Exploring New Methods of Ramsey Spectroscopy for Collinear Ion Beams

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  - Near Degeneracy Probe (*)
- Summary and Future Plans

Goal: Higher Precision in CLS

- Rabi Type → Ramsey Type

  Increased precision

Goal: Higher Precision in CLS

Rabi

- Driving a transition with a continuous tuneable laser + probing the averaged exited population
- $Ex\ Pop \sim \frac{1}{\Delta^2+\Gamma^2+\Omega_{Rabi}^2}$
- Frequency Scanning

Ramsey

- Driving a transition with a two pulses separated by a well defined separation *t* + probing the averaged exited population
- $Ex\ Pop \sim e^{-\Gamma t/2} \sin(\Omega' t + \phi)$
- ${\Omega'}^2 = \Omega_{Rabi}^2 + \Delta^2$
- Time and/or Frequency Scanning

Goal: Higher Precision in CLS

- Rabi Type $\longrightarrow$ Ramsey Type

  Increased precision

  - Removal of Power Broadening
  - No more Frequency Scanning
  - Partial removal of Lifetime Broadening

Motivation:

- Searching for New Physics using the Isotope Shift

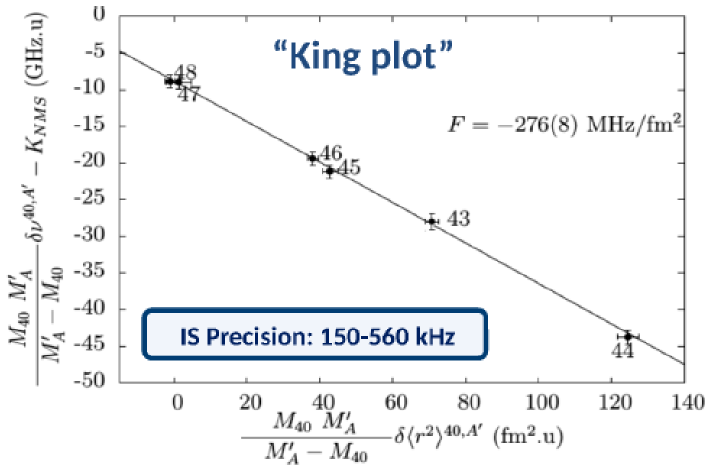
- Accessing New Observables

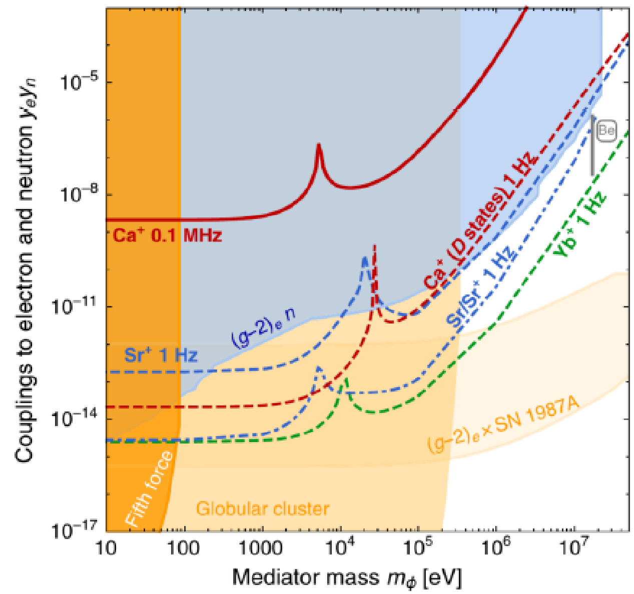
Motivation: Isotope Shift

A new force between electrons and nucleons will cause a "King plot" non-linearity

[Stadnik et al. Phys Rev Lett 120, 223202 (2018)]
[Flambaum et al. Phys Rev A 97, 032510 (2018)]
[Frugiuele et al. Phys Rev D 96, 015011 (2017)]
[Berengut et al. Phys Rev Lett 120, 091801 (2018)]

[R.F. Garcia Ruiz et al., Nature Physics 12, 594 (2016)]





$$\delta\nu^{A,A'} = K_{MS}\frac{M_{A'} - M_A}{M_{A'}M_A} + F\delta\langle r^2\rangle^{A,A'} + \alpha_{\mathrm{NP}} X_i \gamma_{AA'}$$

