A Spectroscopic Test of the Bose-Einstein Statistics of Photons

Damon English, Dmitry Budker,

David DeMille[†], Valeriy Yashchuk[††]

Physics Department
University of California at Berkeley

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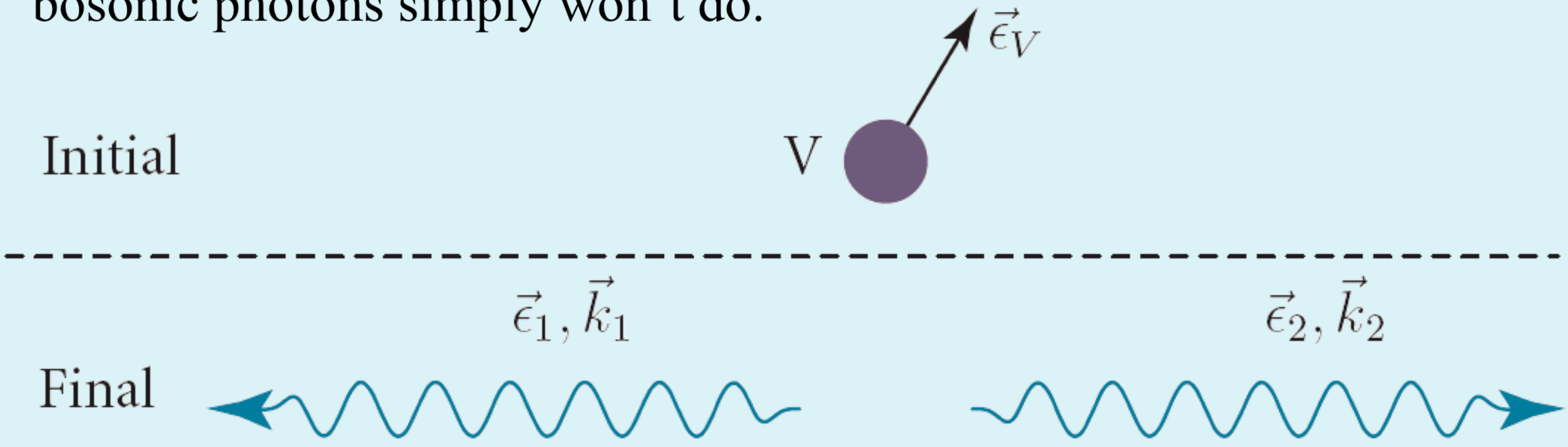
† Physics Dept., Yale University
† † Lawrence Berkeley National Laboratory

The principle of the experiment

According to the Landau-Yang theorem, there are some things bosonic photons simply won't do.



Decay of vector particle V to two photons, in the rest frame of V, $k_1 = -k_2$.

L. D. Landau, Dokl. Akad. Nauk SSSR **60**, 207 (1948)

C. N. Yang, Phys. Rev. **77**, 242 (1950)

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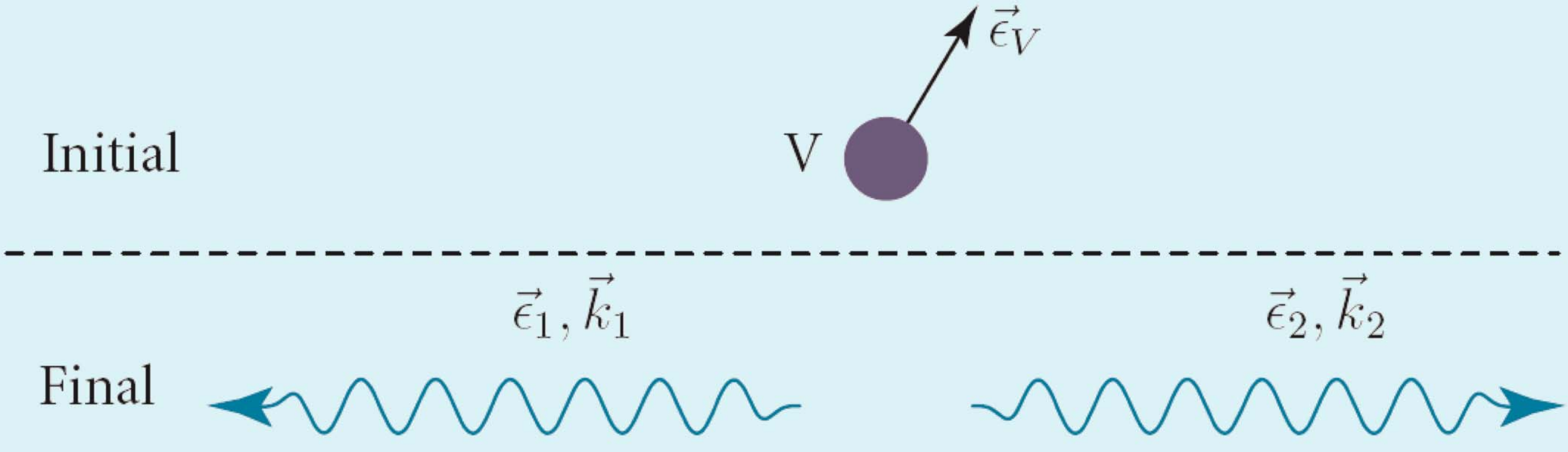

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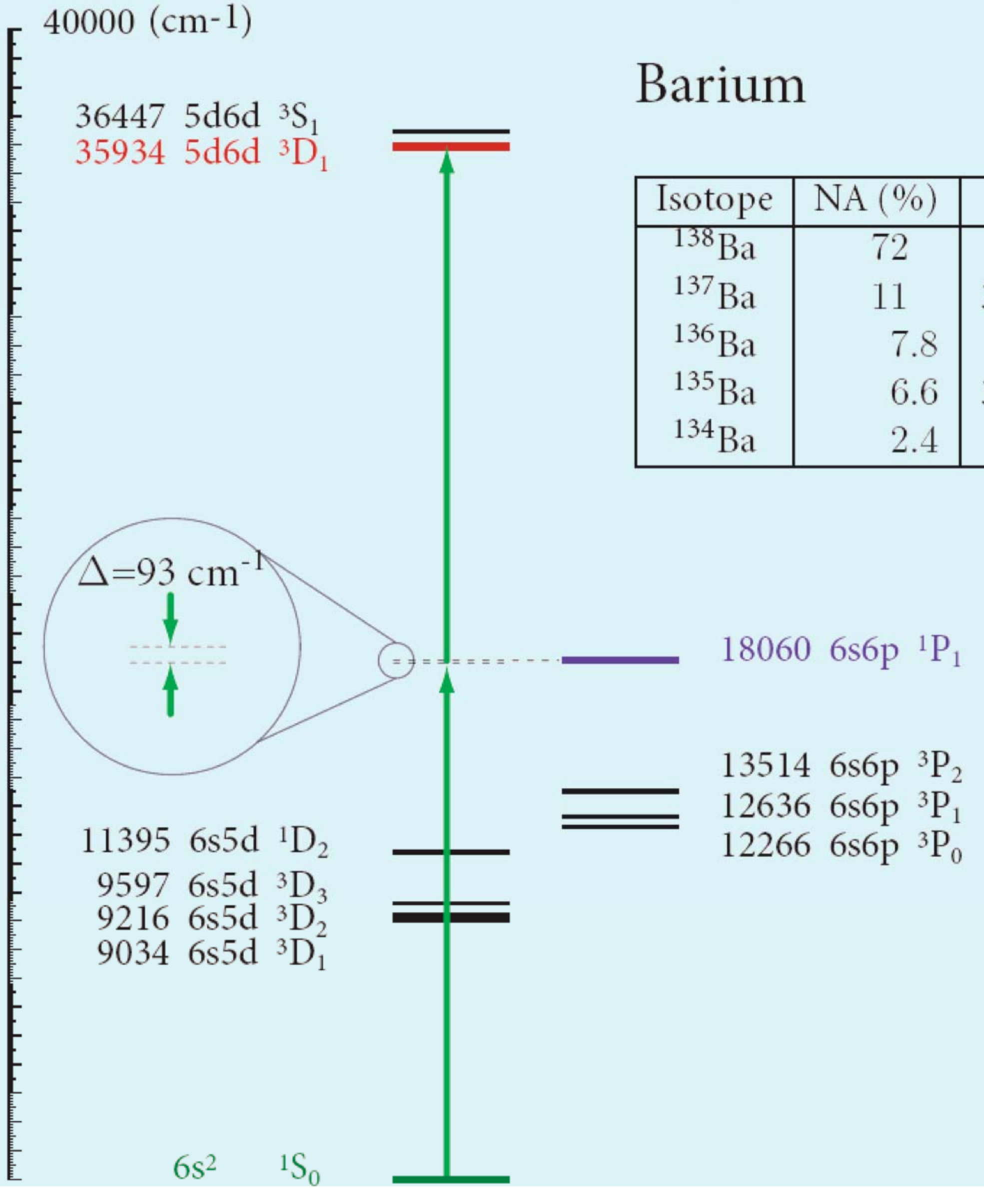
Final state 2-γ WF must be proportional to... $\vec{\epsilon}_1 \times \vec{\epsilon}_2$

