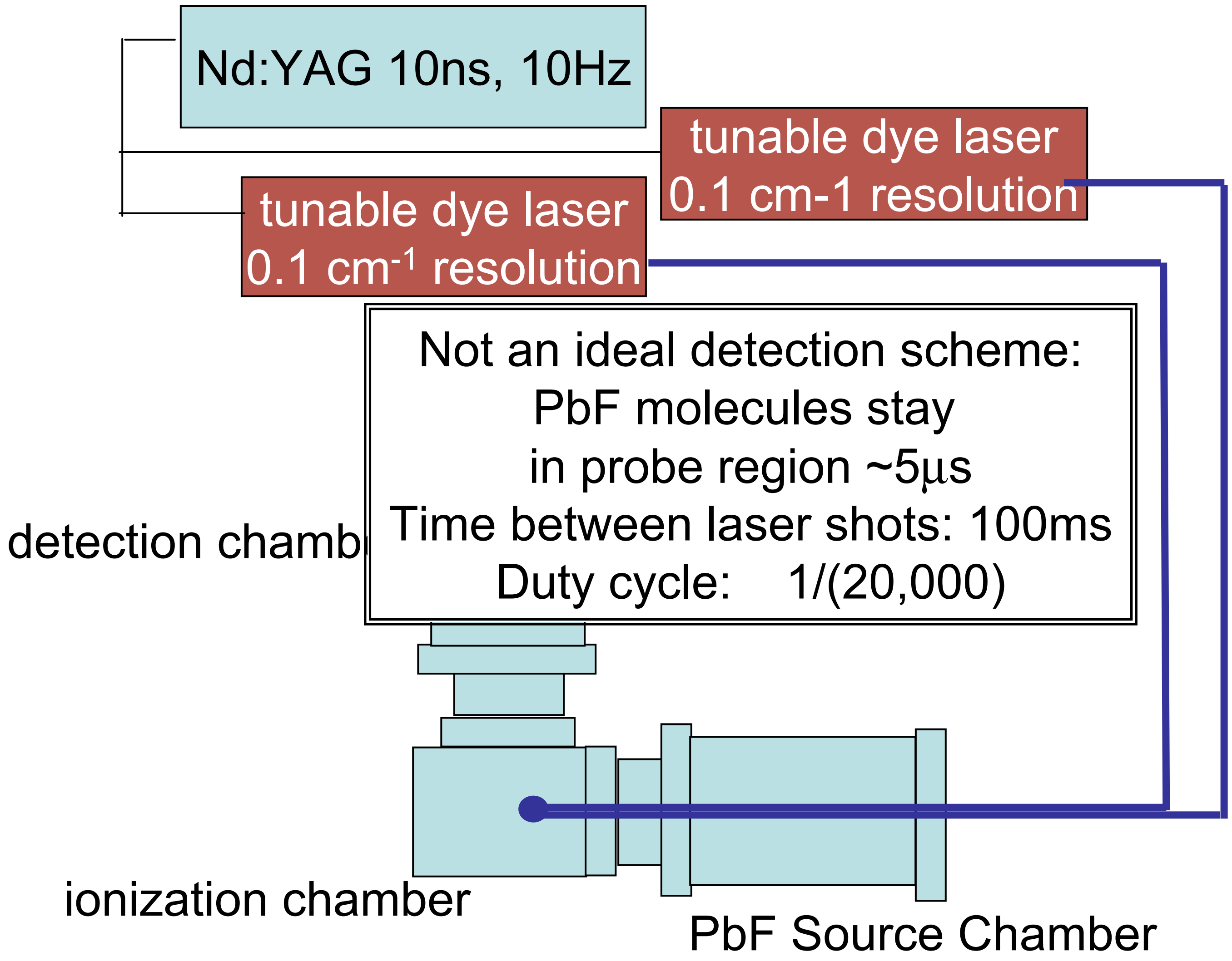
Pb +MgF_2 reactor: Operational Temperature 1200K

Pb +PbF_2 reactor: Operational Temperature 1200K

Schematic of PbF g=0 measurement



Current Apparatus for Exploring PbF Spectroscopy



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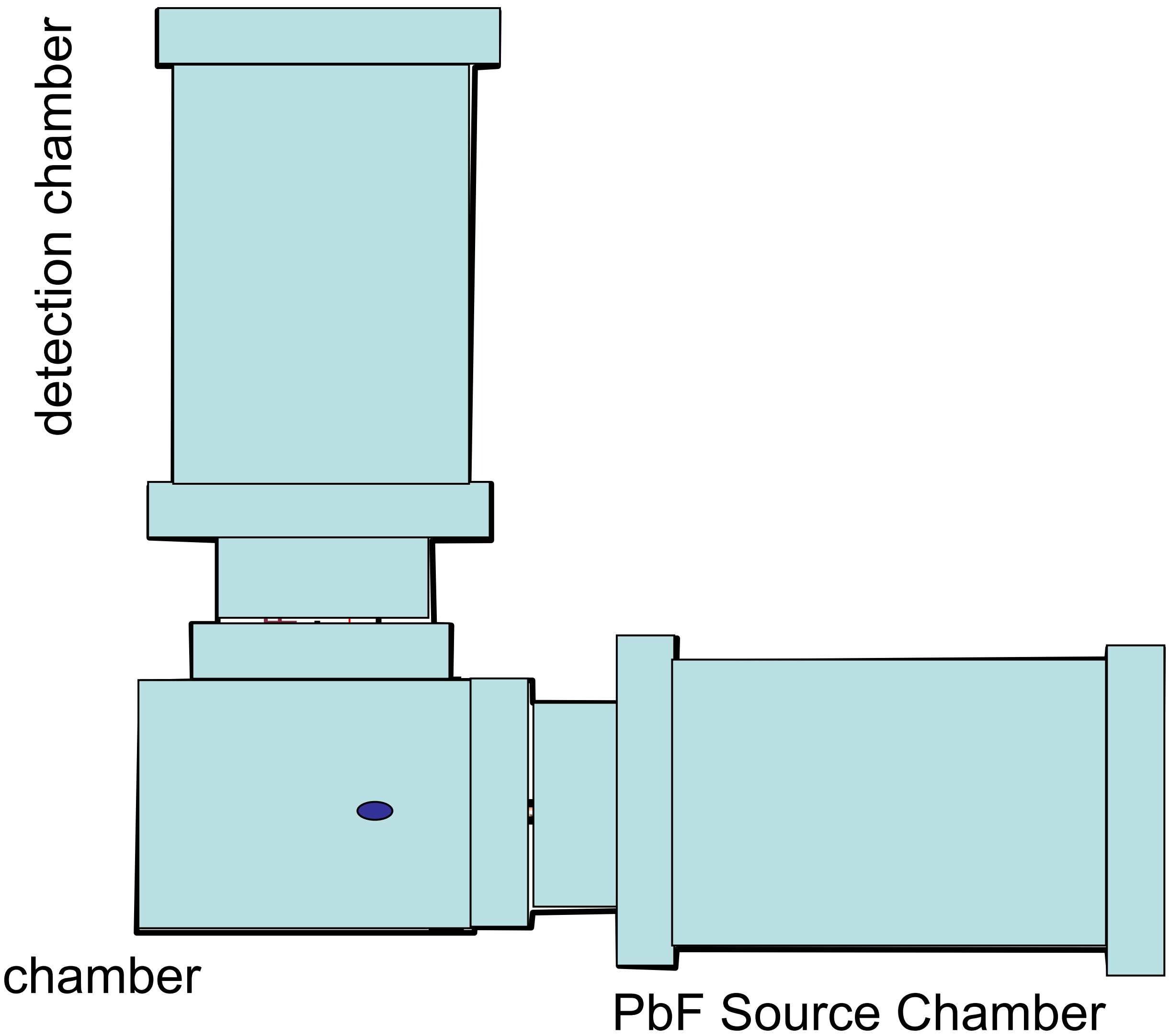

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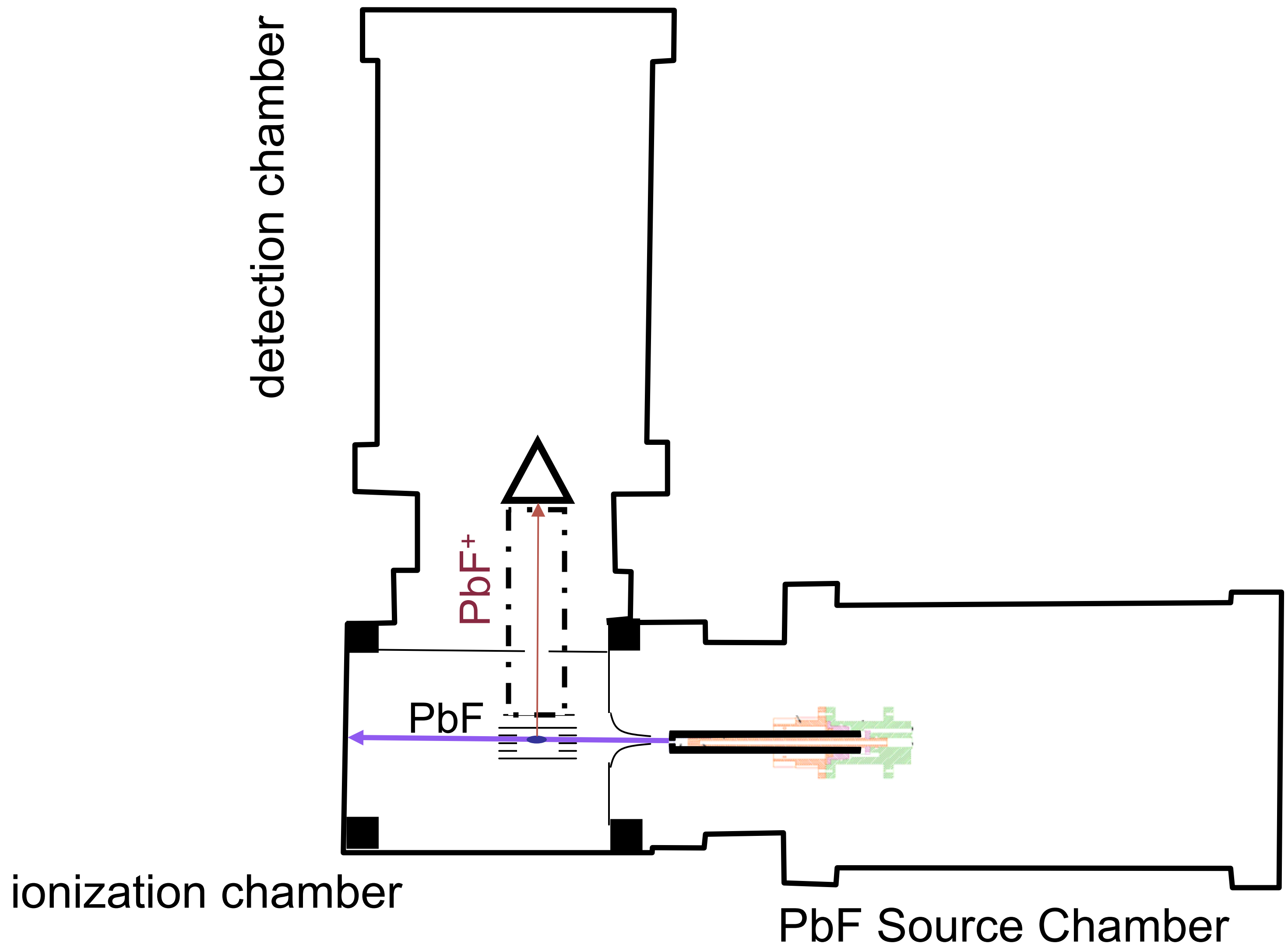
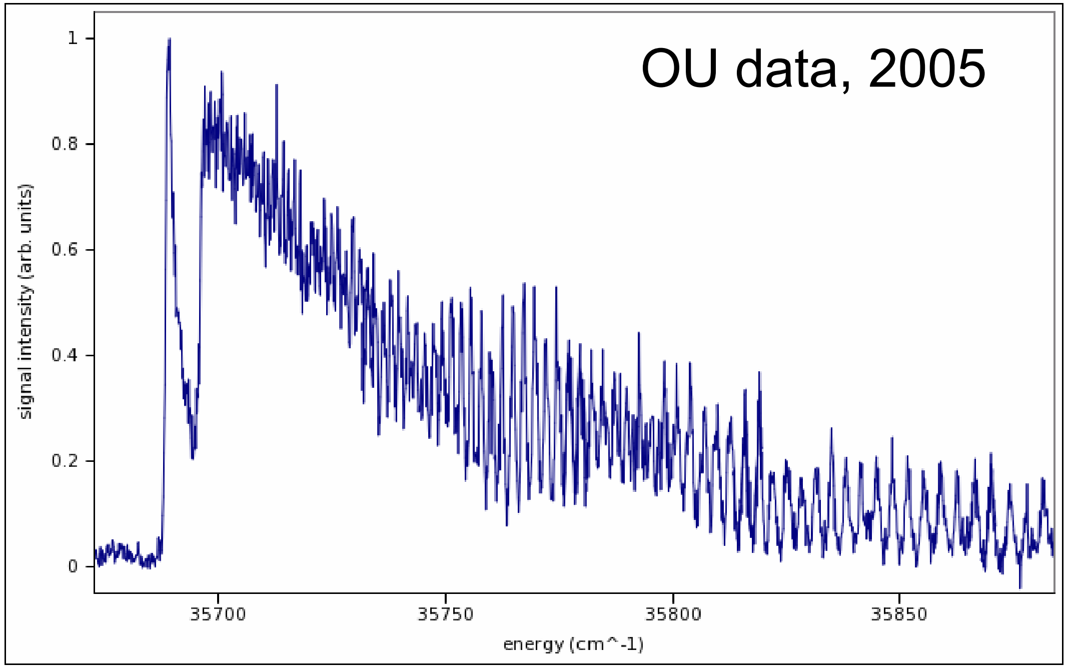
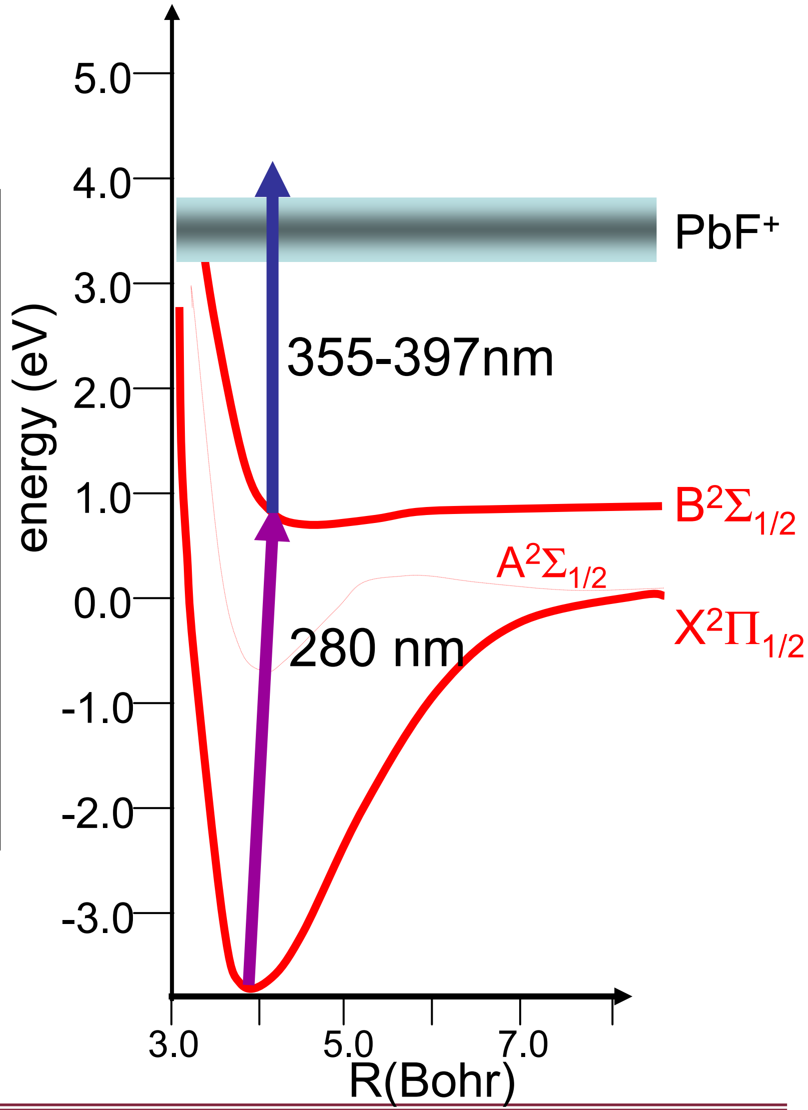