Atomic
Nuclear

$$V_\phi(r) = -\alpha_{\mathrm{NP}}(A-Z)e^{-m_\phi r}/r$$

$$\alpha_{\mathrm{NP}} = (-1)^s y_e y_n / 4\pi$$

Motivation:

- Searching for New Physics using the Isotope Shift
  - Observing non-linearity in the King Plot
    - $\longrightarrow$ New Gauge Fields
    - $\longrightarrow$ Dark Matter Coupling (dark photon)
- Accessing New Observables
  - E1 nuclear polarizability
  - Higher spatial moments e.g. $\langle r^4 \rangle$ ect.

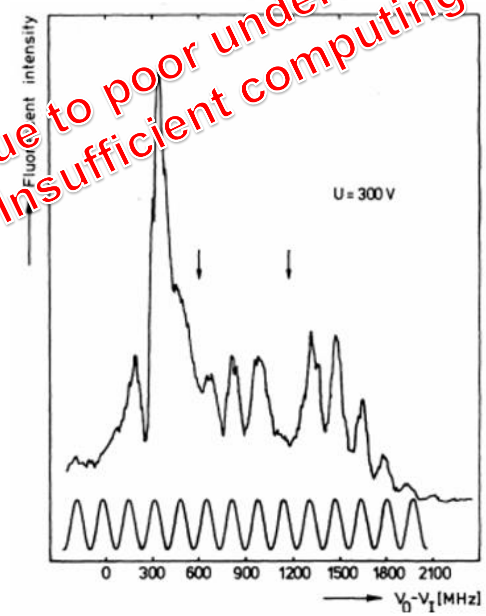
Motivation: Previous Attempts

Volume 82A, number 2 PHYSICS LETTERS 9 March 1981

OBSERVATION OF OPTICAL RAMSEY INTERFERENCE FRINGES IN COLLINEAR ION BEAM–LASER BEAM INTERACTION BY DOPPLER SWITCHING

R.E. SILVERANS [1], P. De BISSCHOP [2], M. Van HOVE, J.M. Van den CRUYCE and G. BORGHS
Instituut voor Kern- en Stralingsfysika, Leuven University, B-3030 Leuven, Belgium

Received 15 October 1980



Failed due to poor understanding of the line shape.
Insufficient computing to model this.

Appl. Phys. B 56, 62–64 (1993)
Applied Physics B Photo-physics and Laser Chemistry

High-Resolution Isotope Shift Measurement of the Mg I $^1S_0 - {}^3P_1$ Intercombination Transition

U. Sterr, K. Sengstock, J. H. Müller, and W. Ertmer
Institut für Angewandte Physik, Wegelerstrasse 8, W-5300 Bonn, Germany (Fax: +49-228/733474)

Received 7 August 1992/Accepted 3 November 1992

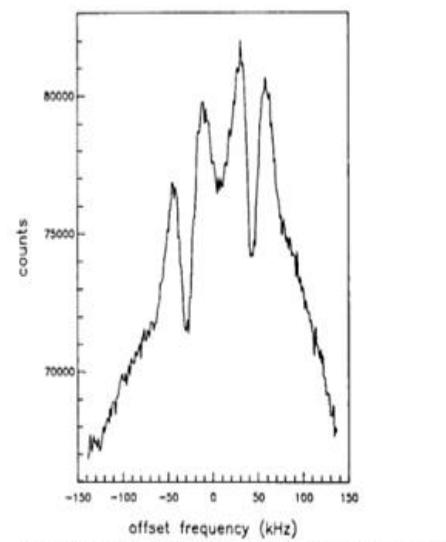
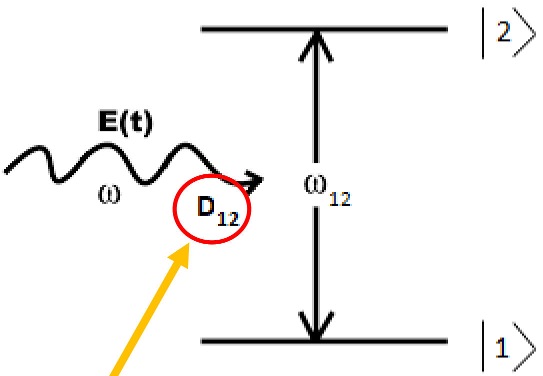