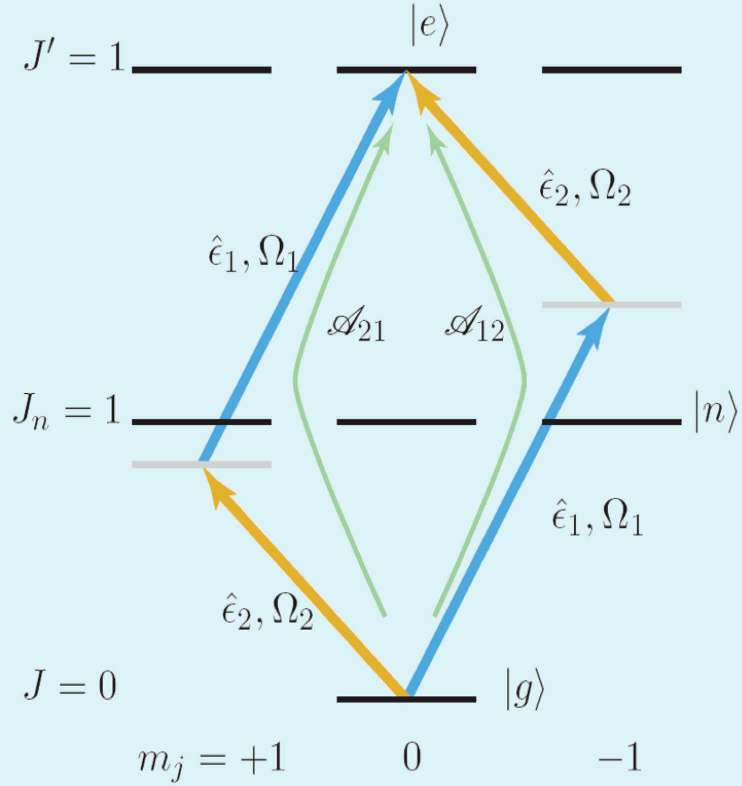
or... $(\vec{\epsilon}_1 \cdot \vec{\epsilon}_2)\vec{k}$

or... $\vec{k} \times (\vec{\epsilon}_1 \times \vec{\epsilon}_2) = \vec{\epsilon}_1\left(\vec{k} \cdot \vec{\epsilon}_2\right) - \vec{\epsilon}_2\left(\vec{k} \cdot \vec{\epsilon}_1\right)$

T-reversed LY violation in atoms.



Isotope	NA (%)	I
^{138}Ba	72	0
^{137}Ba	11	3/2
^{136}Ba	7.8	0
^{135}Ba	6.6	3/2
^{134}Ba	2.4	0



Atomic two-γ transition

$$W = \frac{2\pi}{\hbar^4} \times \left| \sum_n \overbrace{\left(\frac{\langle e|\hat{\epsilon}_1 \cdot \mathscr{D}|n\rangle\langle n|\hat{\epsilon}_2 \cdot \mathscr{D}|g\rangle}{\omega_{ng} - \Omega_2 + i\Gamma_n/2} \right)}^{\mathscr{A}_{12}^{(n)}} + \overbrace{\left(\frac{\langle e|\hat{\epsilon}_2 \cdot \mathscr{D}|n\rangle\langle n|\hat{\epsilon}_1 \cdot \mathscr{D}|g\rangle}{\omega_{ng} - \Omega_1 + i\Gamma_n/2} \right)}^{\mathscr{A}_{21}^{(n)}} \right|^2$$

$$\times \frac{1}{\pi} \frac{\Gamma/2}{\left(\Omega_1 + \Omega_2 - \omega_{\mathrm{eg}}\right)^2 + (\Gamma/2)^2} \frac{\bar{I}_1 \bar{I}_2}{4\epsilon_0^2\, c^2},$$

$|g\rangle, |n\rangle, |e\rangle$: ground-, intermediate-, excited-state

Γ_n, Γ : intermediate-, excited-state natural widths

$\hat{\epsilon}_{1,2}, \Omega_{1,2}$: polarization & energy of photon 1,2

$\omega_{kl} \equiv \omega_k - \omega_l$: energy difference between states k & l

$\mathscr{D}$: Dipole moment operator

Atomic two-γ transition

$$W_{\pm} = \frac{2\pi}{\hbar^4} \times \left| \sum_n \frac{\langle e|\hat{\epsilon}_1 \cdot \mathscr{D}|n\rangle\langle n|\hat{\epsilon}_2 \cdot \mathscr{D}|g\rangle}{\omega_{ng} - \Omega_2 + i\Gamma_n/2} \pm \frac{\langle e|\hat{\epsilon}_2 \cdot \mathscr{D}|n\rangle\langle n|\hat{\epsilon}_1 \cdot \mathscr{D}|g\rangle}{\omega_{ng} - \Omega_1 + i\Gamma_n/2} \right|^2$$

$$\times \frac{1}{\pi} \frac{\Gamma/2}{(\Omega_1 + \Omega_2 - \omega_{eg})^2 + (\Gamma/2)^2} \frac{\bar{I}_1 \bar{I}_2}{4\epsilon_0^2 c^2}$$

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Atomic two-γ transition $J = 0 \rightarrow J' = 1$

$$W_{\pm} = \frac{2\pi}{\hbar^4} \times \frac{\mathcal{D}_1^2 \mathcal{D}_2^2}{2} \left| f_{\pm} \right|^2$$

$$\times \frac{1}{\pi} \frac{\Gamma/2}{\left(\Omega_1 + \Omega_2 - \omega_{eg}\right)^2 + \left(\Gamma/2\right)^2} \frac{\bar{I}_1 \bar{I}_2}{4\epsilon_0^2 \, c^2}$$

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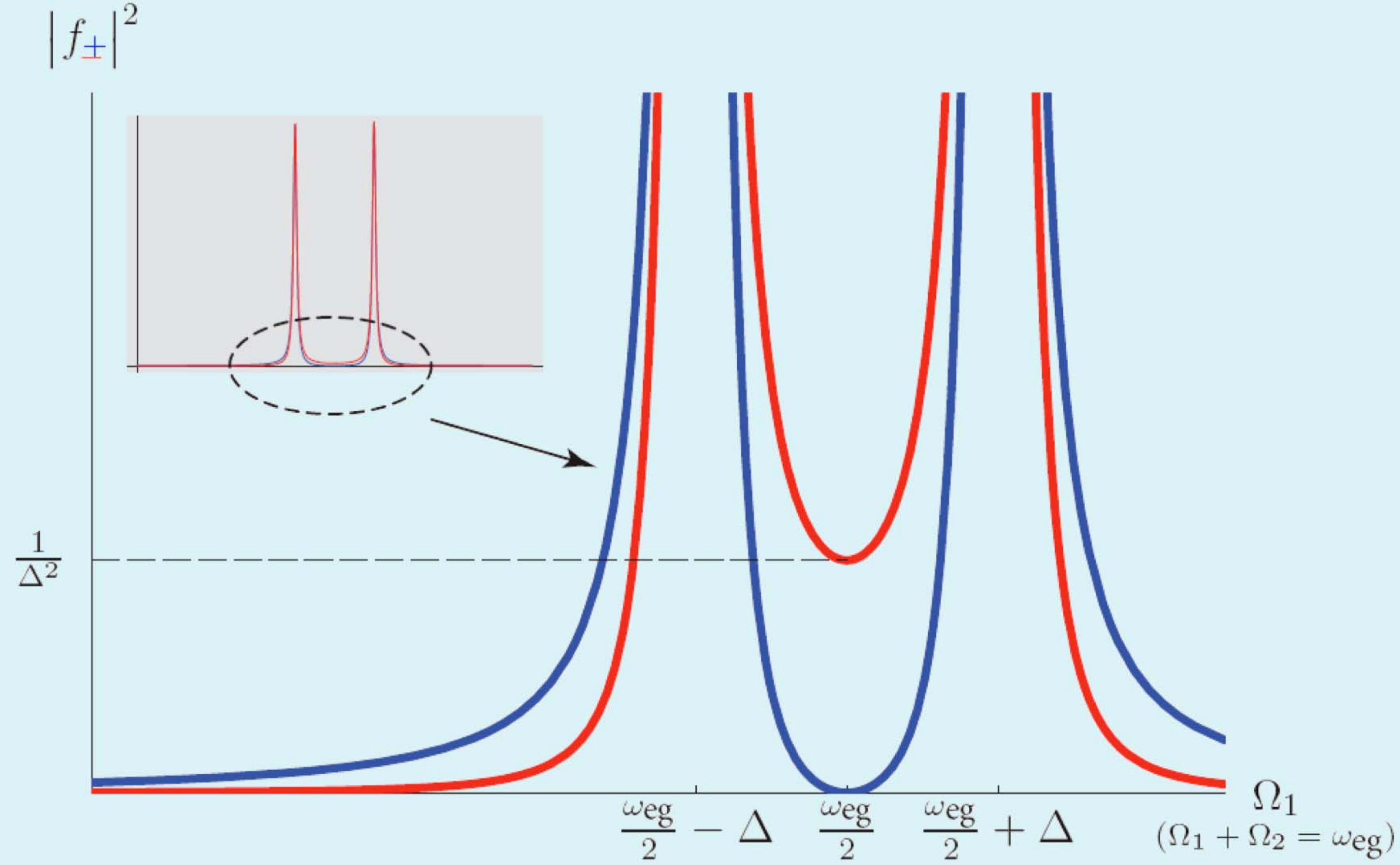


Atomic two-γ absorption

$$W_- = \boxed{\frac{2\,\mathcal{D}_1^2\mathcal{D}_2^2\,\bar{I}_1\bar{I}_2}{\Gamma\hbar^4\Delta^2\epsilon_0^2\,c^2}\left(1+\frac{\delta^2}{\Delta^2}\right)^{-2}}$$

$$W_+ = \boxed{W_-\frac{\delta^2}{\Delta^2}.}$$

$$W_{\text{measured}} = W_+ + \nu\, W_- + W_{\text{backgrounds}}$$

$$\Rightarrow \nu \le \nu_{\text{limit}} = W_{\text{backgrounds}}/W_-$$

$$\boxed{\Rightarrow \nu_{\text{limit}} \propto W_{\text{backgrounds}} \times \frac{\Gamma\Delta^2}{\mathcal{D}_1^2\mathcal{D}_2^2 I^2}}$$