1+1 $X_1{}^2\Pi_{1/2} \rightarrow B^2\Sigma_{1/2}$ REMPI of PbF

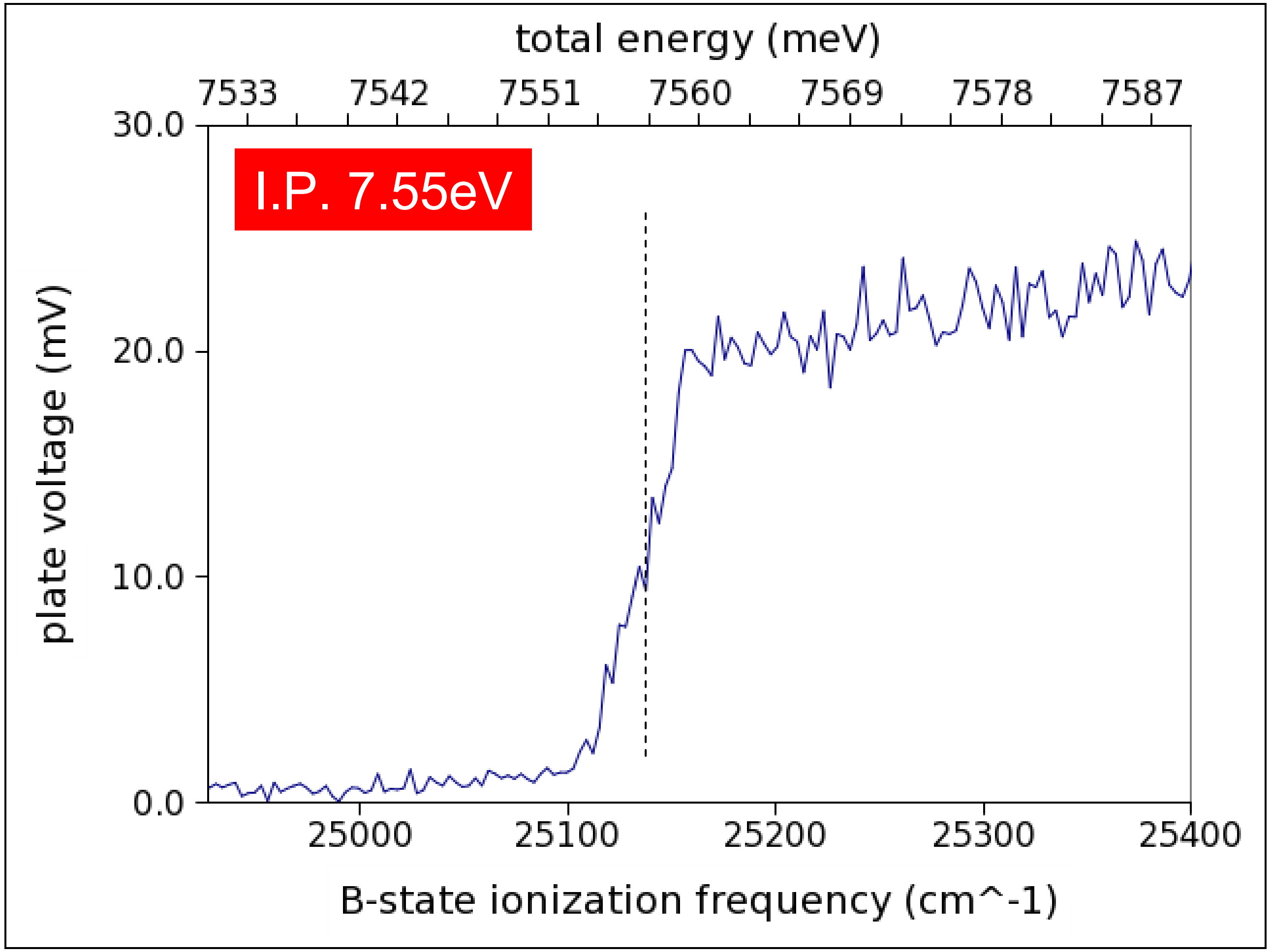
McRaven, Poopalasingam, Shafer-Ray, Chemical Physics Letters, In Progress.





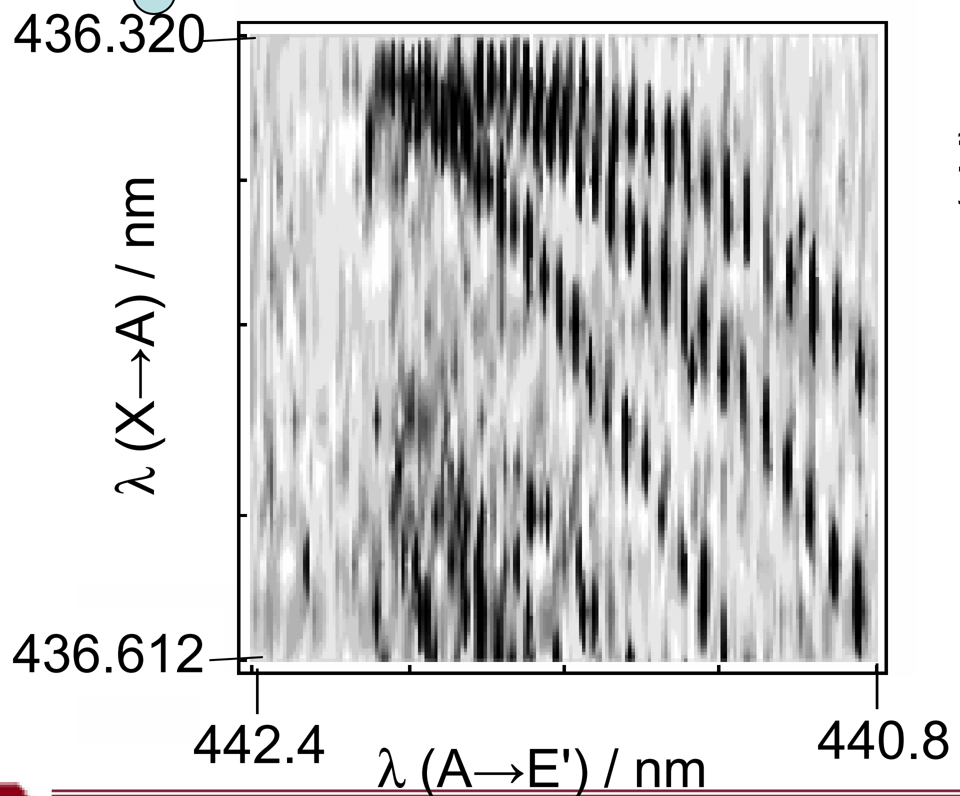
Observation of an ionization threshold for PbF

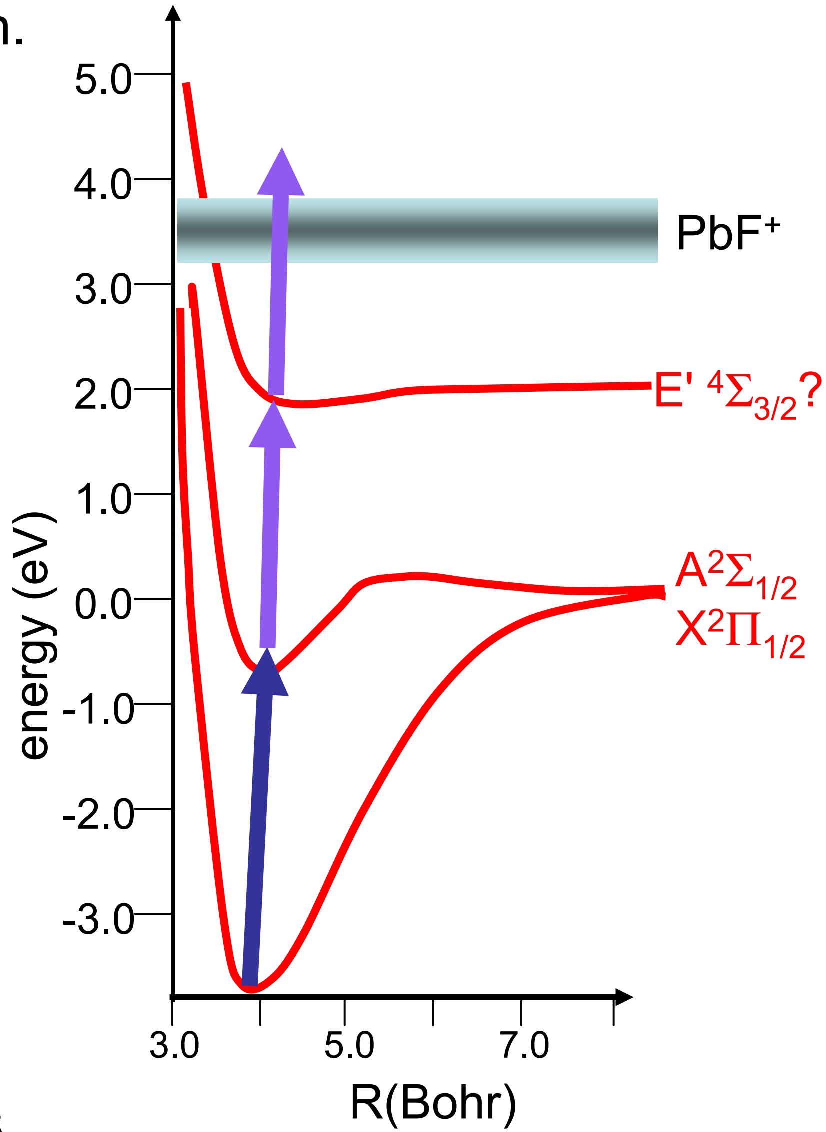
McRaven, Poopalasingam, Shafer-Ray,
Chemical Physics Letters, In Progress.



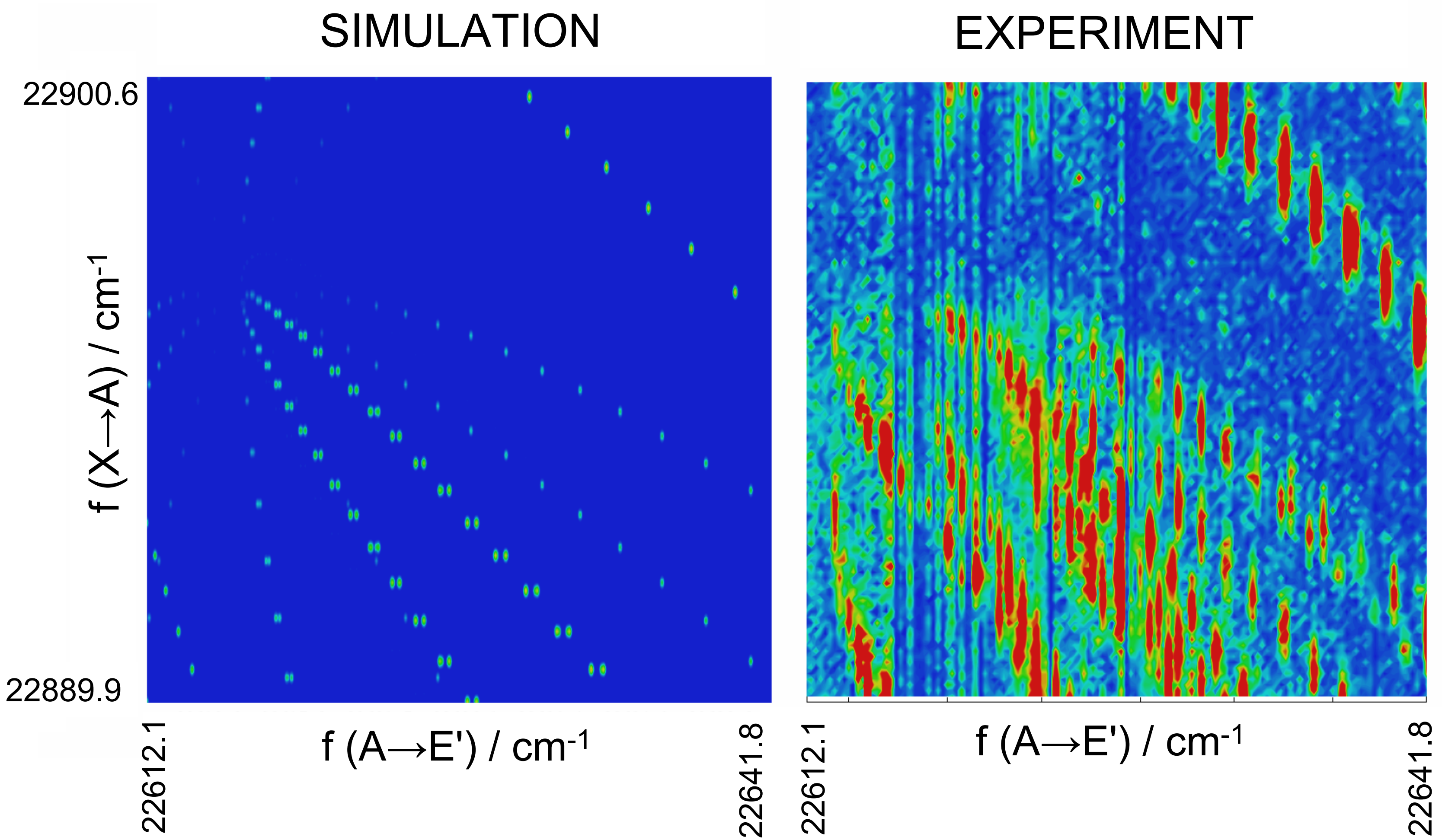
State selective ionization of PbF^+ via 1+1+1 doubly-resonant multi-photon ionization.