Fig. 2. Scan of the central part of the ^{24}Mg intercombination line, showing the Lamb dip with superimposed Ramsey fringes

The Model:



- Two Level System Coupled to a Single EM Mode:

$$\frac{1}{\hbar}\hat{H} = \omega_{12}|2\rangle\langle 2| + \omega \hat{a}^{\dagger}\hat{a} + \boxed{\sum_{\mu,\nu} \boldsymbol{F}\cdot\boldsymbol{D}_{\mu,\nu} i(\hat{a}e^{i\omega t} - \hat{a}^{\dagger}e^{-i\omega t})|\nu\rangle\langle\mu|}$$

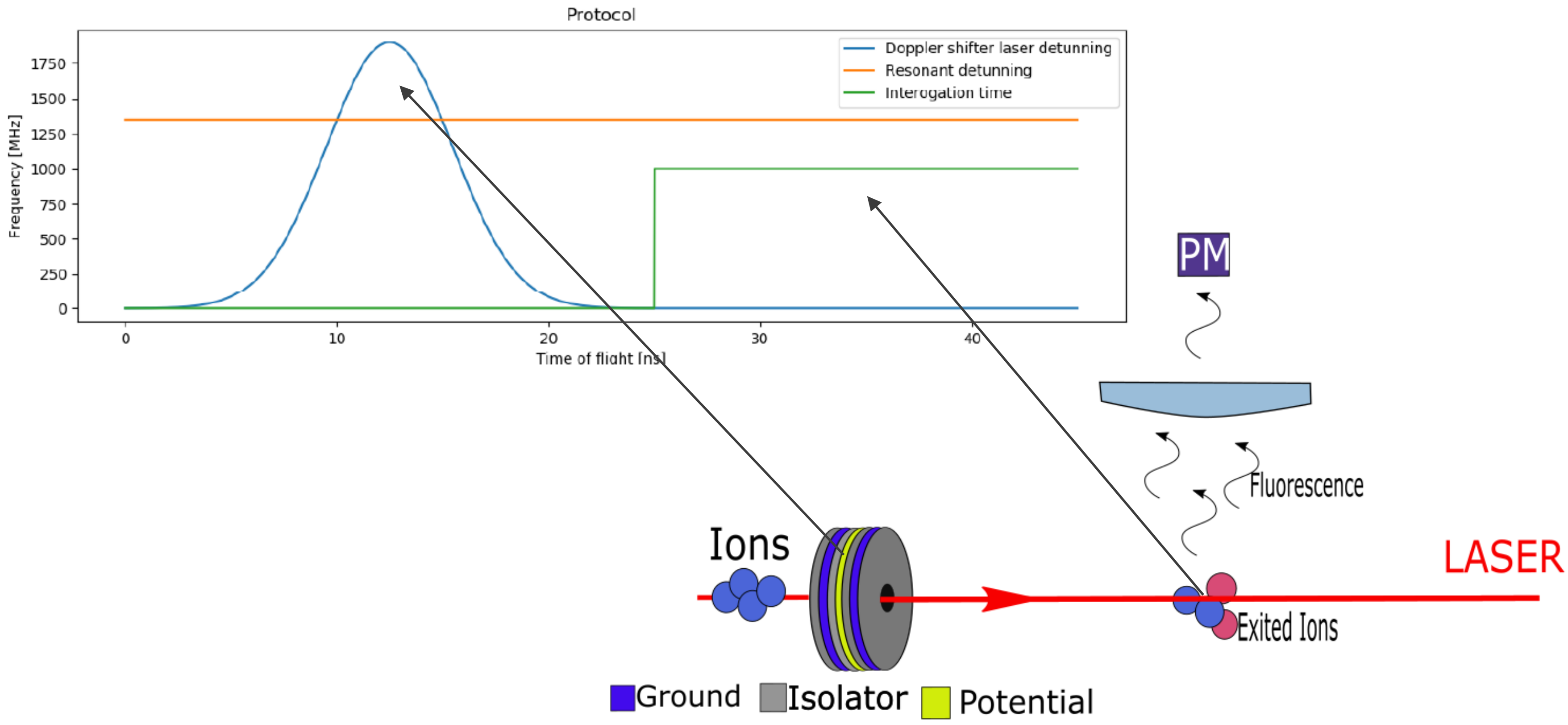
- Work in Density Matrix Formalism → Maxwell-Bloch Equations:

$$\frac{d\rho_{1,1}}{dt} = -i\frac{\Omega_{Rabi}}{2}\rho_{1,2} + i\frac{\Omega^*_{Rabi}}{2}\rho_{2,1} + \Gamma\rho_{2,2}$$

$$\frac{d\rho_{1,2}}{dt} = -i\frac{\Omega^*_{Rabi}}{2}(\rho_{1,1} - \rho_{2,2}) + (i\Delta - \frac{\Gamma}{2})\rho_{1,2}$$

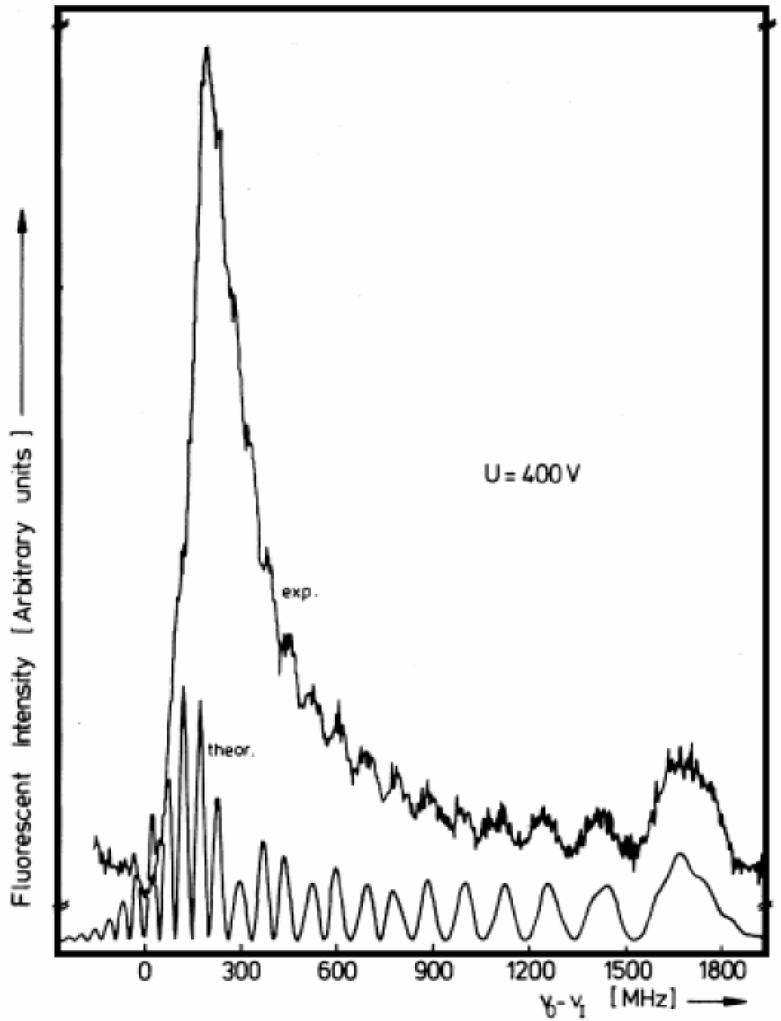
Benchmarks against Experiments

- My Model vs Borghs et al. (1981)