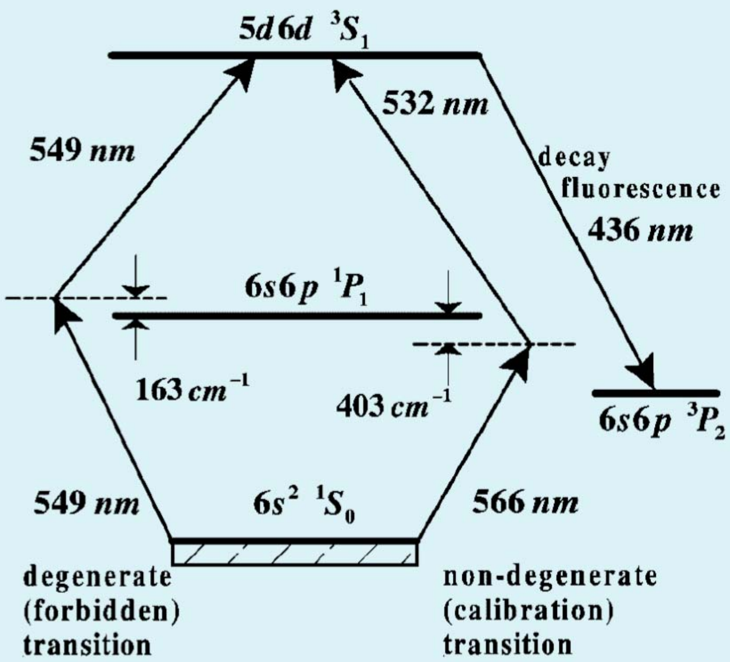
$$\nu = \frac{S(\omega_H)}{S(\omega_H+\delta)}\,\frac{\delta^2}{\Delta^2}$$

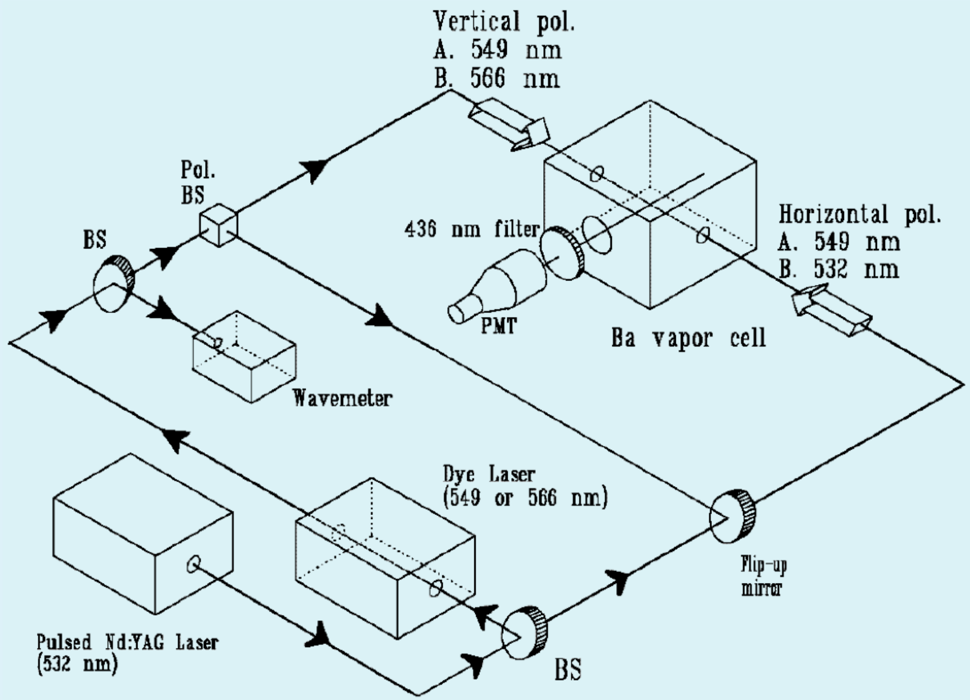
Summary of Previous Experiment

VOLUME 83, NUMBER 20 PHYSICAL REVIEW LETTERS 15 NOVEMBER 1999

Search for Exchange-Antisymmetric Two-Photon States

D. DeMille,[1] D. Budker,[2] N. Derr,[3,*] and E. Deveney[3,†]





Summary of Previous Experiment

- $\nu = 1.2 \times 10^{-7}$
- Ba vapor cell
- Pulsed lasers
- Limited by laser linewidth

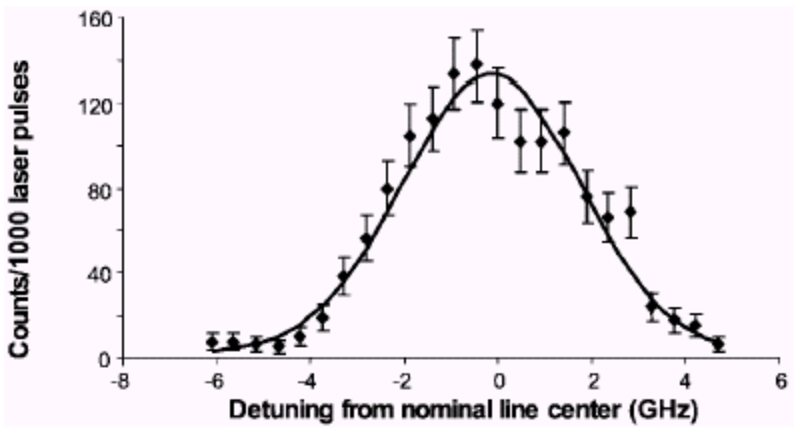


FIG. 3. Typical scan through the nondegenerate calibration transition (points) and fit to determine peak height and linewidth (solid line). Taken with 230 μJ/pulse at 566 nm and 0.4 μJ/pulse at 532 nm.