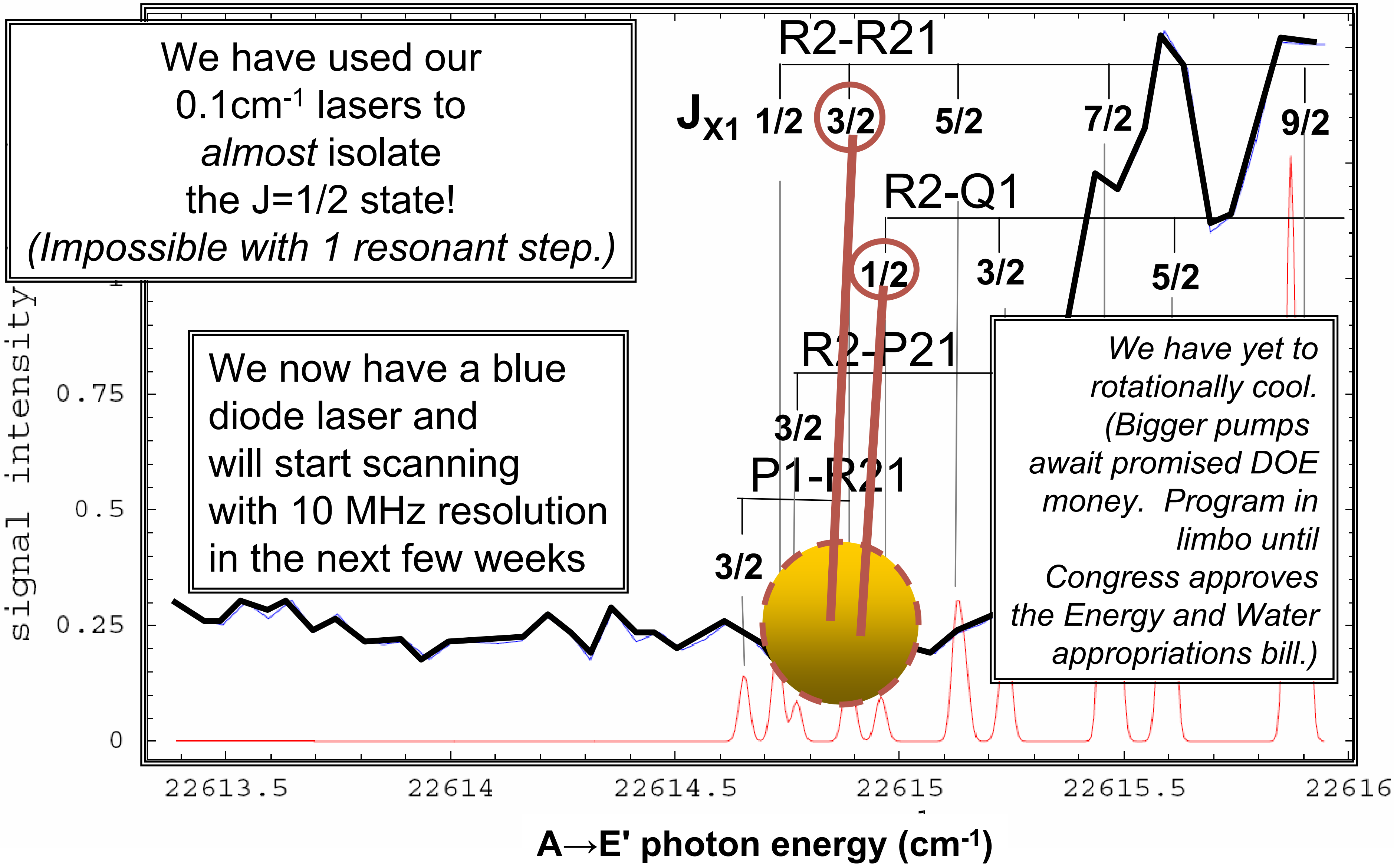
WE HAVE DISCOVERED A NEW ELECTRONIC STATE OF PbF (tentative assignment: $E'^4\Sigma_{3/2}$)