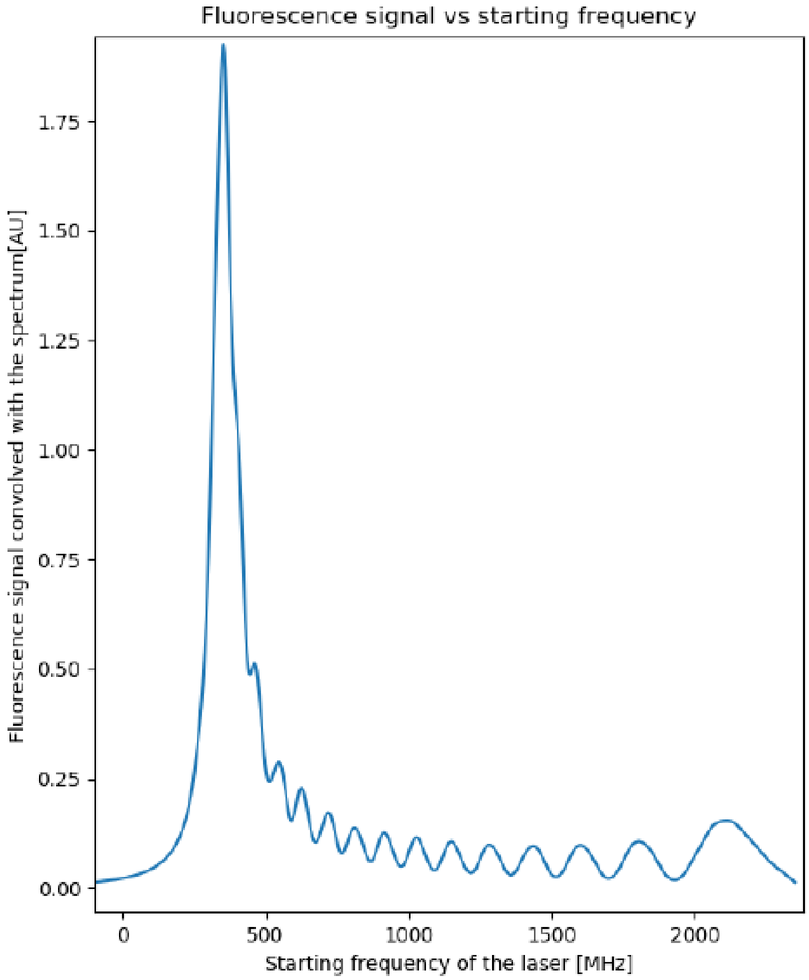
Gustaaf Borghs et al. Physical Review Letters, 46(16):1074, 1981.

Benchmarks against Experiments



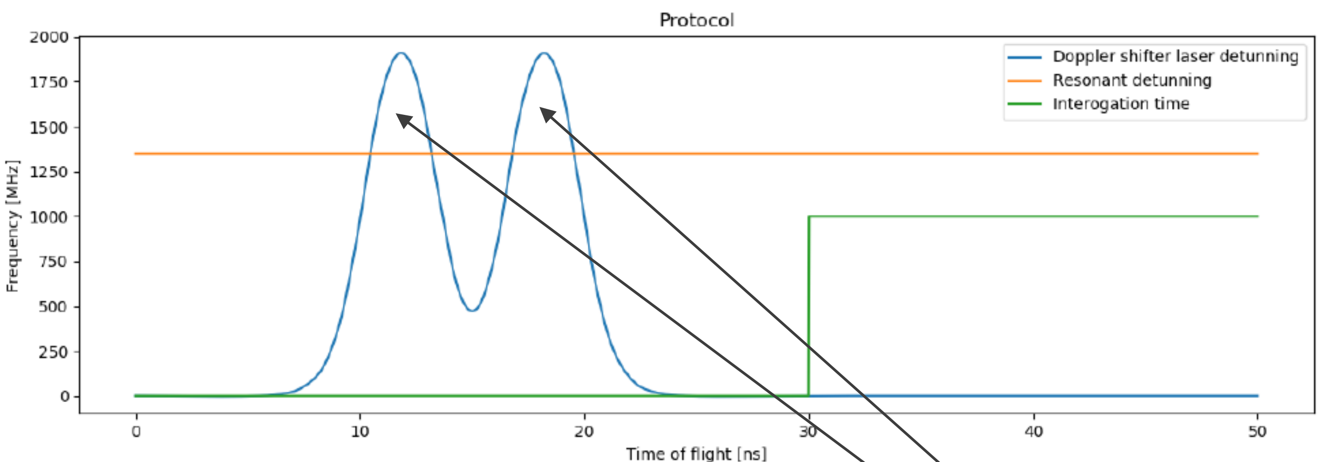
Gustaaf Borghs et al. Physical Review Letters, 46(16):1074, 1981.