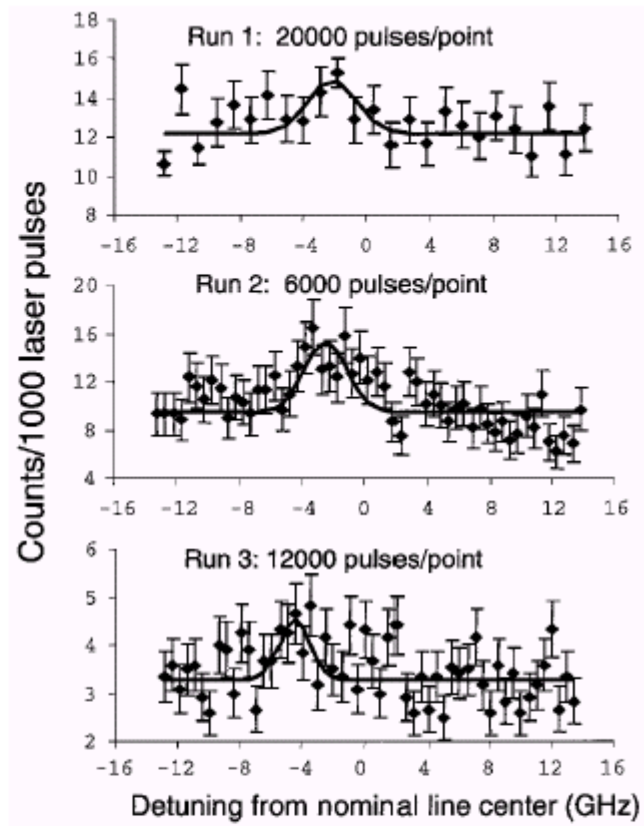
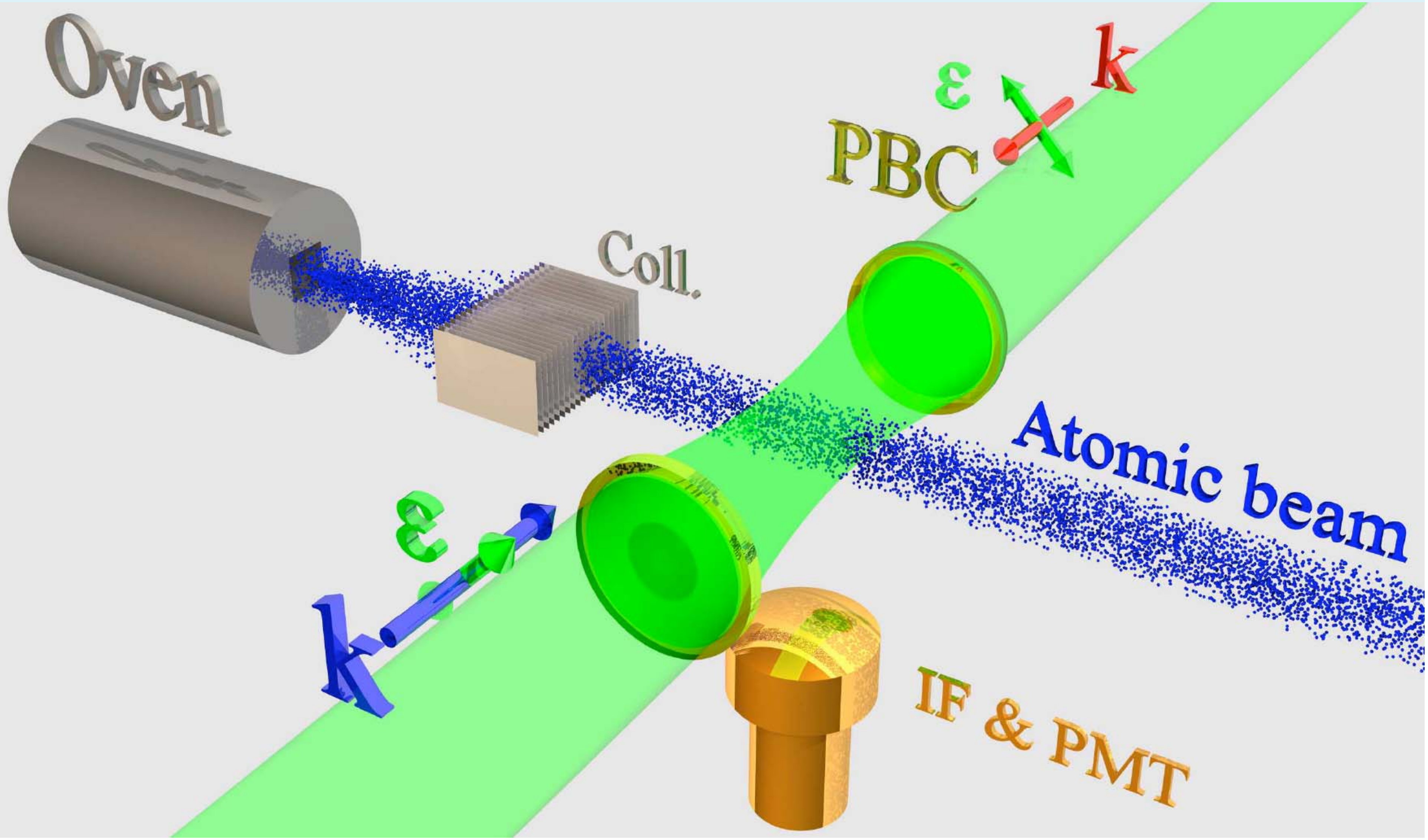
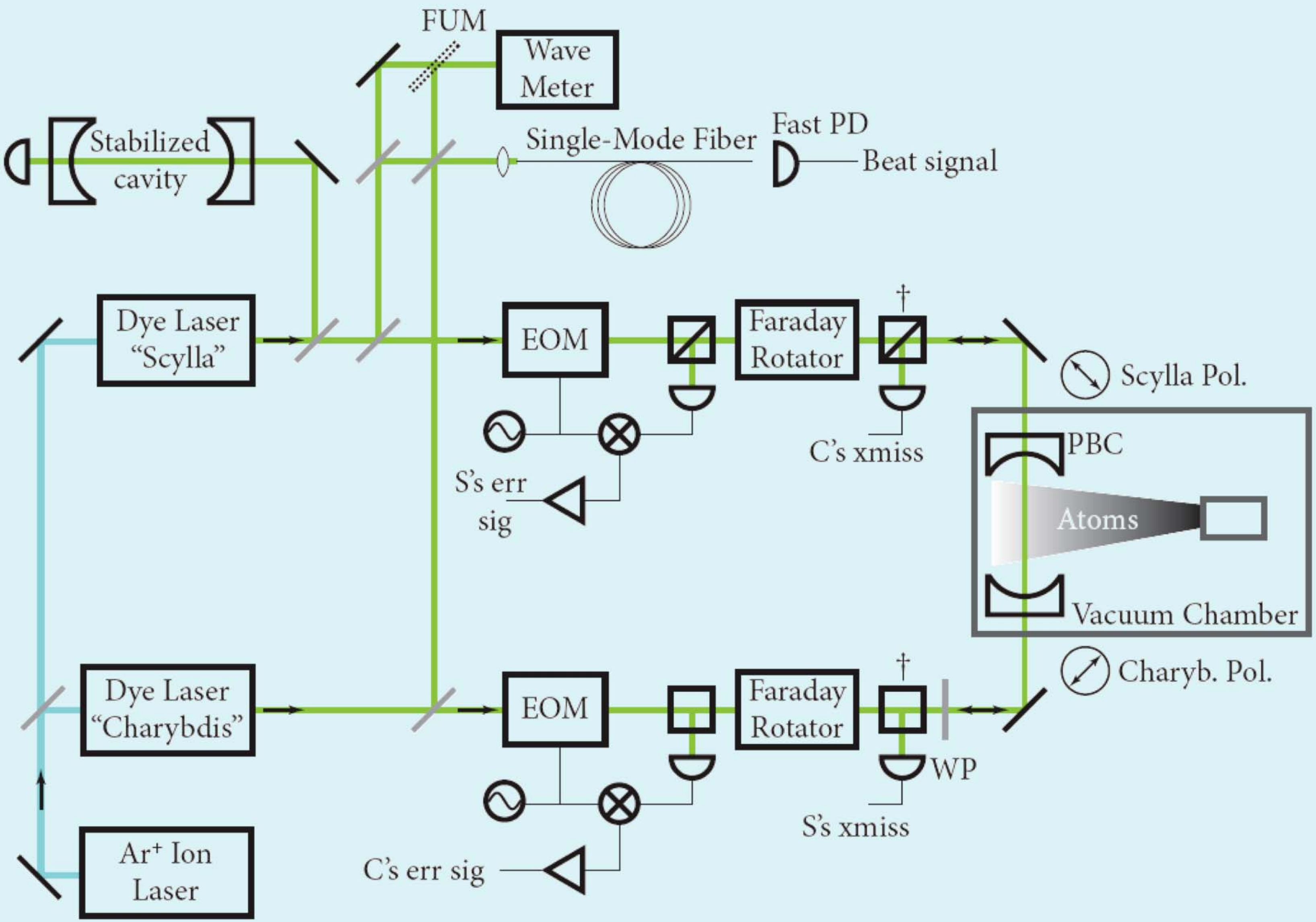


FIG. 4. Scans through the degenerate transition and best fits to peak plus background.