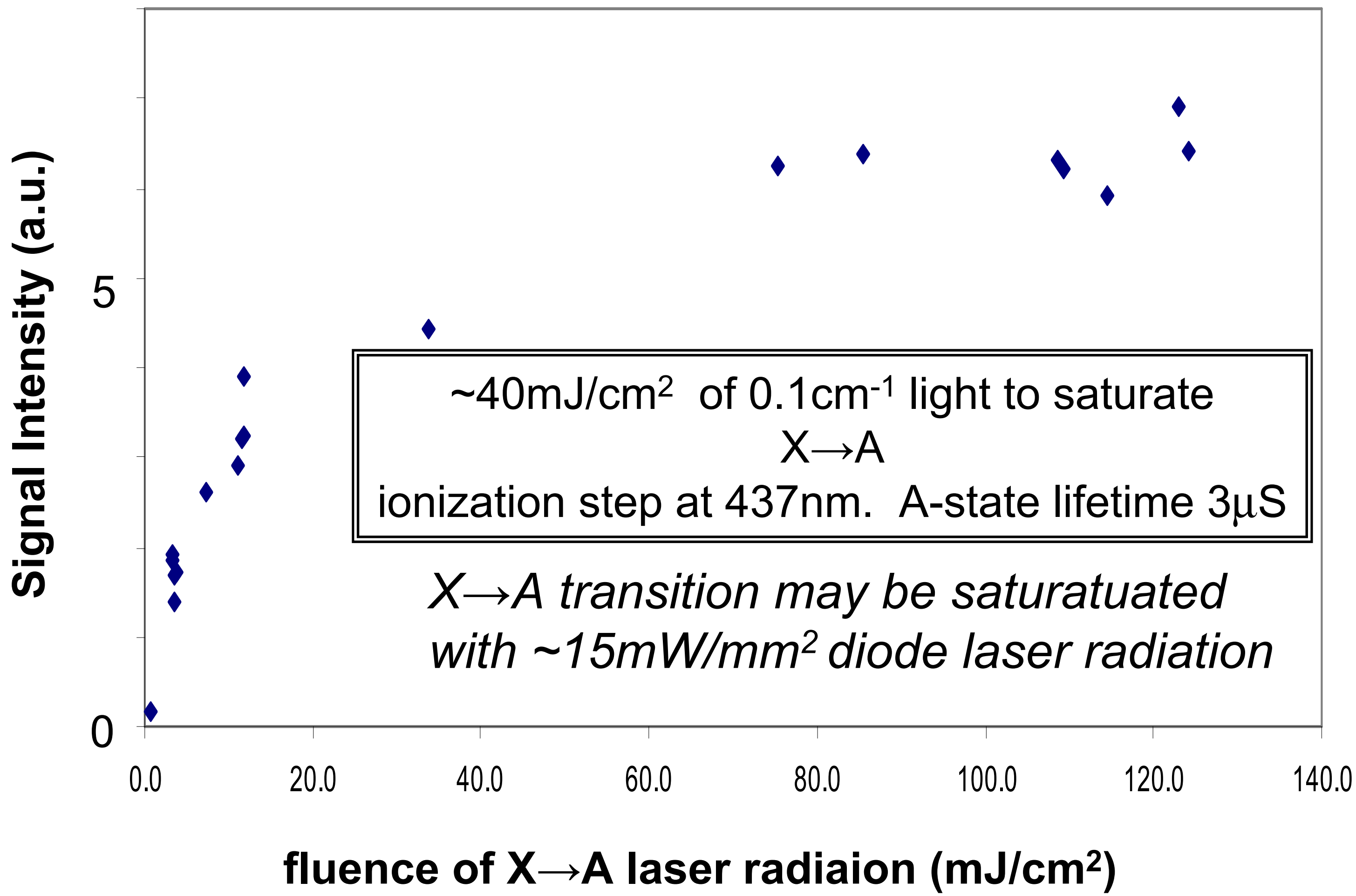


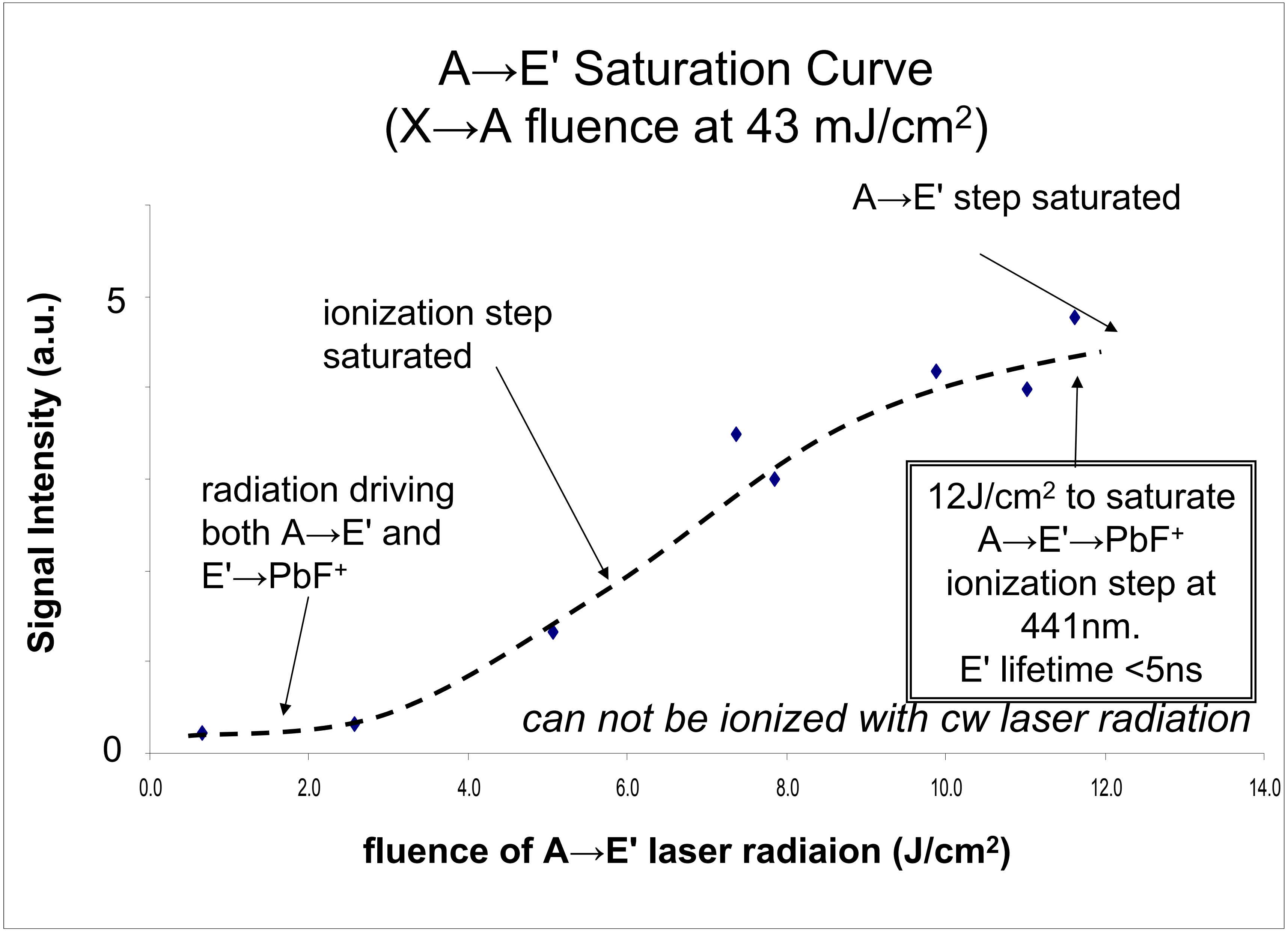
Double Resonant Ionization of PbF



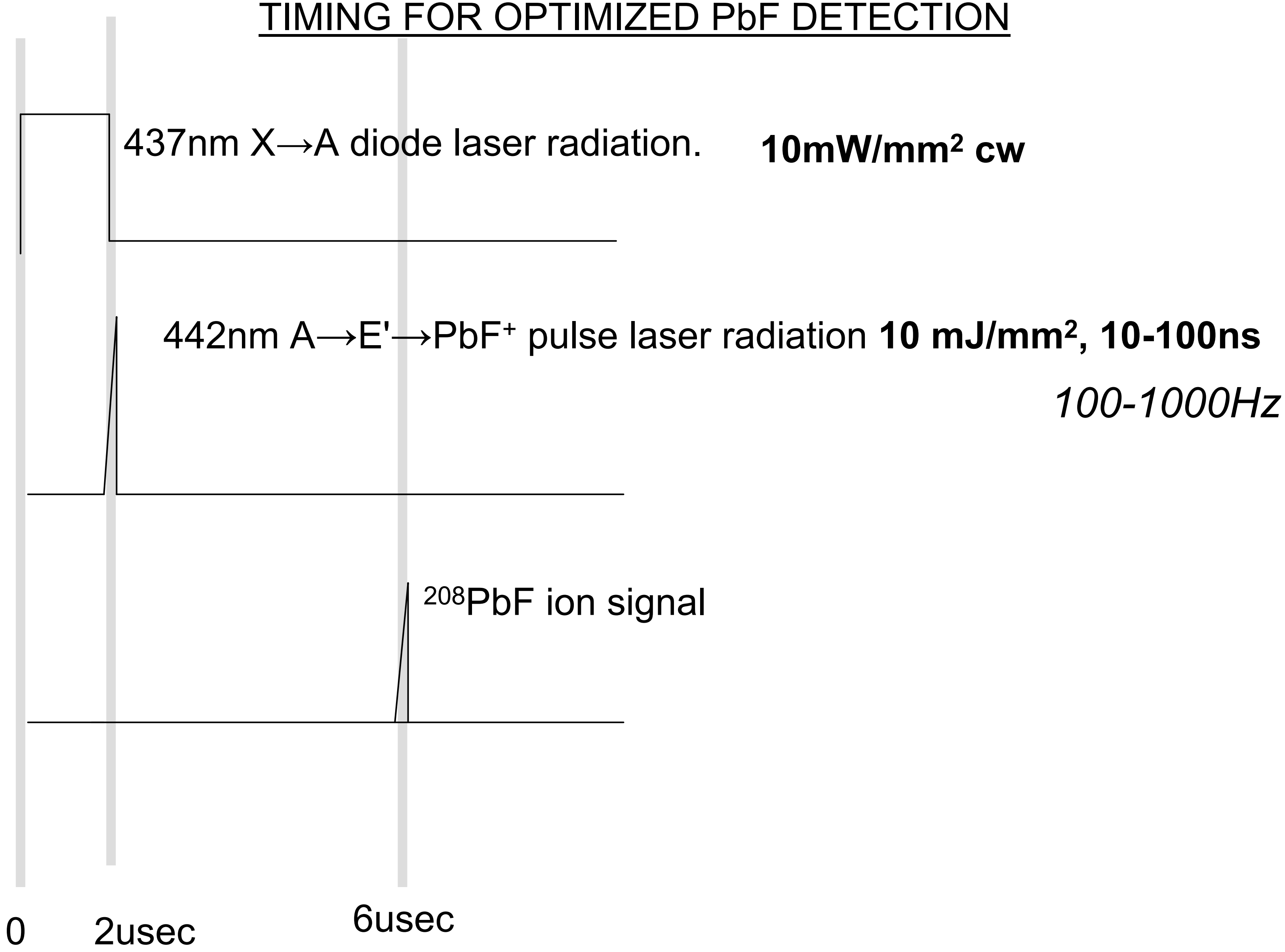

We have used our 0.1cm-1 lasers to *almost* isolate the J=1/2 state! *(Impossible with 1 resonant step.)*
We now have a blue diode laser and will start scanning with 10 MHz resolution in the next few weeks
We have yet to rotationally cool. (Bigger pumps await promised DOE money. Program in limbo until Congress approves the Energy and Water appropriations bill.)
R2-R21
J X1
1/2
3/2
5/2
7/2
9/2
R2-Q1
1/2
3/2
5/2
R2-P21
3/2
P1-R21
3/2
signal intensity
0.75
0.5
0.25
0
22613.5
22614
22614.5
22615
22615.5
22616
A→E' photon energy (cm-1)

X→A Saturation Curve
(A→E' fluence at 0.12 J/cm²)

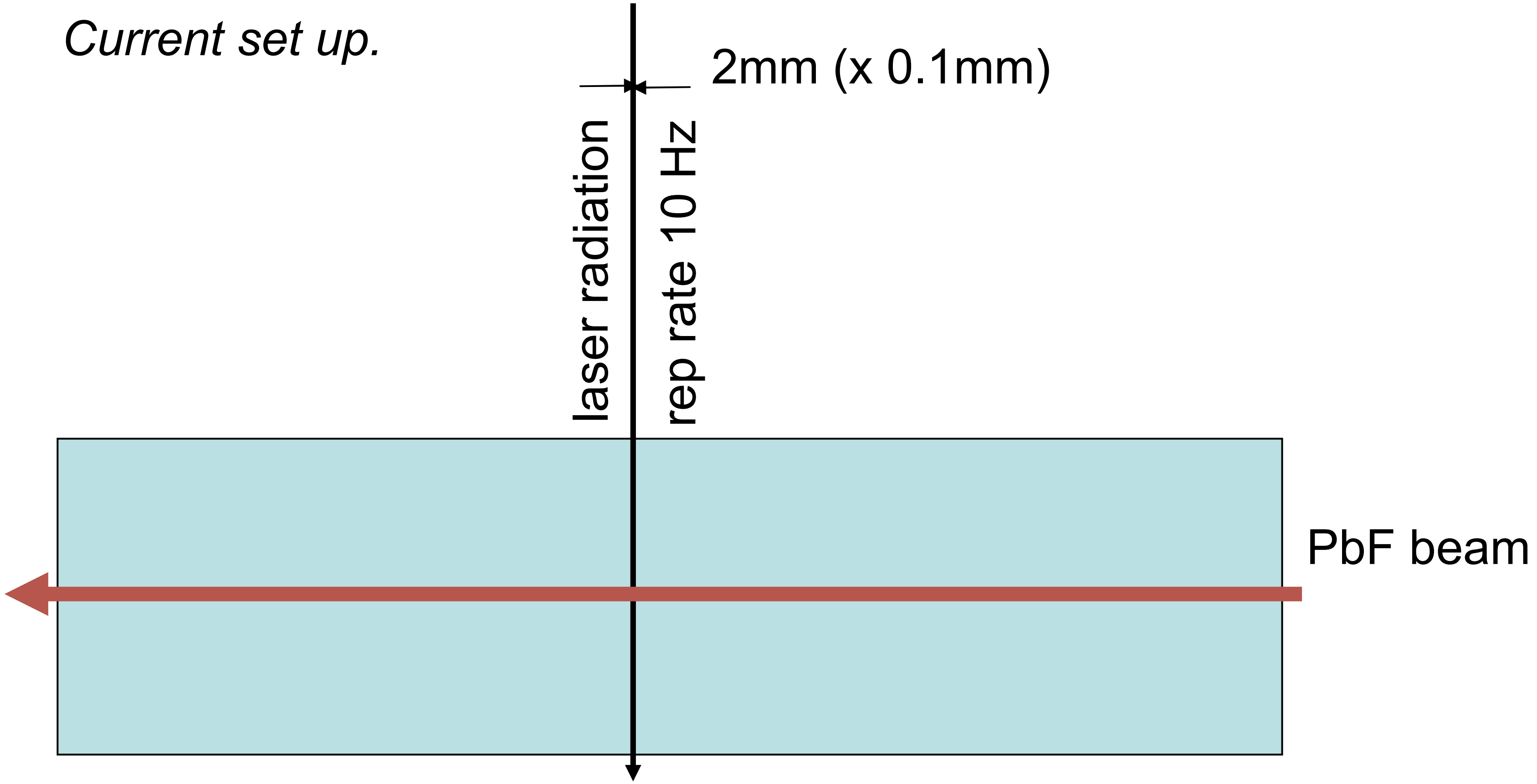



A→E' Saturation Curve
(X→A fluence at 43 mJ/cm2)
A→E' step saturated
Signal Intensity (a.u.)
5
0
ionization step
saturated
radiation driving
both A→E' and
E'→PbF+
12J/cm2 to saturate
A→E'→PbF+
ionization step at
441nm.
E' lifetime <5ns
can not be ionized with cw laser radiation
0.0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
fluence of A→E' laser radiaion (J/cm2)

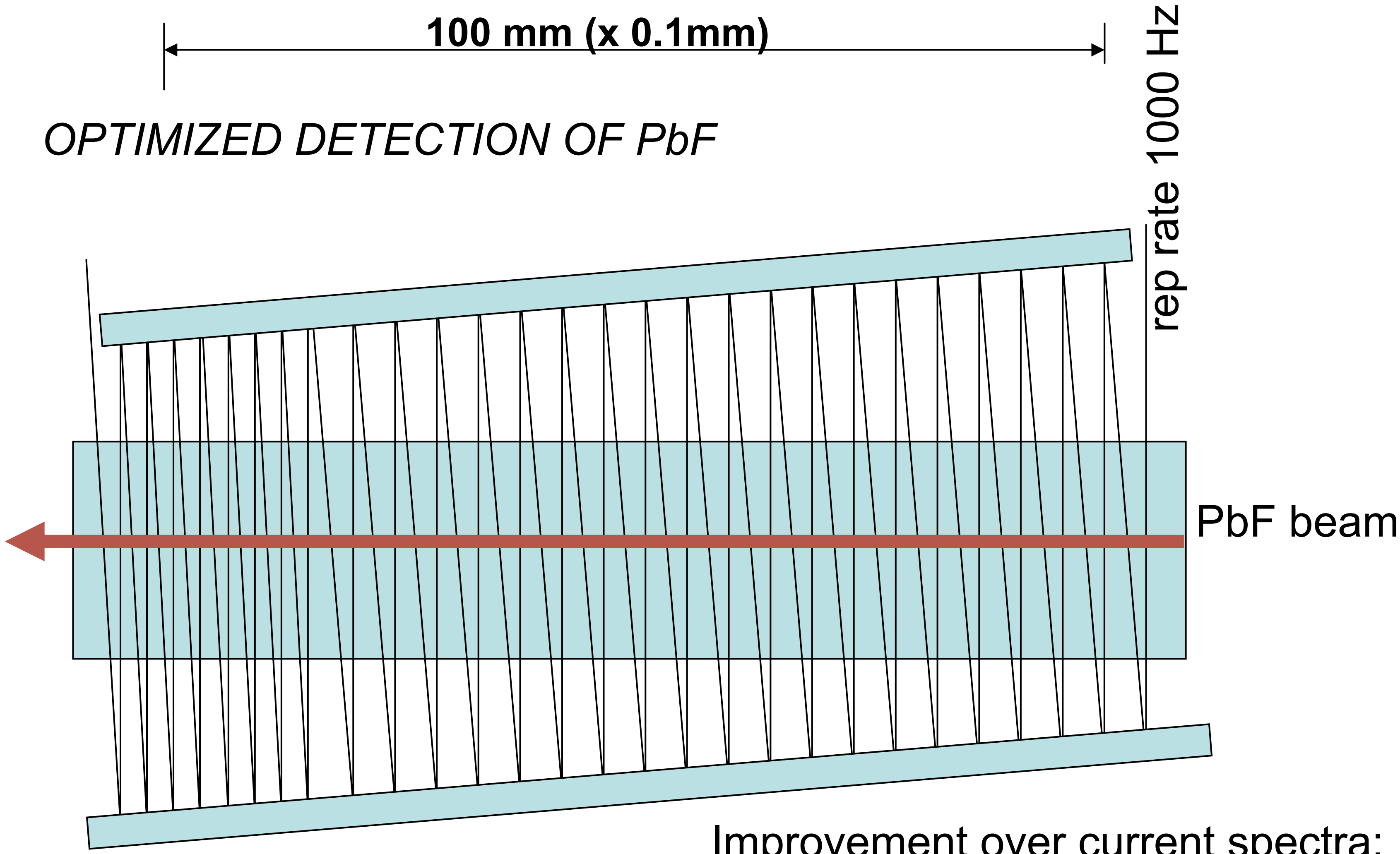
TIMING FOR OPTIMIZED PbF DETECTION



Current set up.