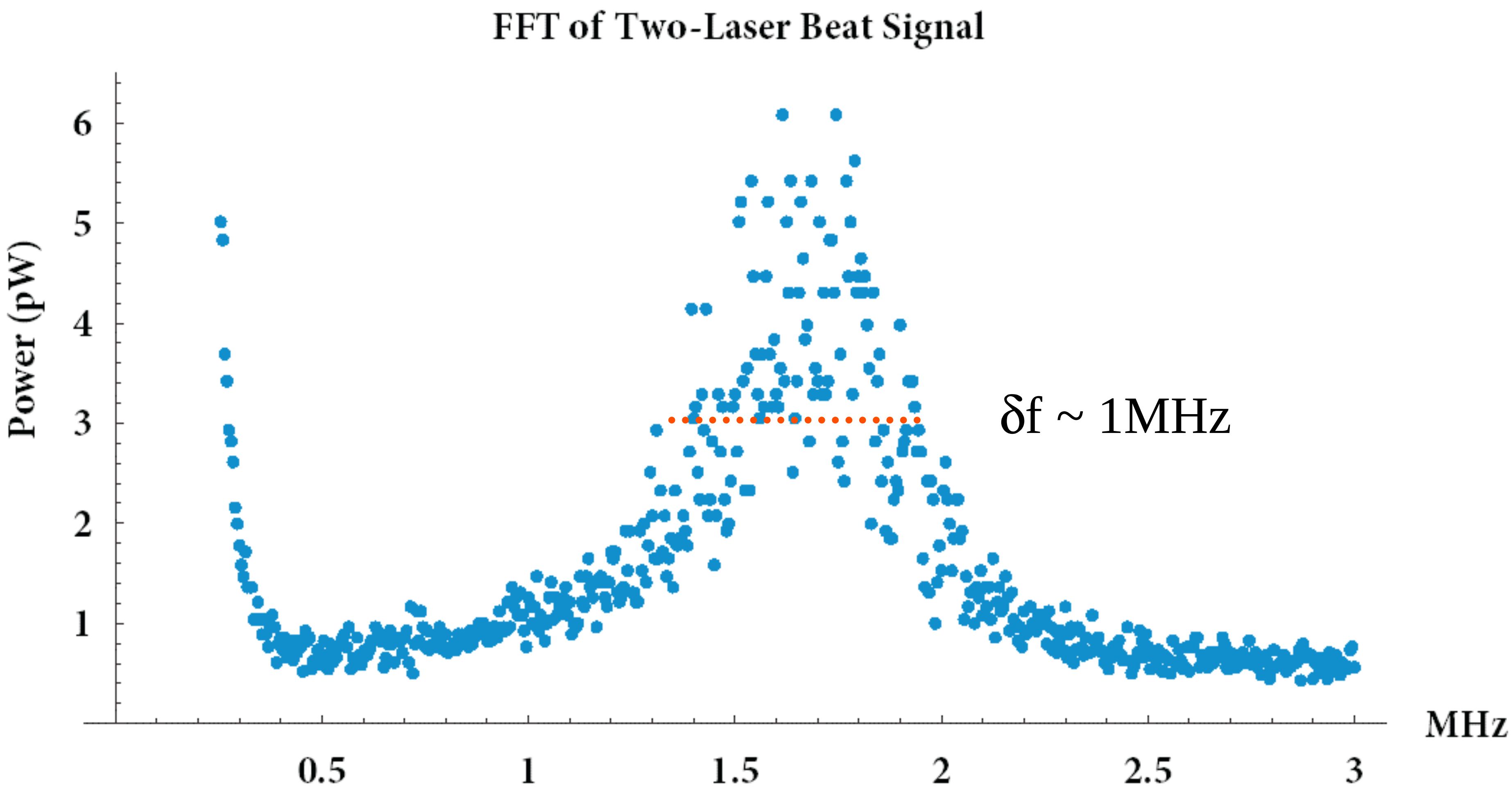
The New Apparatus

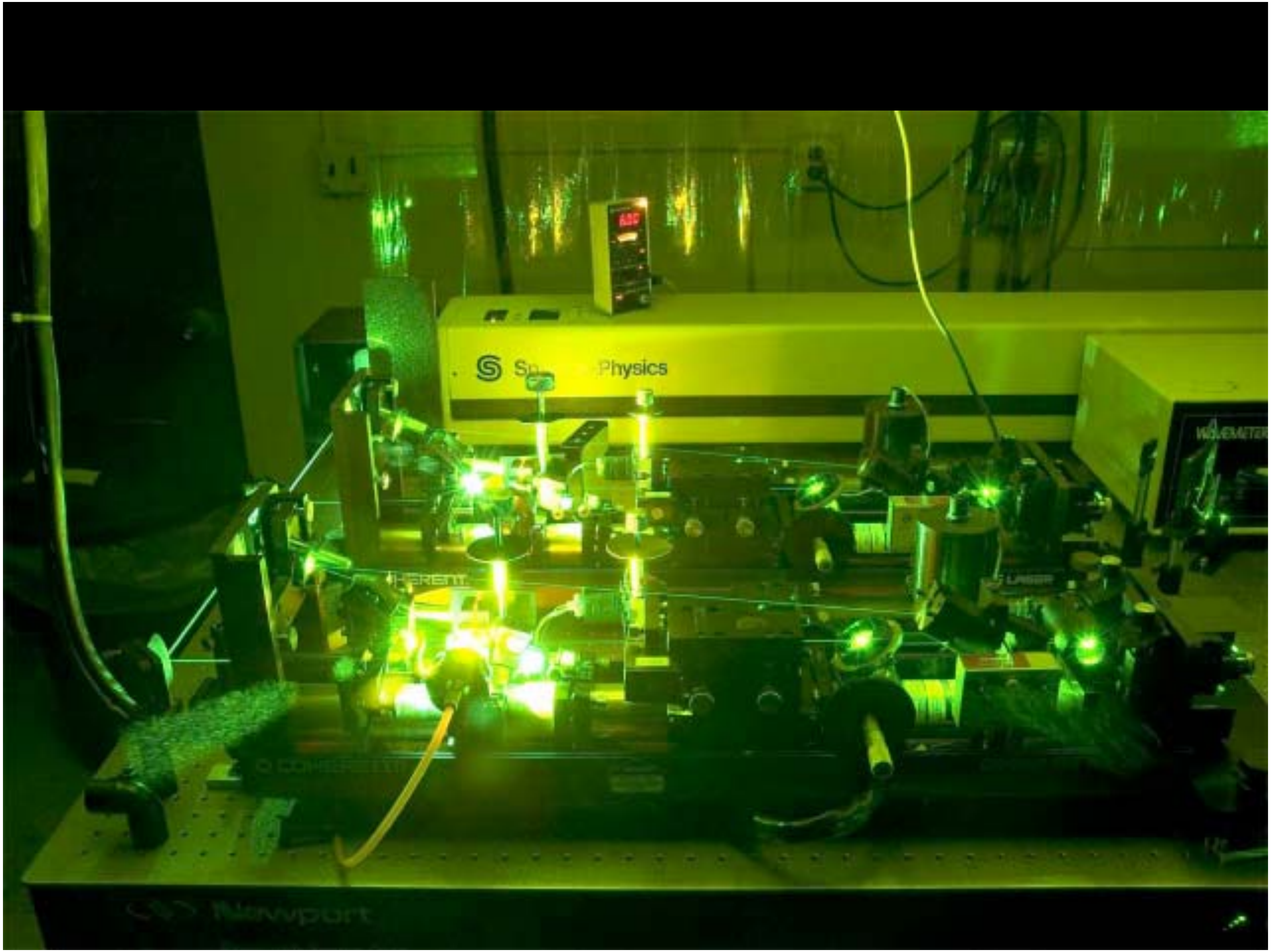


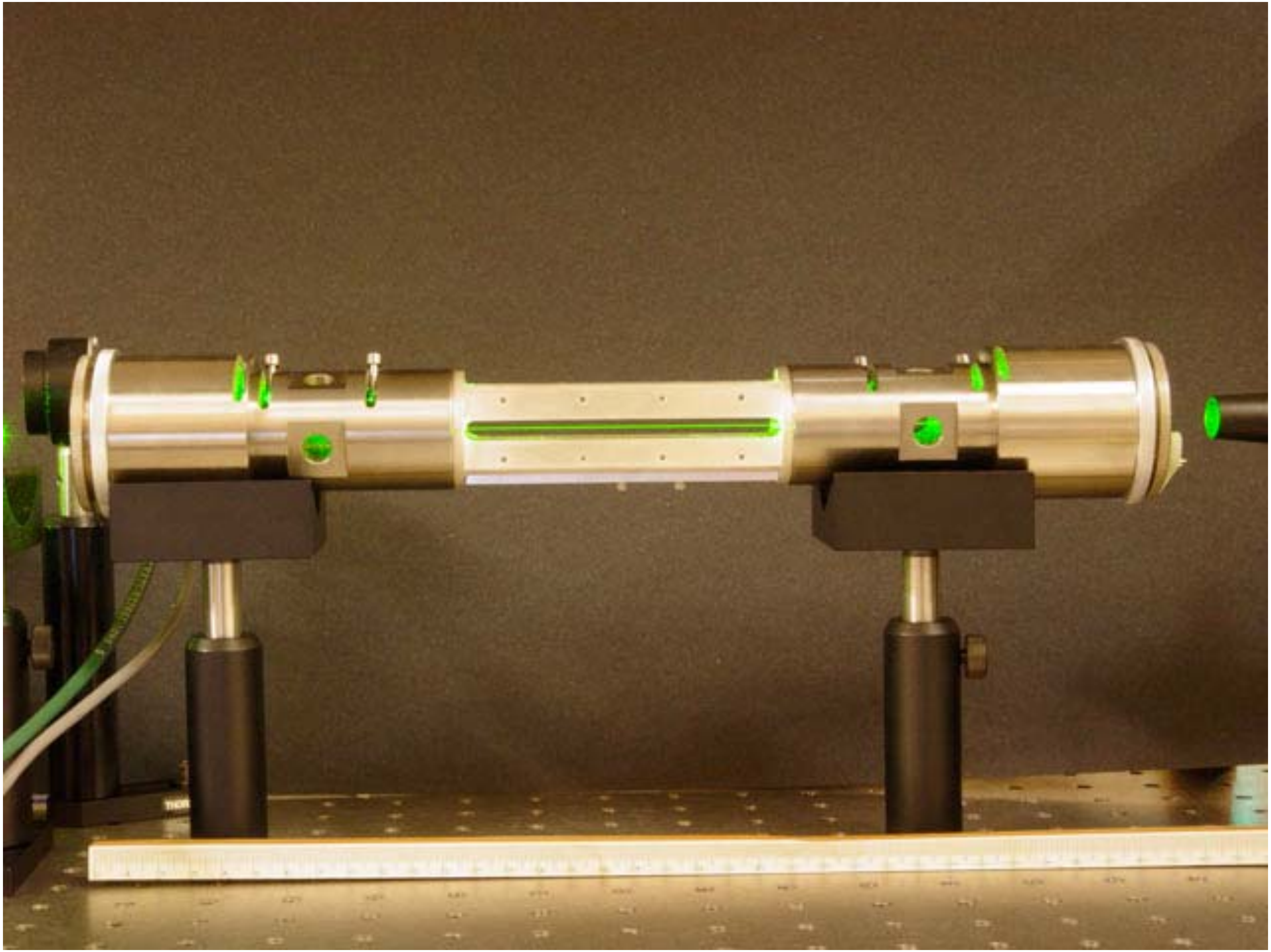
New Apparatus: Optical Schematic

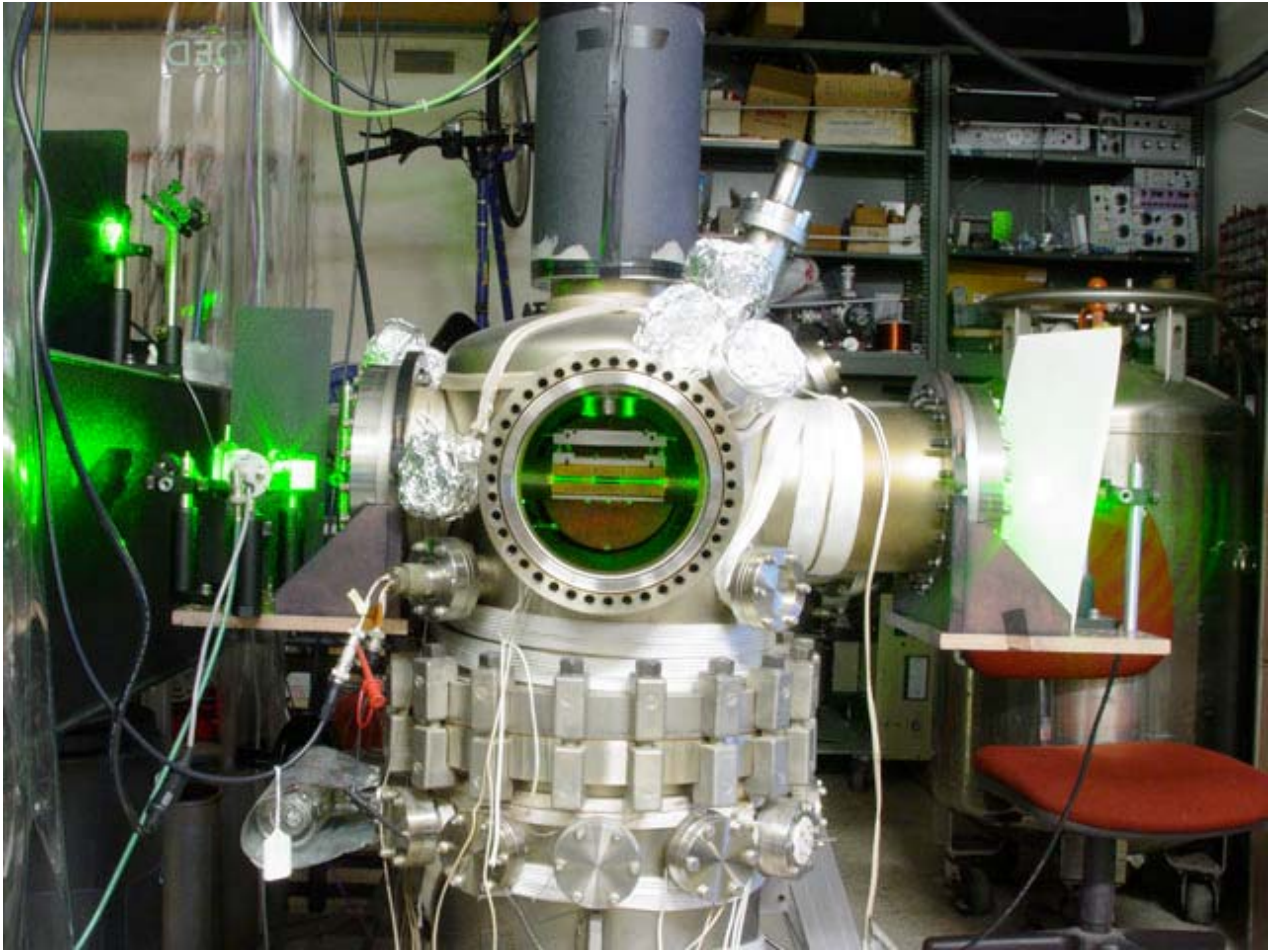