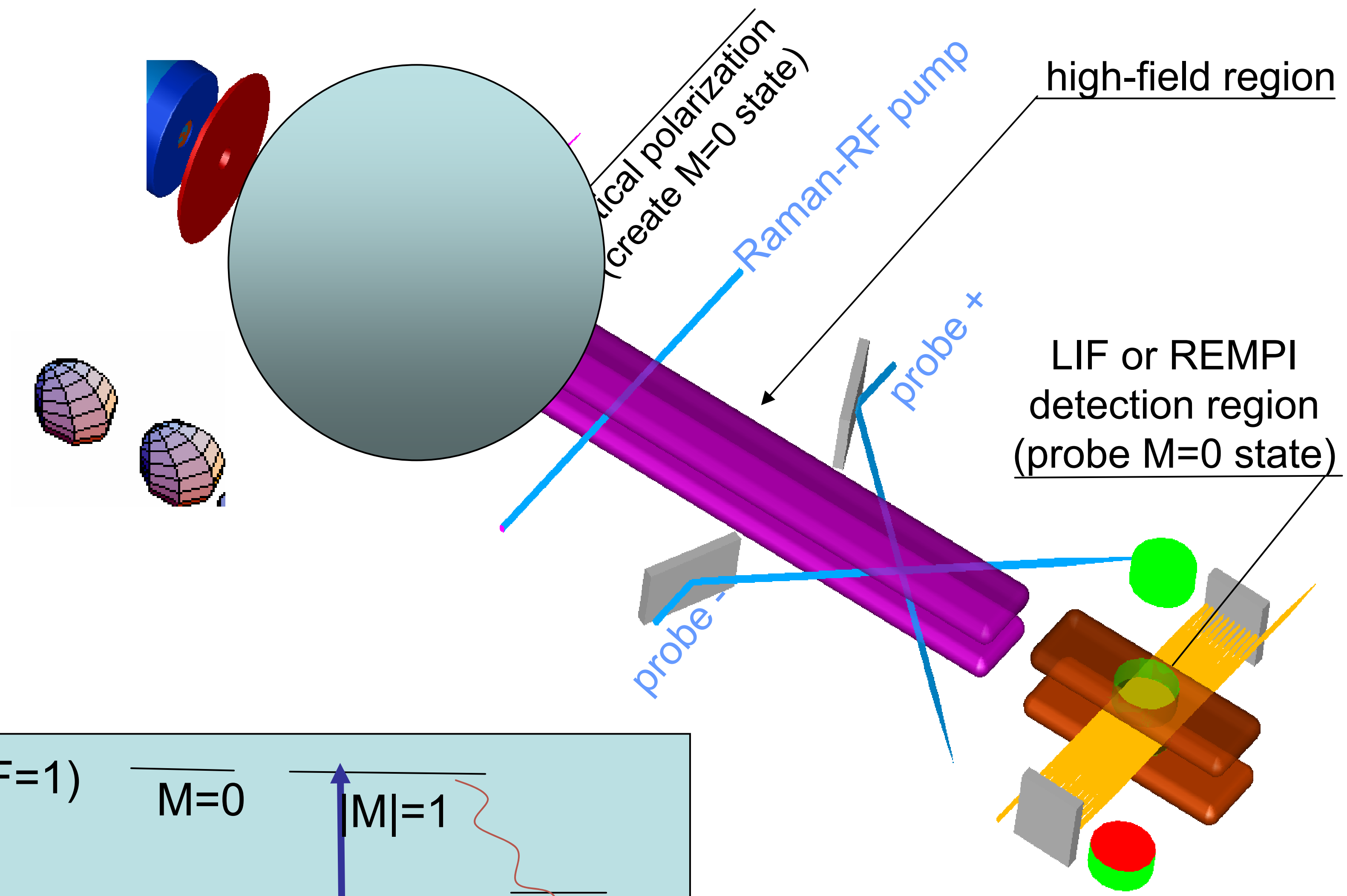


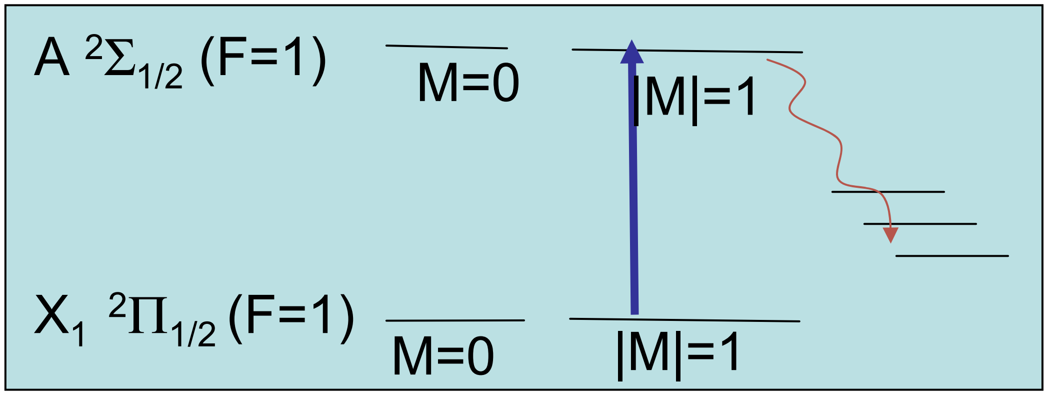
OPTIMIZED DETECTION OF PbF

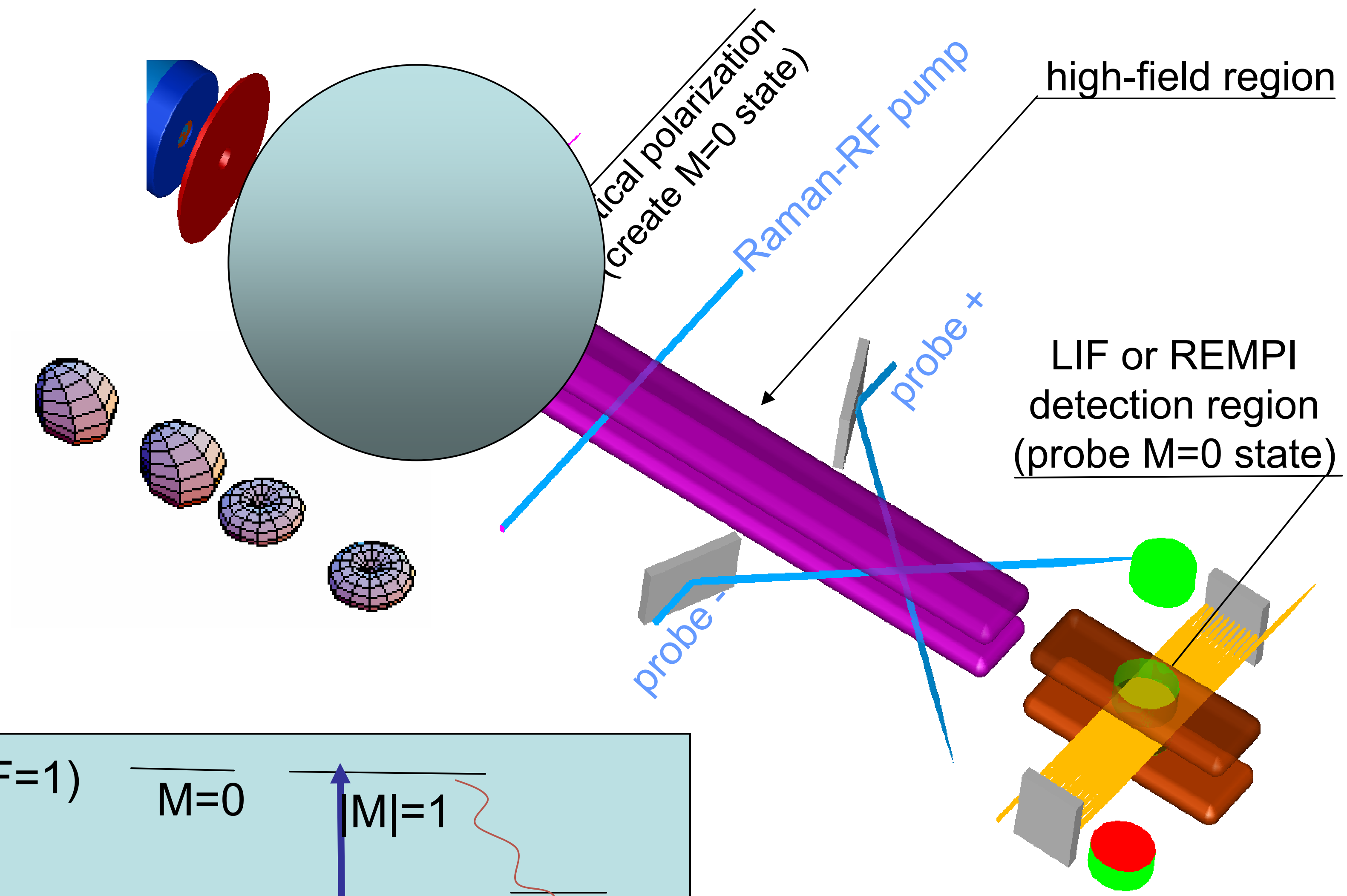


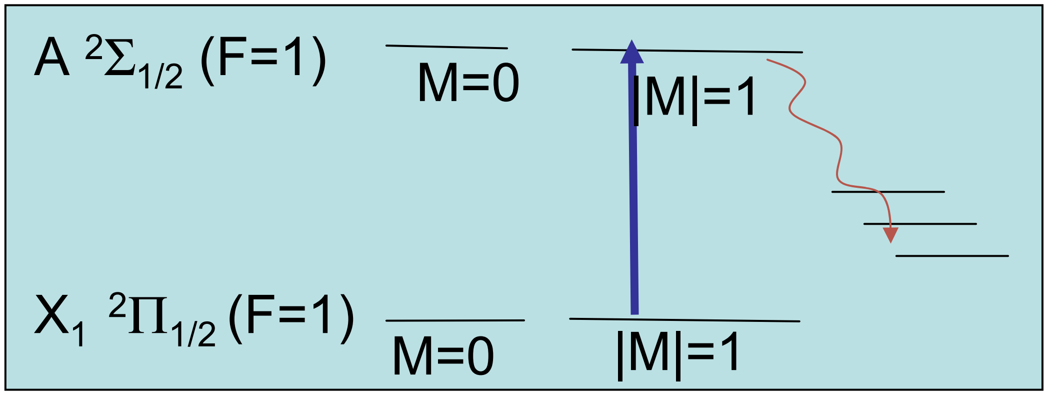
Improvement over current spectra:

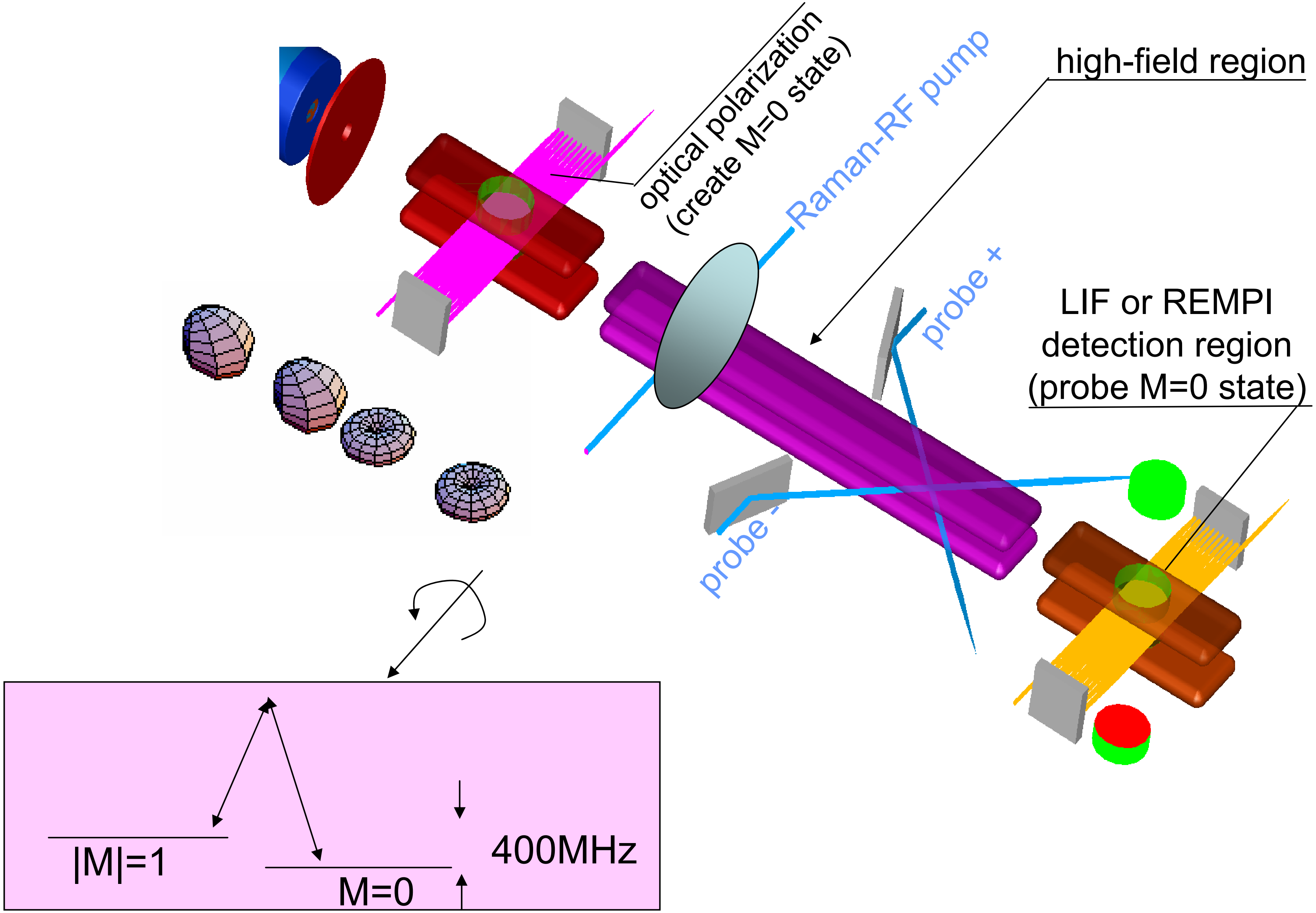
$$\frac{100mm}{2mm} \times \frac{10mJ/cm^2}{1mJ/cm^2} \times \frac{10Hz \text{ to } 1{,}000Hz}{10Hz} = 500 \text{ to } 50{,}000$$

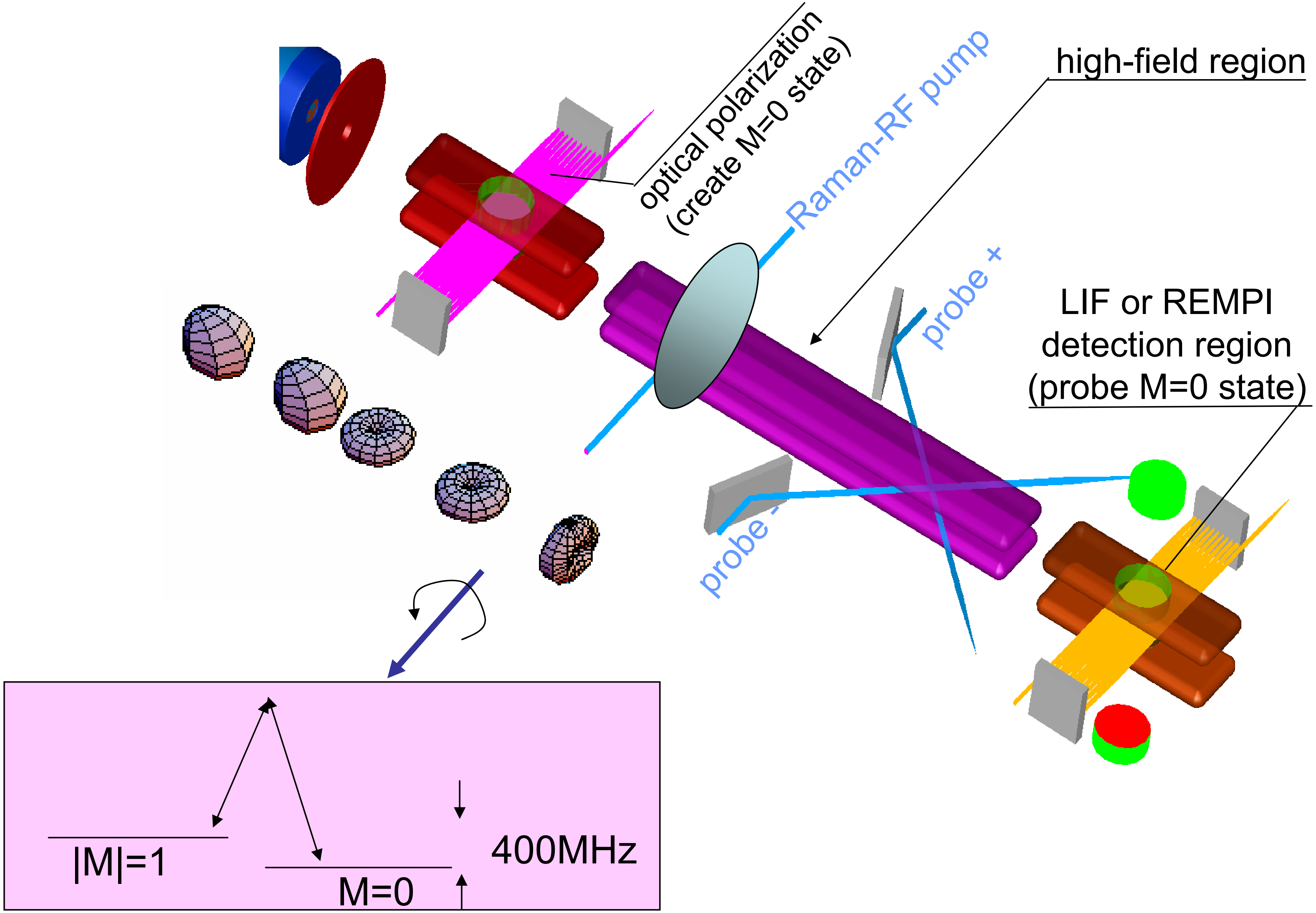

ical polarization
(create M=0 state)
Raman-RF pump
high-field region
probe +
LIF or REMPI
detection region
(probe M=0 state)
probe