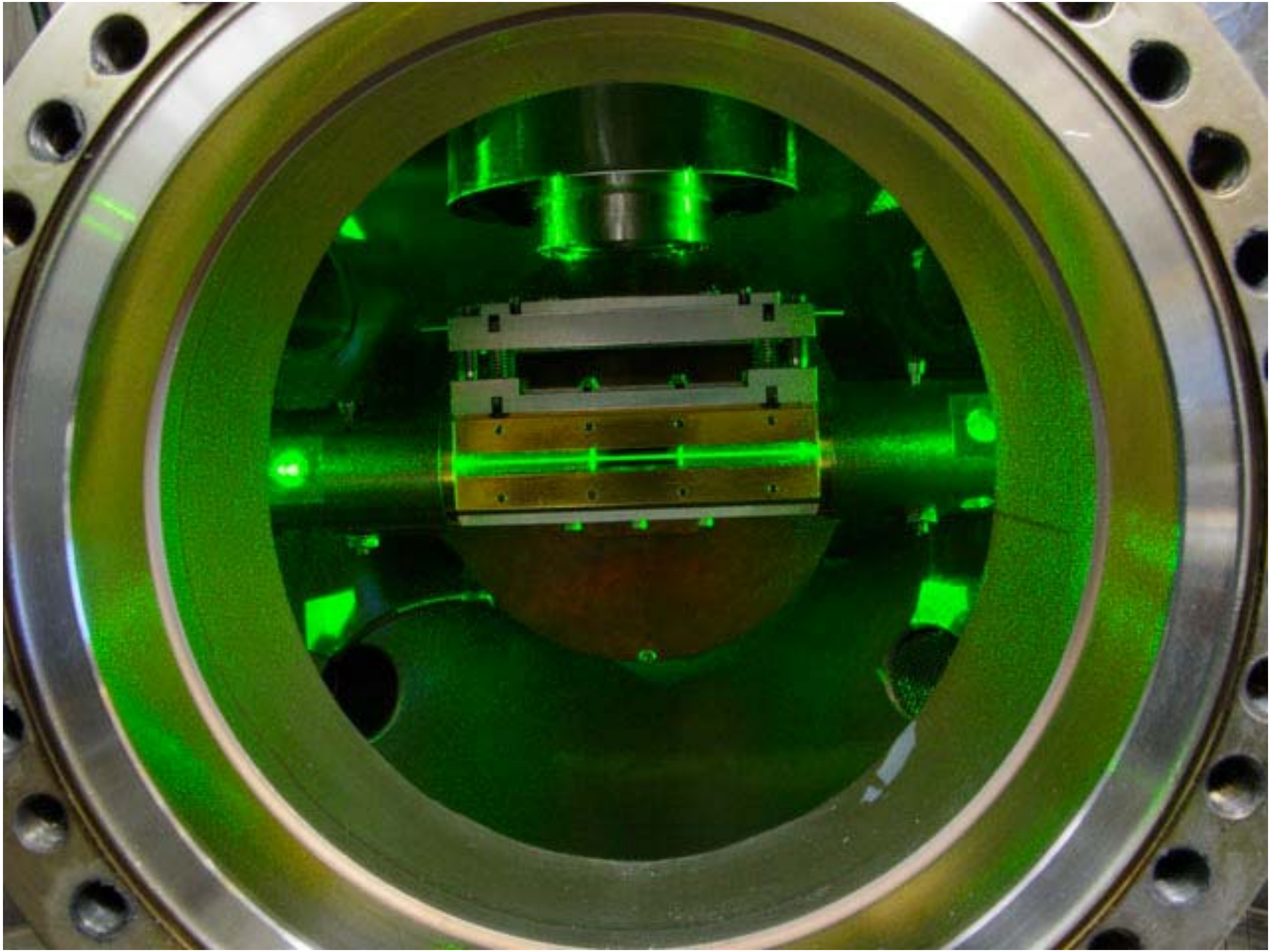
New Apparatus: Laser linewidth

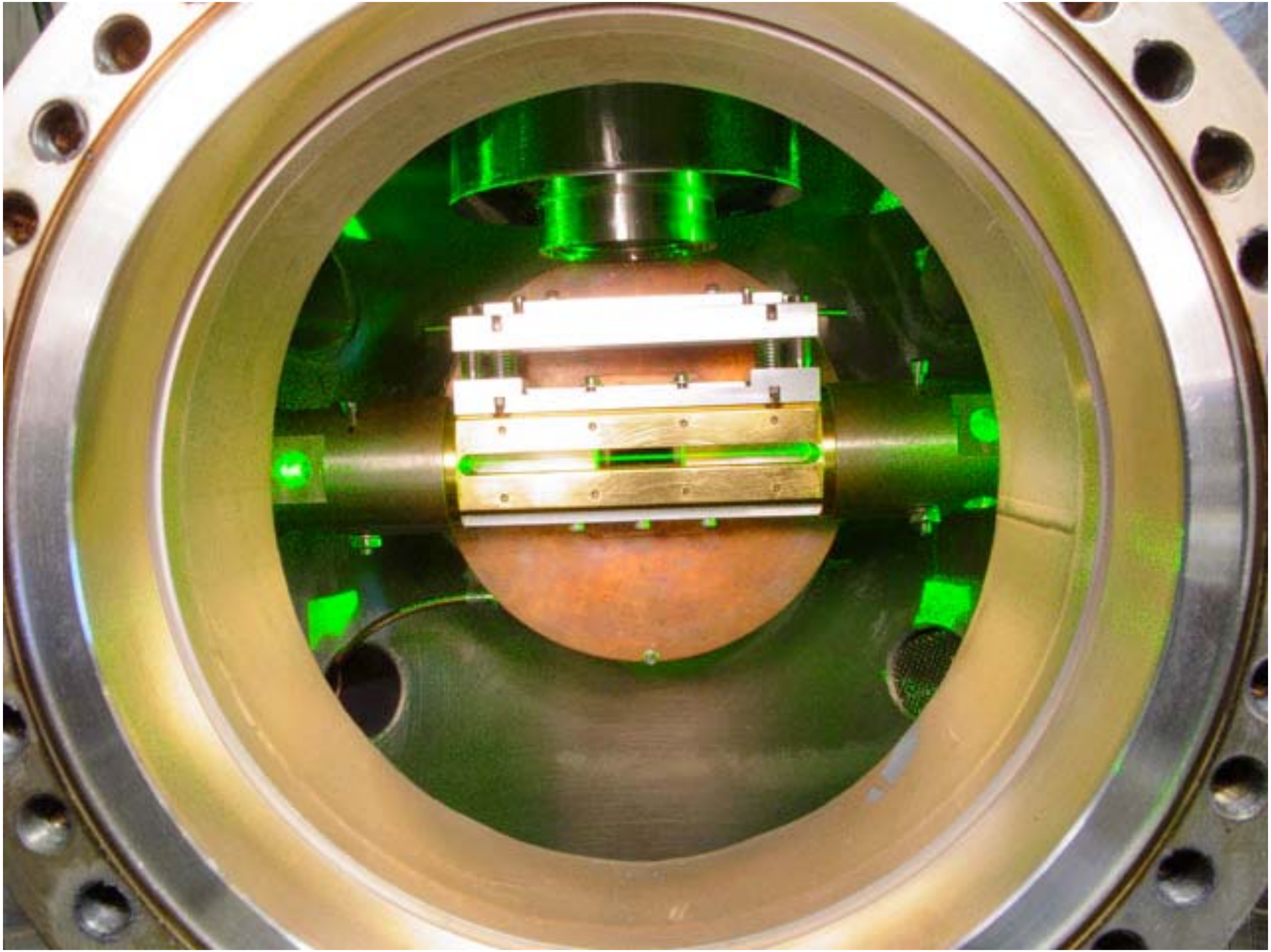


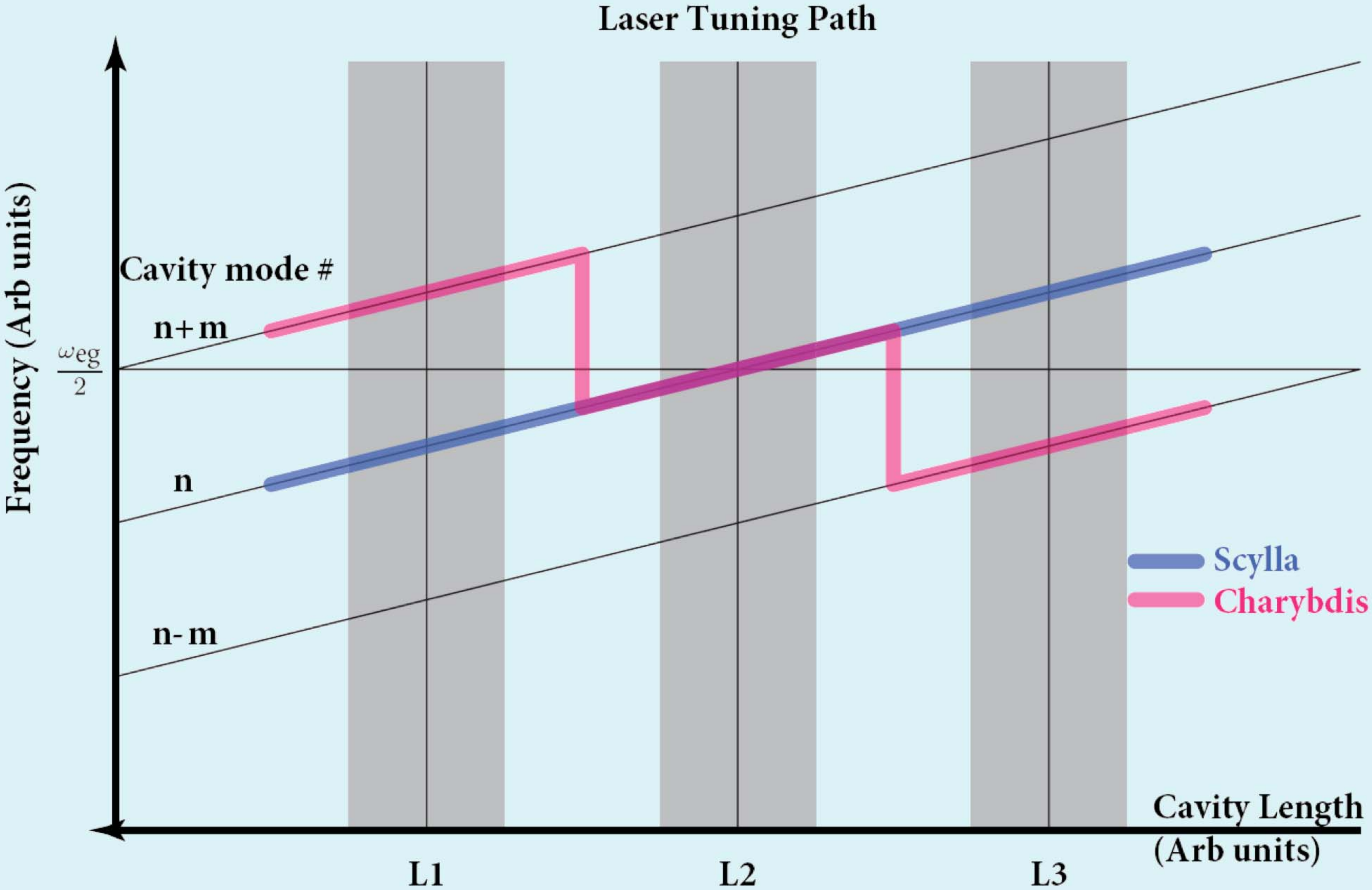

Physics

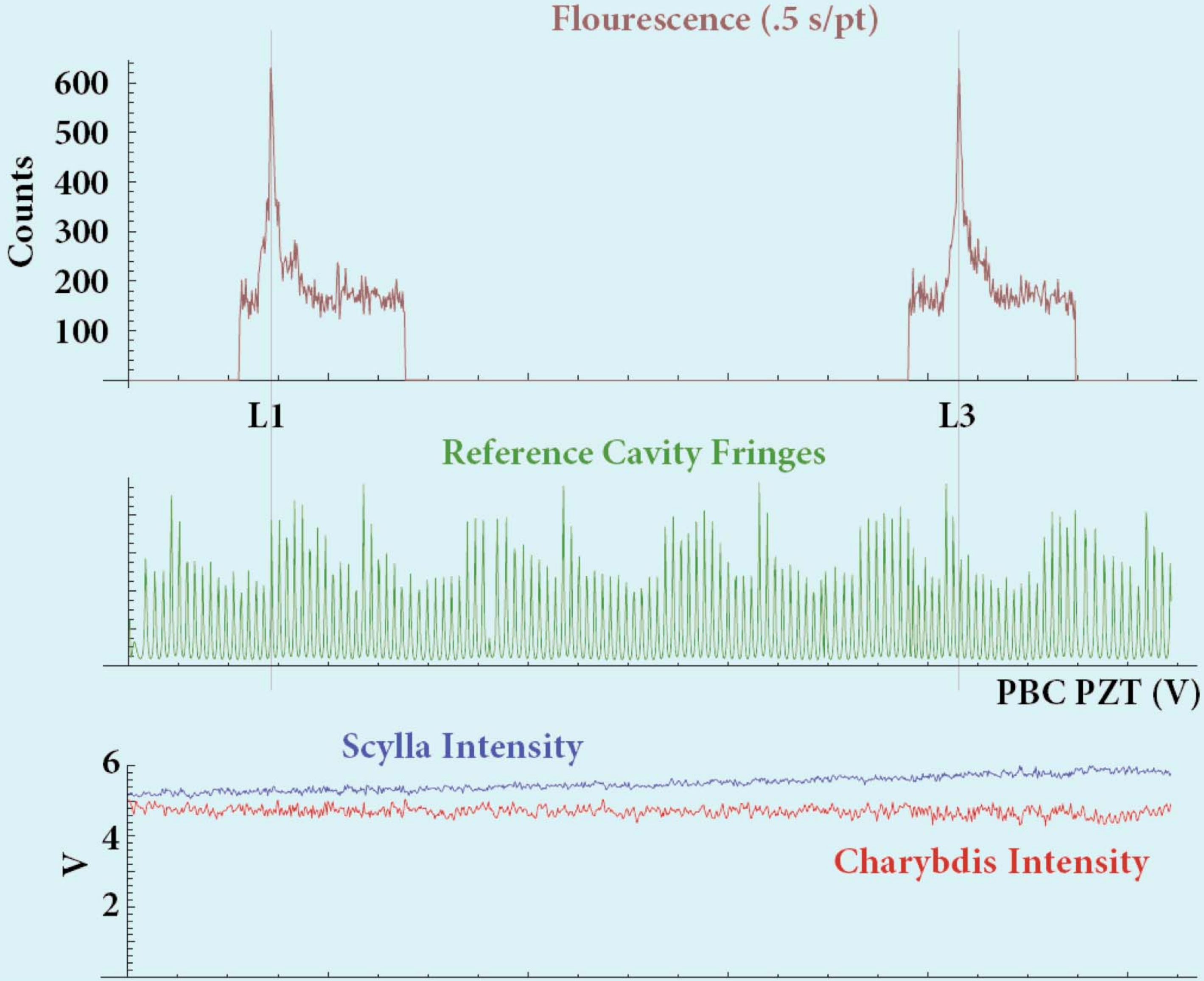