A $^2\Sigma_{1/2}$ (F=1)
M=0
|M|=1
X_1 $^2\Pi_{1/2}$ (F=1)
M=0
|M|=1

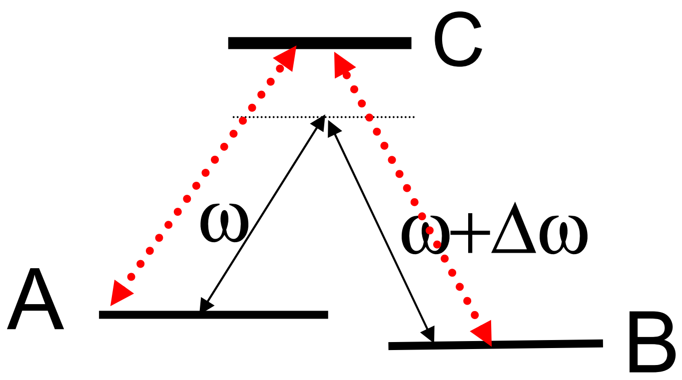

(create M=0 state)
Raman-RF pump
high-field region
probe +
LIF or REMPI
detection region
(probe M=0 state)
probe


A $^2\Sigma_{1/2}$ (F=1)
M=0
|M|=1
X_1 $^2\Pi_{1/2}$ (F=1)
M=0
|M|=1


optical polarization
(create M=0 state)
Raman-RF pump
high-field region
probe +
LIF or REMPI
detection region
(probe M=0 state)
|M|=1
M=0
400MHz


optical polarization
(create M=0 state)
Raman-RF pump
high-field region
probe +
LIF or REMPI
detection region
(probe M=0 state)
probe -
|M|=1
M=0
400MHz

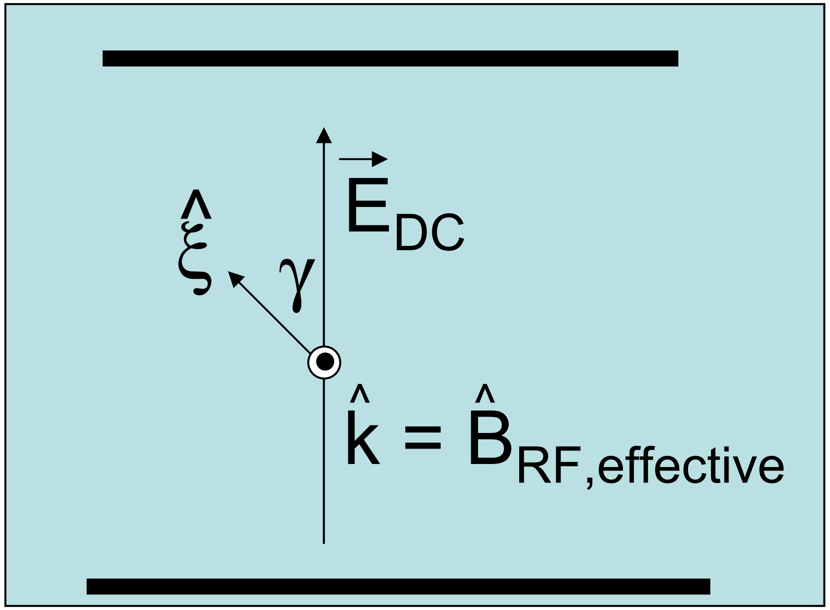
Requirements for large Rabi population amplitude in Raman pumping from a state A to a state B



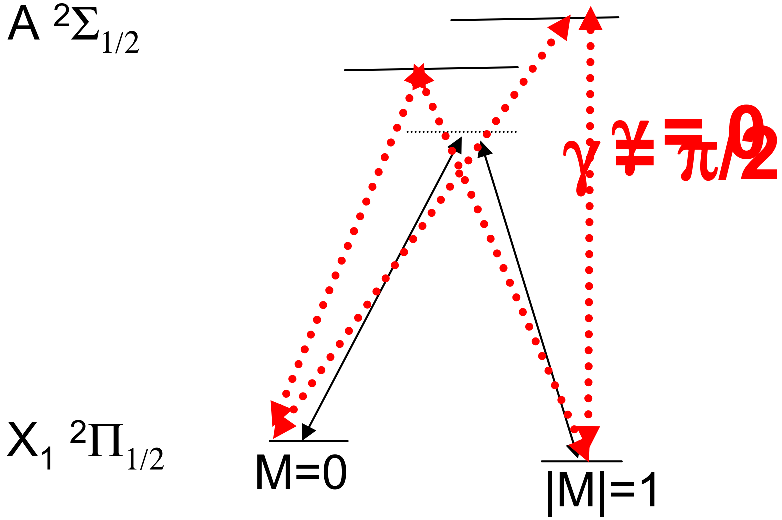
(1) Δω of lasers on resonance.

(2) At least 1 state C that couples to both A and B.

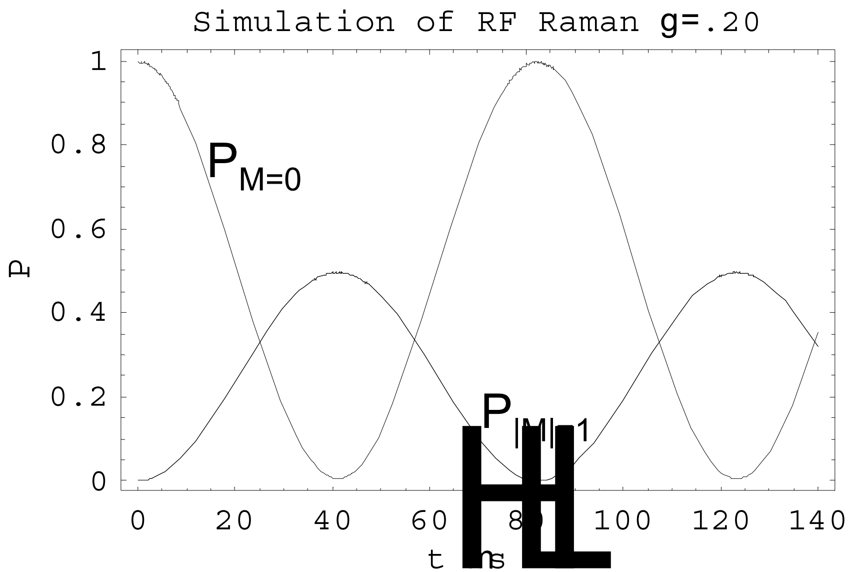
(3) A finely tuned ratio of A-C to B-C coupling.



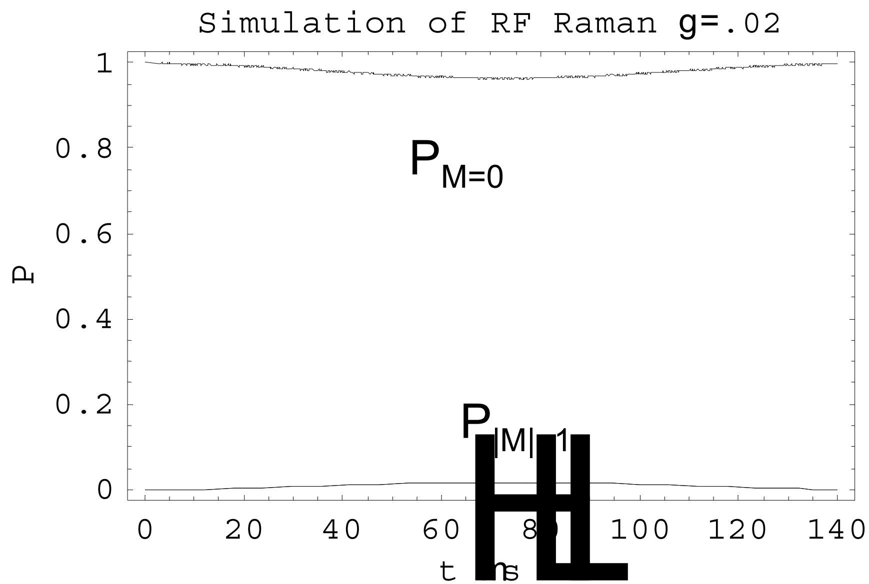
$\vec{E}_{DC}$
$\hat{\xi}$
γ
$\hat{k} = \hat{B}_{RF,effective}$



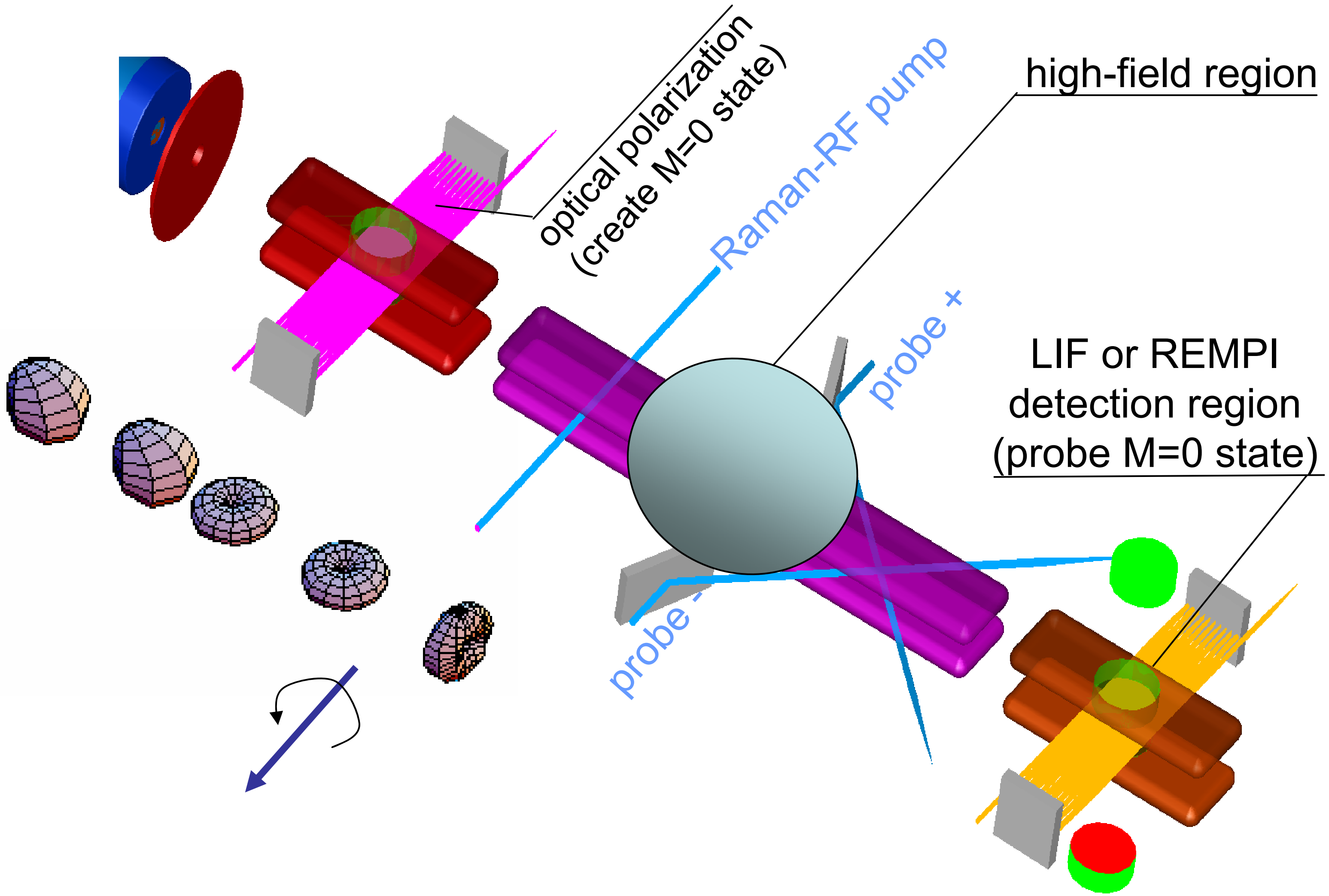
$A\ ^2\Sigma_{1/2}$
$X_1\ ^2\Pi_{1/2}$
M=0
|M|=1

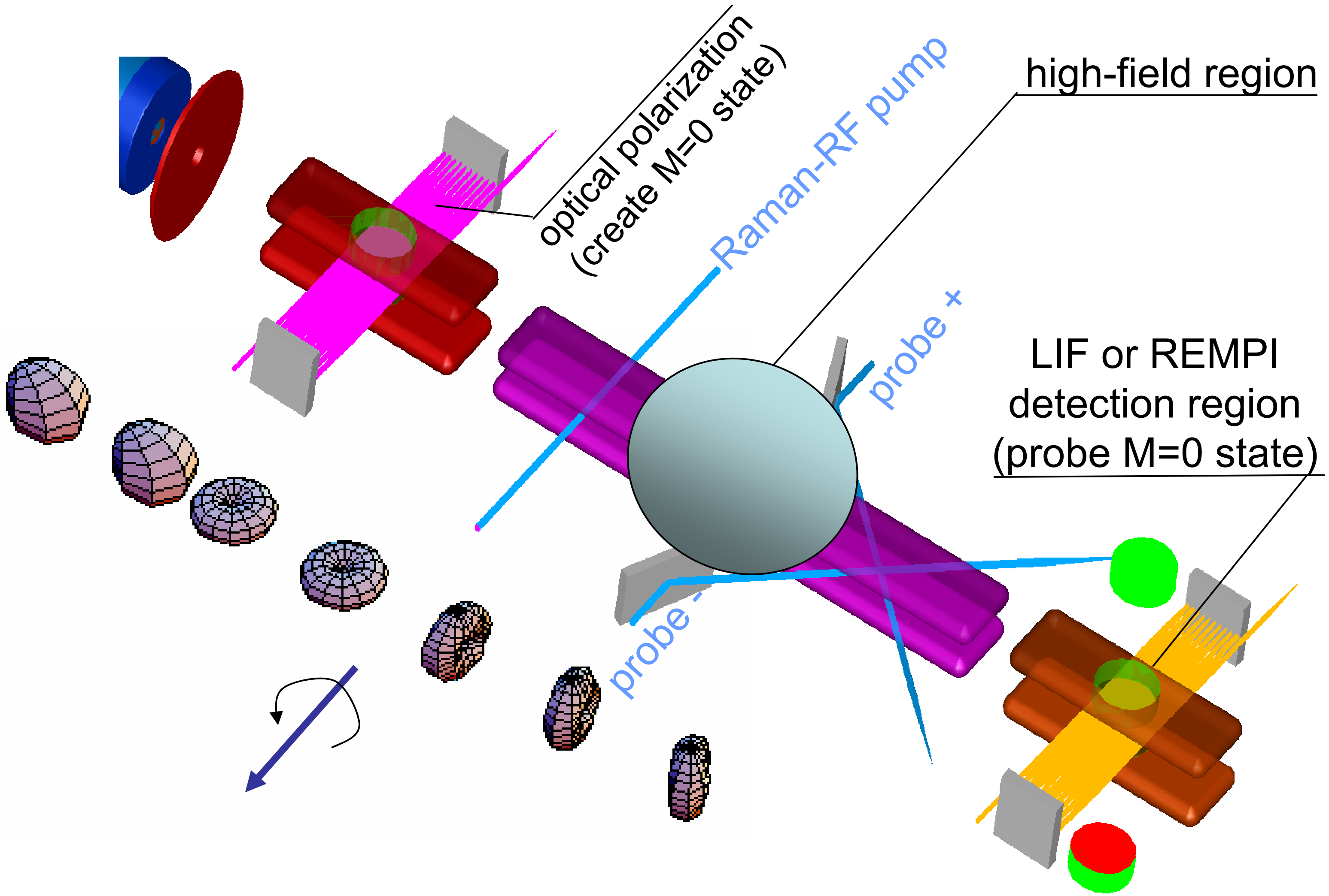


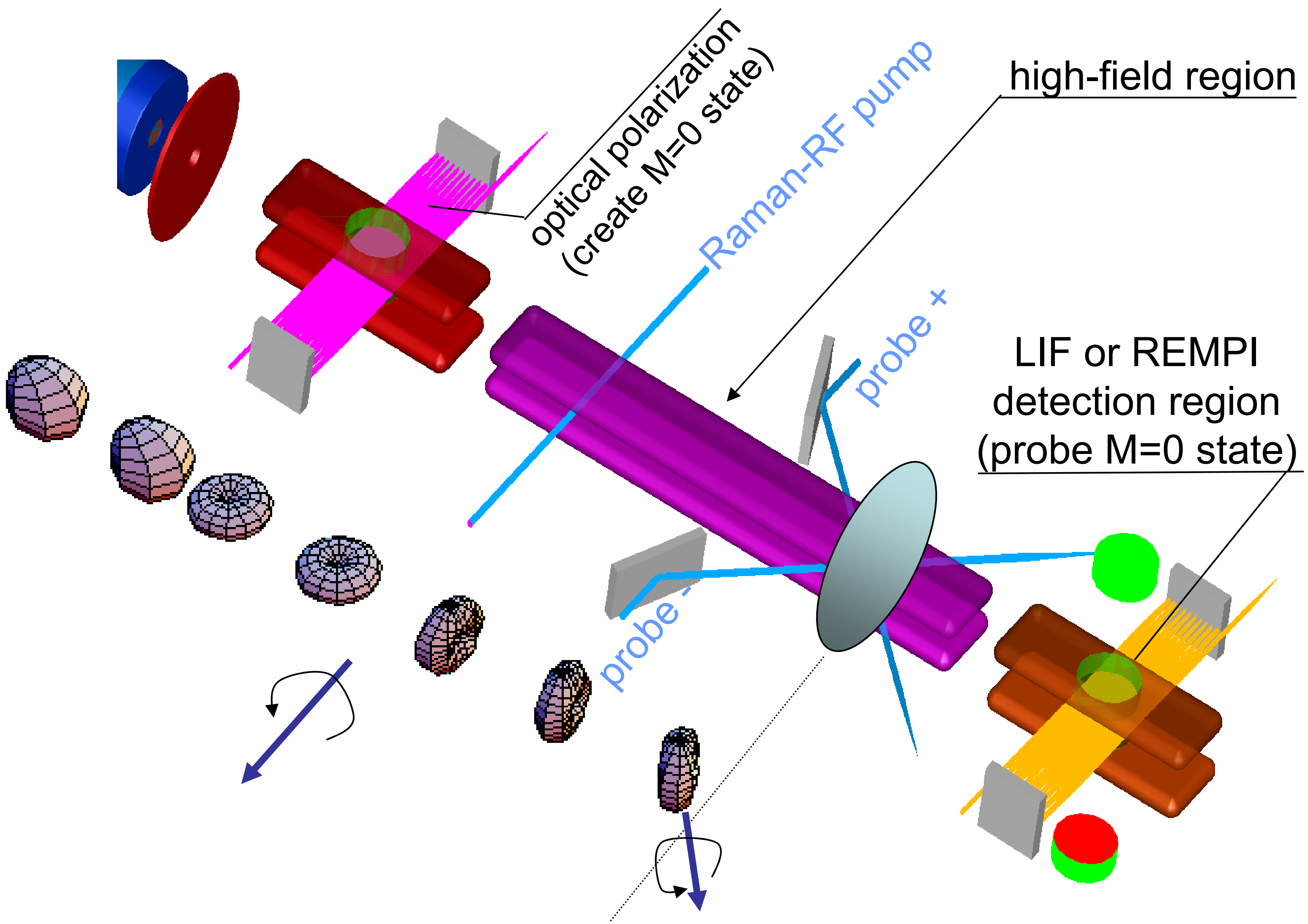
Simulation of RF Raman g=.20
$P_{M=0}$
P
t



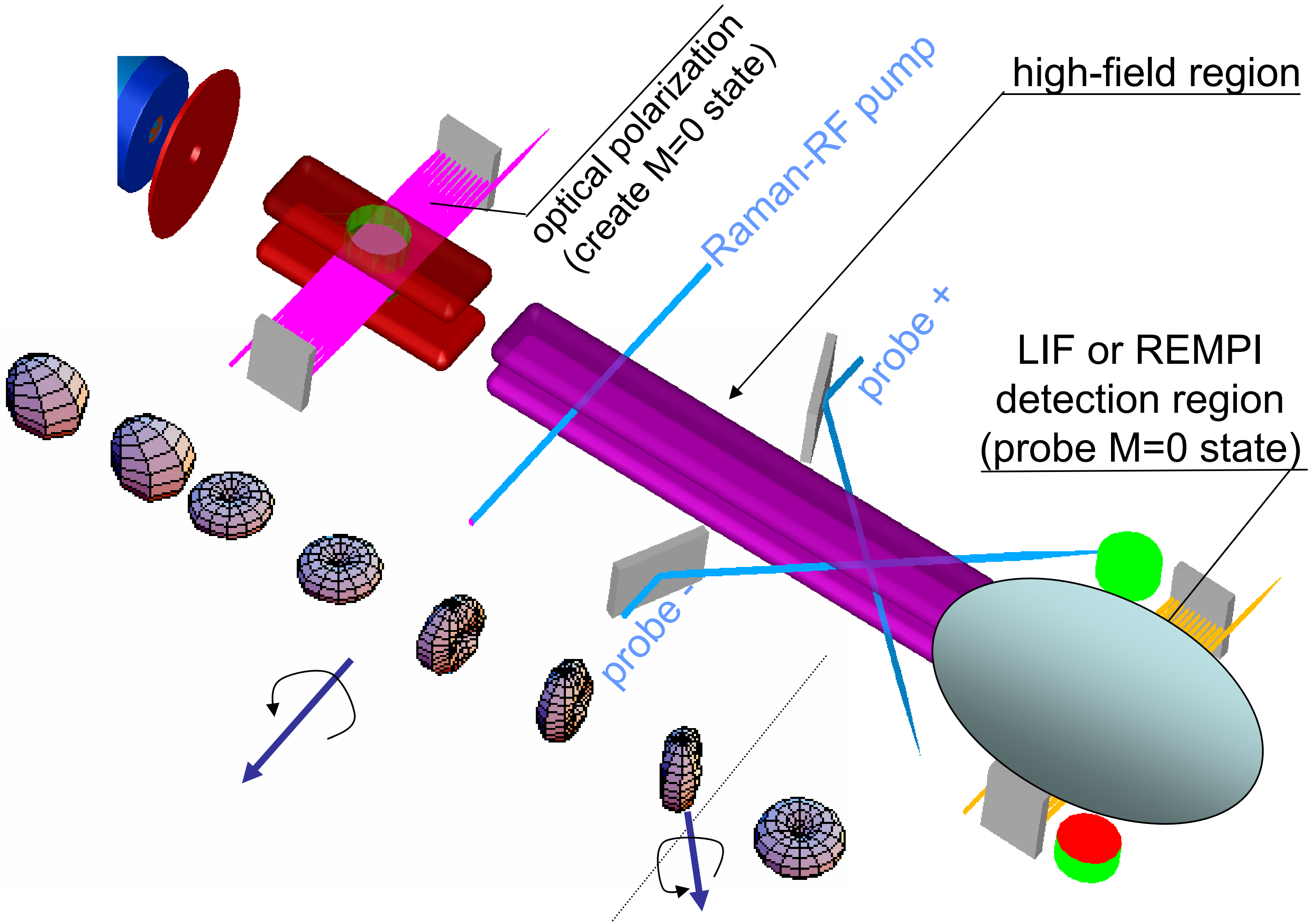
Simulation of RF Raman g=.02
$P_{M=0}$
P
t


optical polarization
(create M=0 state)
Raman-RF pump
high-field region
probe +
LIF or REMPI
detection region
(probe M=0 state)
probe -

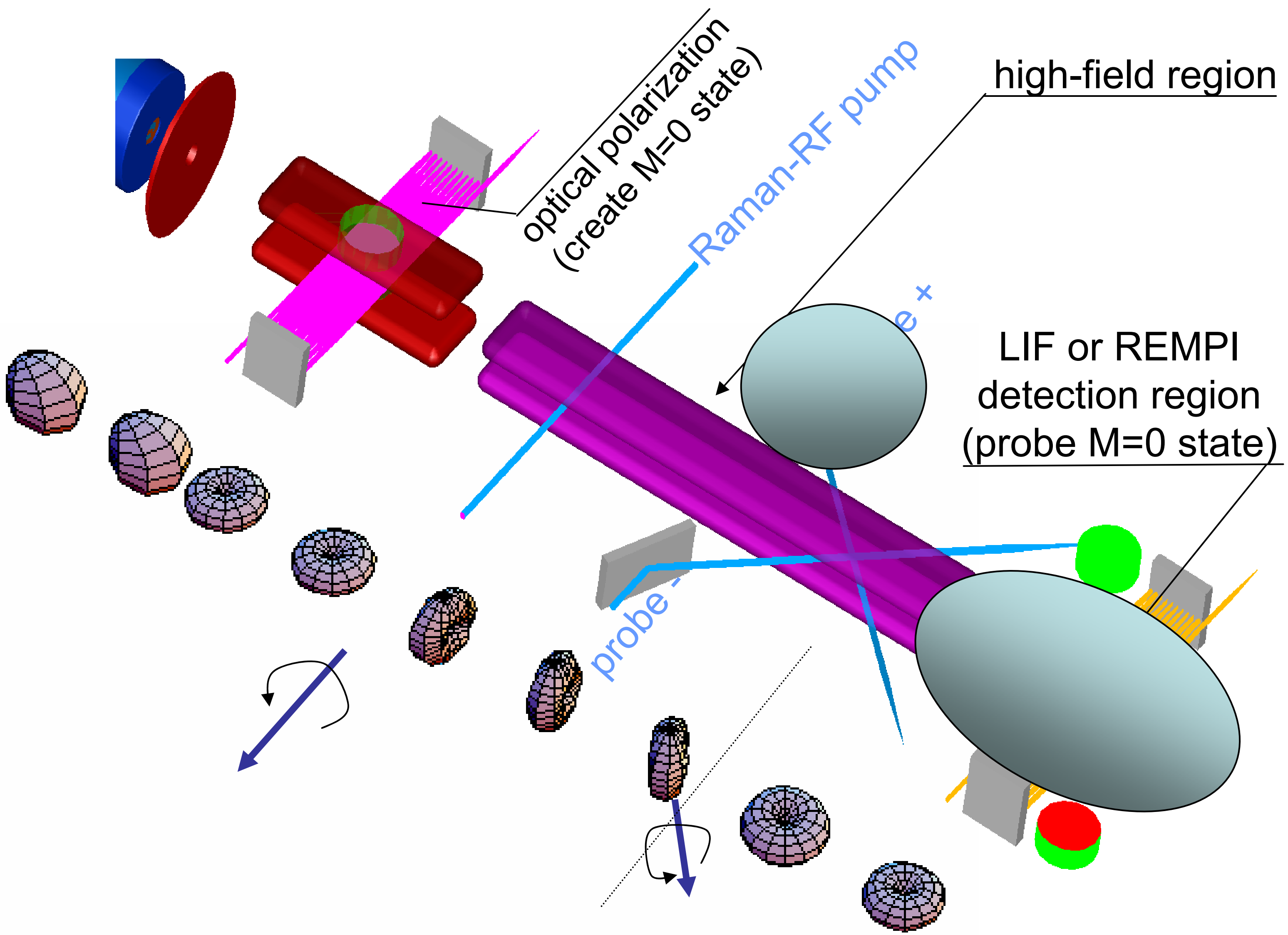

optical polarization
(create M=0 state)
Raman-RF pump
high-field region
probe +
LIF or REMPI
detection region
(probe M=0 state)
probe -


optical polarization
(create M=0 state)
Raman-RF pump
high-field region
probe +
LIF or REMPI
detection region
(probe M=0 state)
probe -