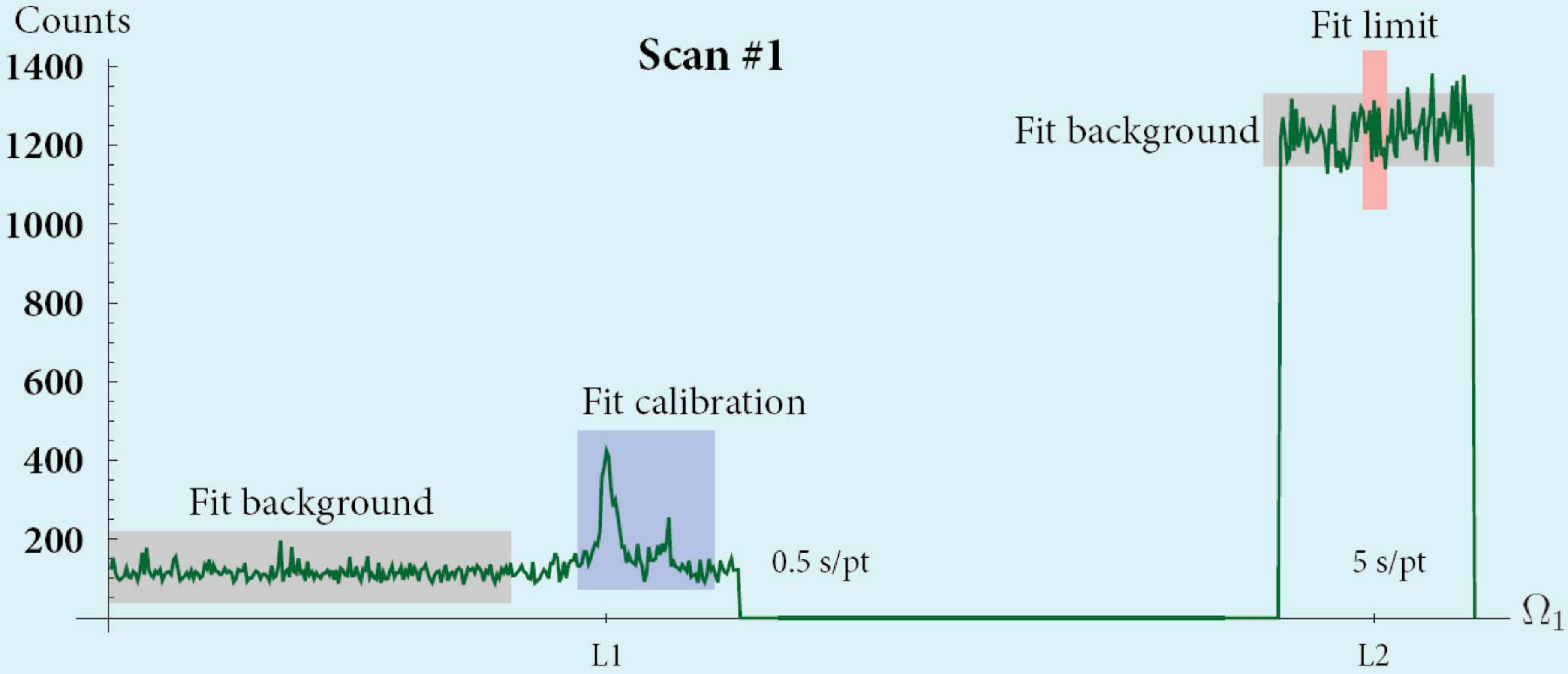



Laser Tuning Path
Frequency (Arb units)
Cavity mode #
n+m
$\frac{\omega_{eg}}{2}$
n
n- m
Scylla
Charybdis
Cavity Length
(Arb units)
L1
L2
L3