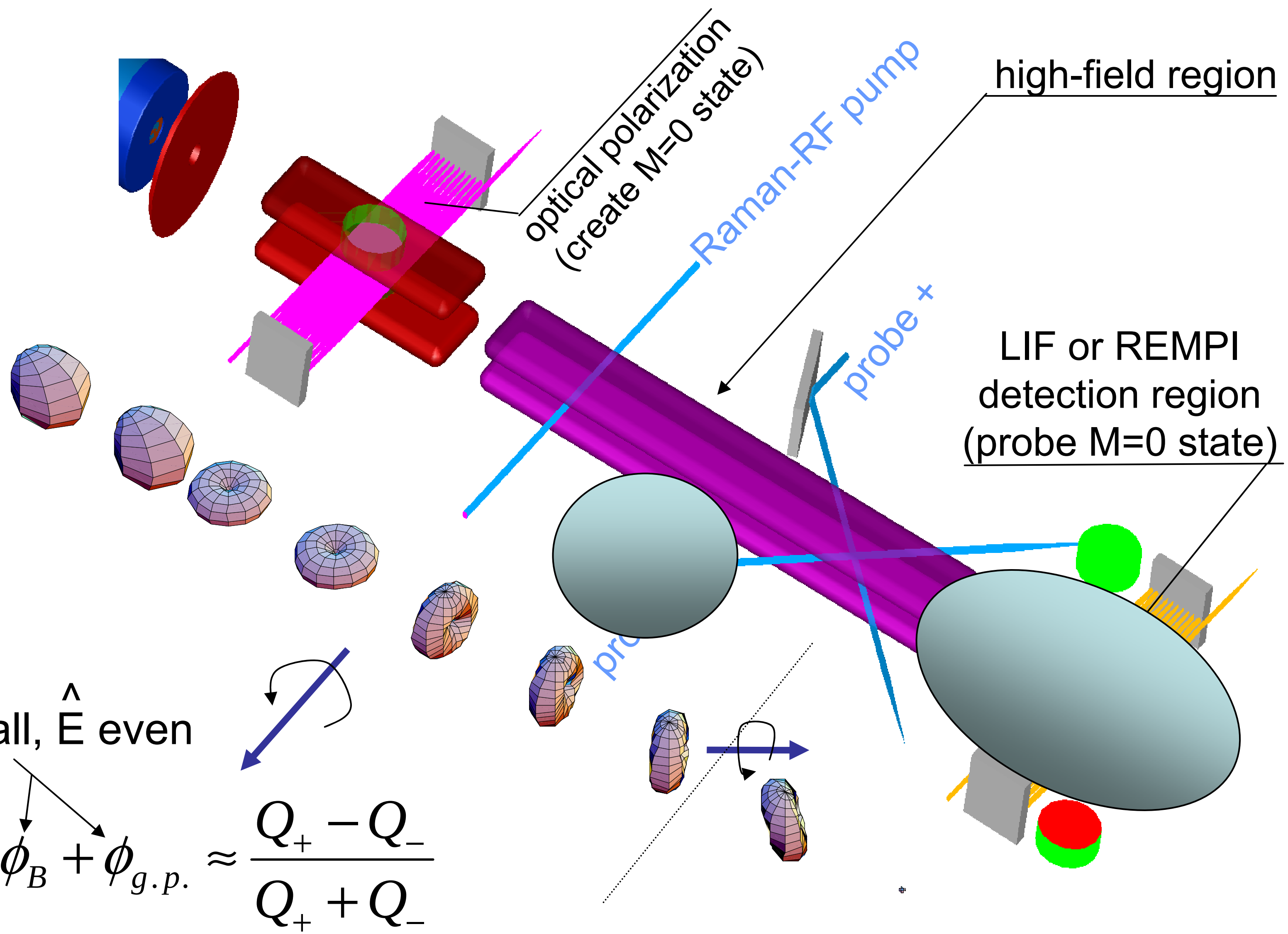
PROBE+


optical polarization
(create M=0 state)
Raman-RF pump
high-field region
probe +
LIF or REMPI
detection region
(probe M=0 state)
probe

PROBE+


optical polarization
(create M=0 state)
Raman-RF pump
high-field region
LIF or REMPI
detection region
(probe M=0 state)
probe

PROBE+



small, $\hat{E}$ even

$$\phi_{edm} + \phi_B + \phi_{g.p.} \approx \frac{Q_+ - Q_-}{Q_+ + Q_-}$$

reverse sign with changing $\hat{E}$.

PROBE-

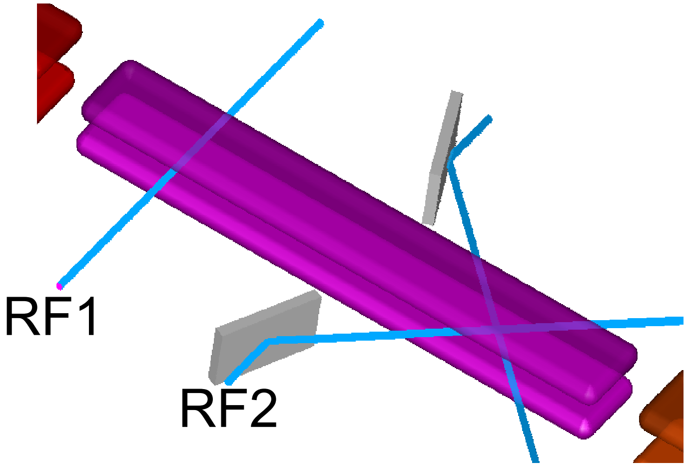
Using Ramsey fringes to lock the electric field:

ω_{RF1} fixed to a frequency standard.

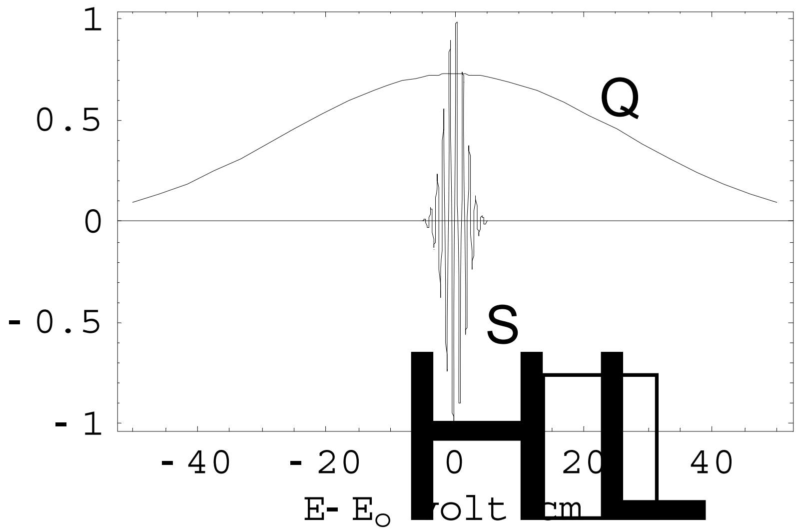
$\omega_{RF2}=\omega_{RF1}+\Delta\omega$

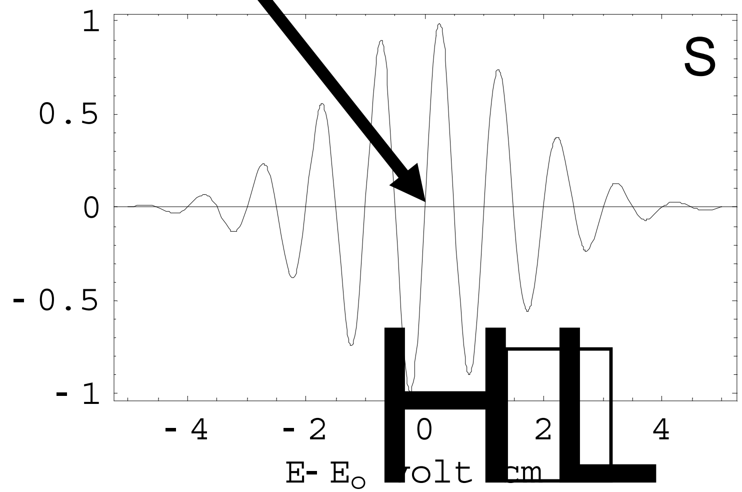
$$Q = \frac{\Delta\omega}{2\pi}\int_0^{2\pi/\Delta\omega} Signal(t)dt = N(\cos^4\theta - \tfrac{1}{2}\sin^4\theta(1-\sin\varphi))$$

$$S = \frac{\Delta\omega}{\pi}\int_0^{2\pi/\Delta\omega} \sin(\Delta\omega t)Signal(t)dt$$

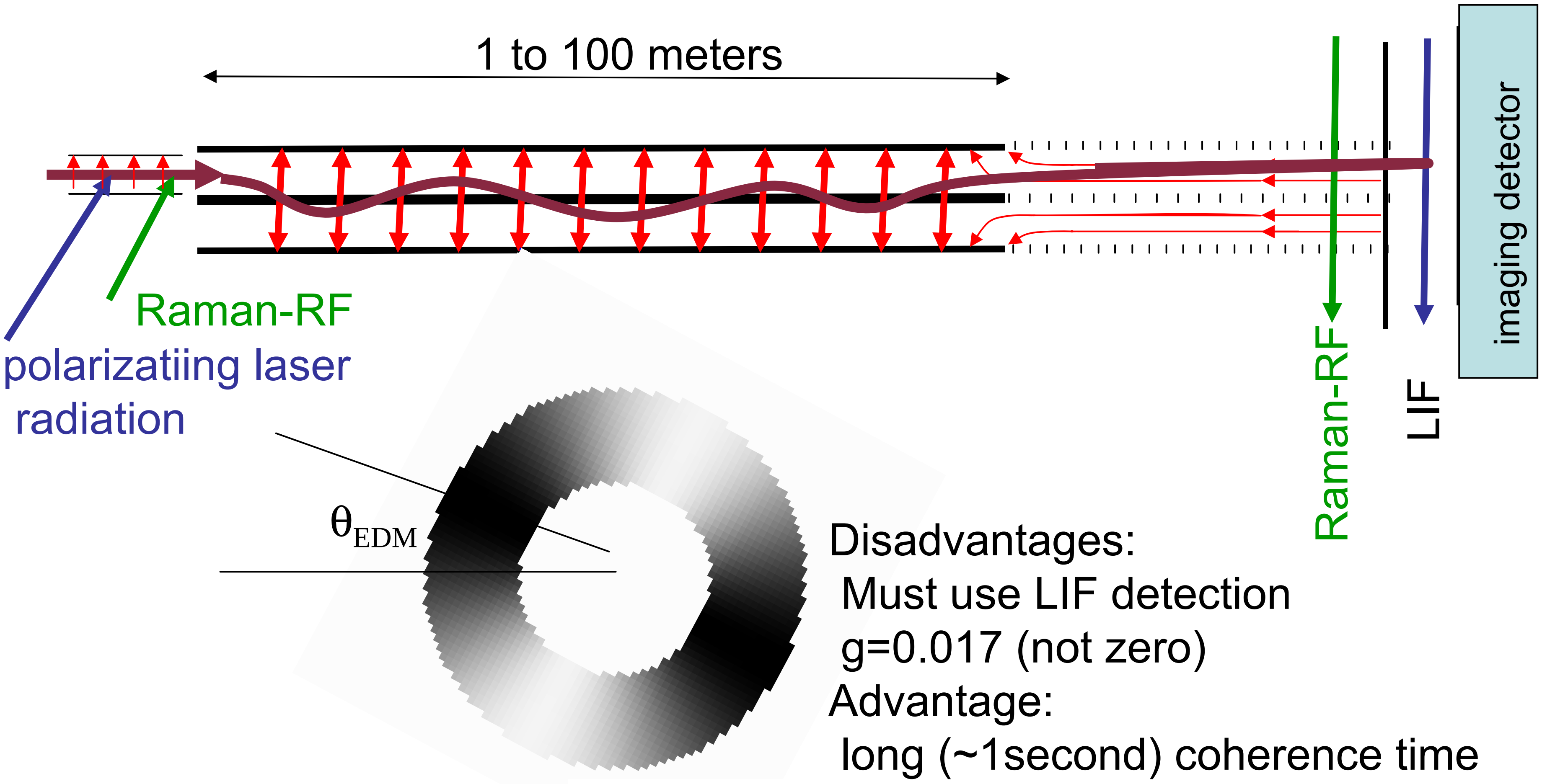


zero crossing independent of ±M phase





A totally different idea: Guided PbF molecules in a Coaxial cable



Disadvantages:
Must use LIF detection
g=0.017 (not zero)
Advantage:
long (~1second) coherence time

LIF image

Conclusions

- We have found a system for which the effect of background magnetic fields may be suppressed by seven orders of magnitude.
- We have developed a source of PbF as well as sensitive state selective REMPI of the molecule.
- We are designing a beam machine to take advantage of this new system.

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Graduate Students: **Chris McRaven** , **Sivakumar Poopalasingam,** Milinda Rupasinghe

Professor George Kalbfleisch:
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