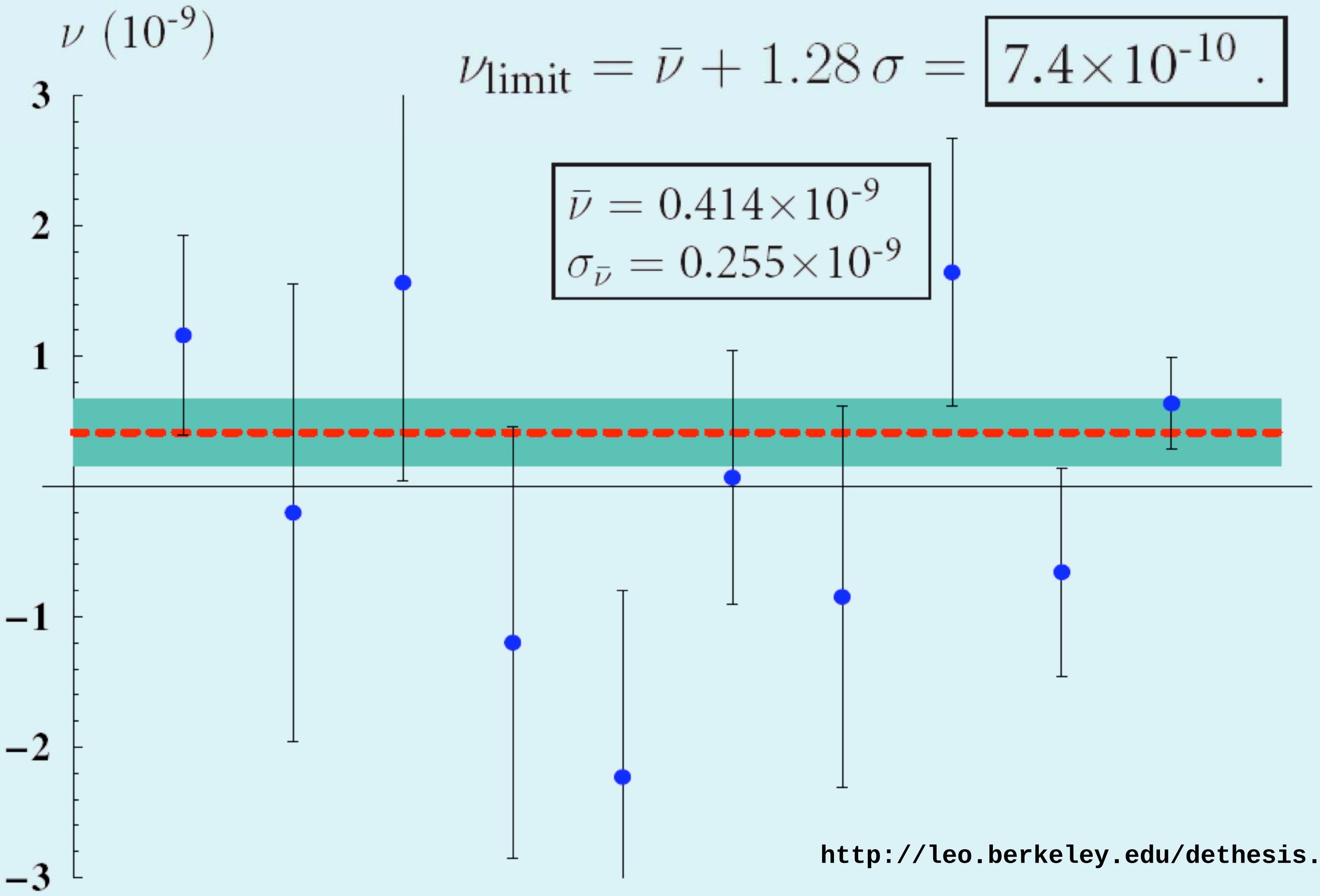
Flourescence (.5 s/pt)
Counts
600
500
400
300
200
100
L1
L3
Reference Cavity Fringes
PBC PZT (V)
Scylla Intensity
6
4
V
2
Charybdis Intensity

One scan.



Counts
Scan #1
1400
1200
1000
800
600
400
200
Fit limit
Fit background
Fit calibration
Fit background
0.5 s/pt
5 s/pt
Ω_1
L1
L2

2007 Result (90% CL)

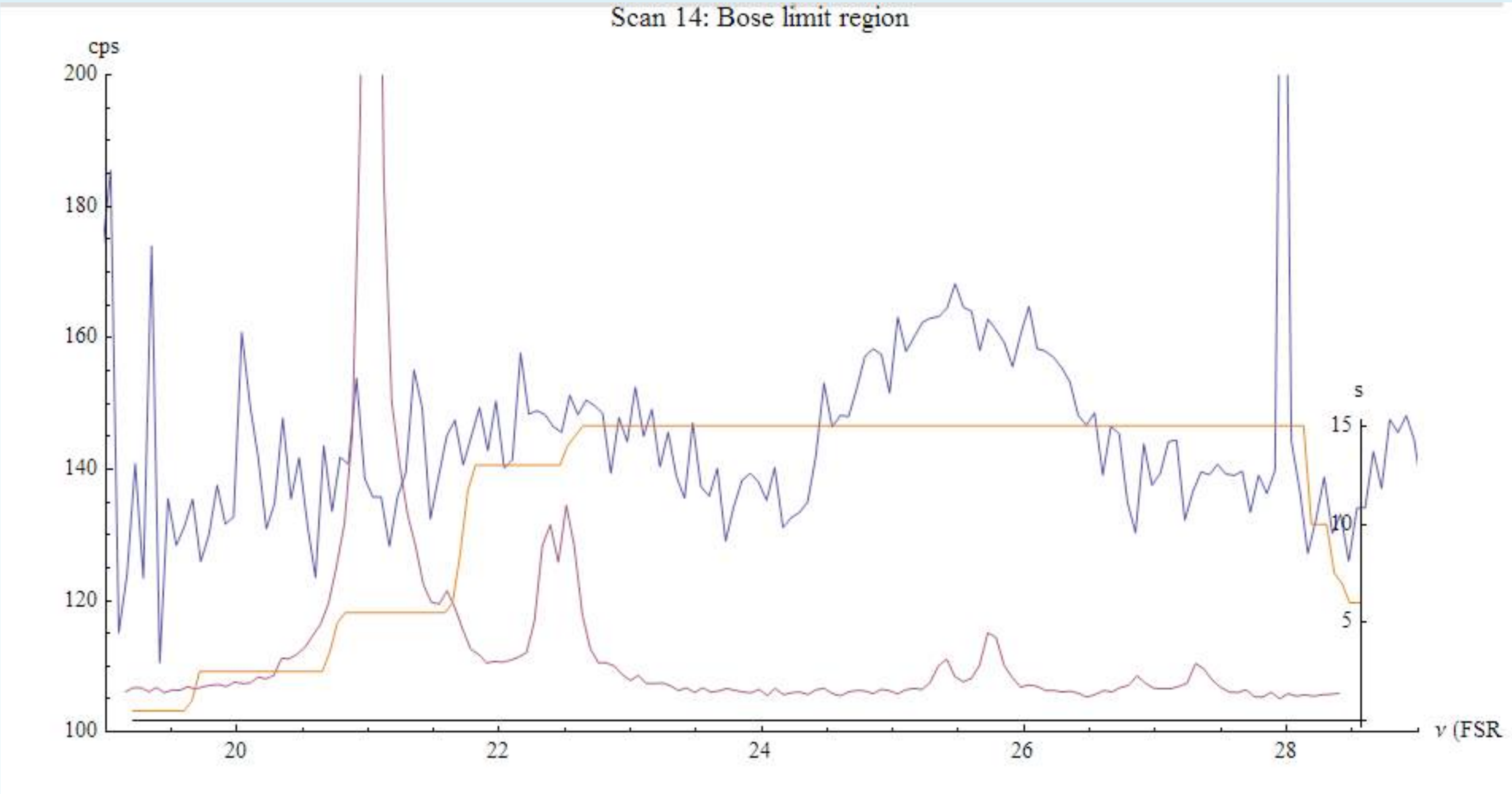


http://leo.berkeley.edu/dethesis.pdf

Since 2007…

- Better light-collection
- Tighter focused laser beams
- New Dye pump
- … + many more small improvements

Raw data from one day's run, ν=1x10^{-10}



Conclusions

- 3 OOM improvement over DeMille et al. (1999)
- 1 to 2 more OOM to come in relatively short time.

Greetings from the Budker group!