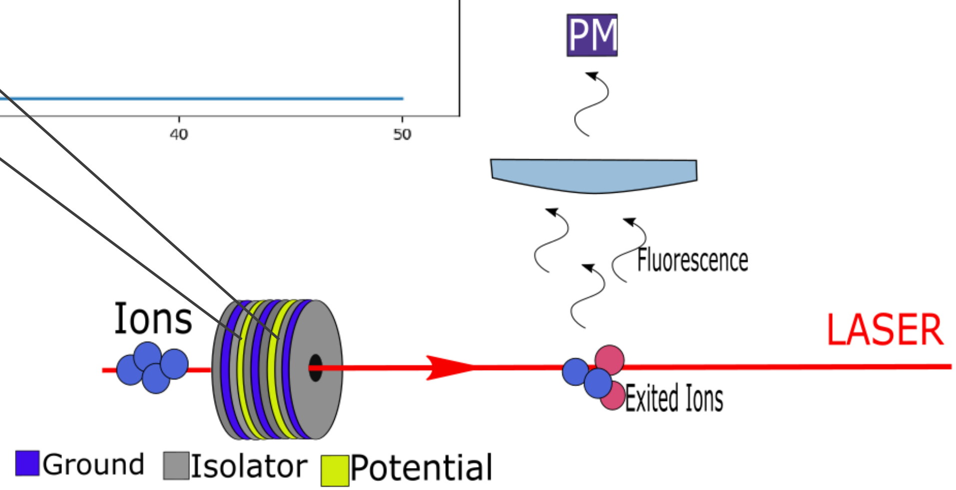
Benchmarks against Experiments



Benchmarks against Experiments

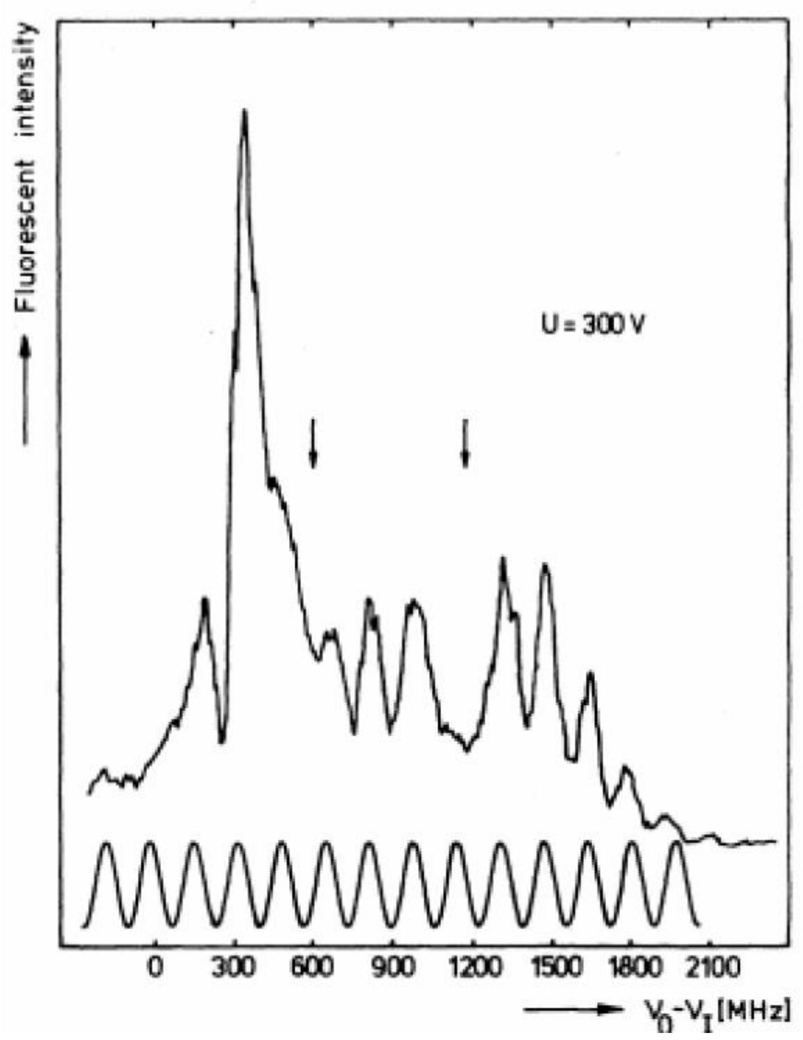
- My Model vs Silverans et al. (1981)





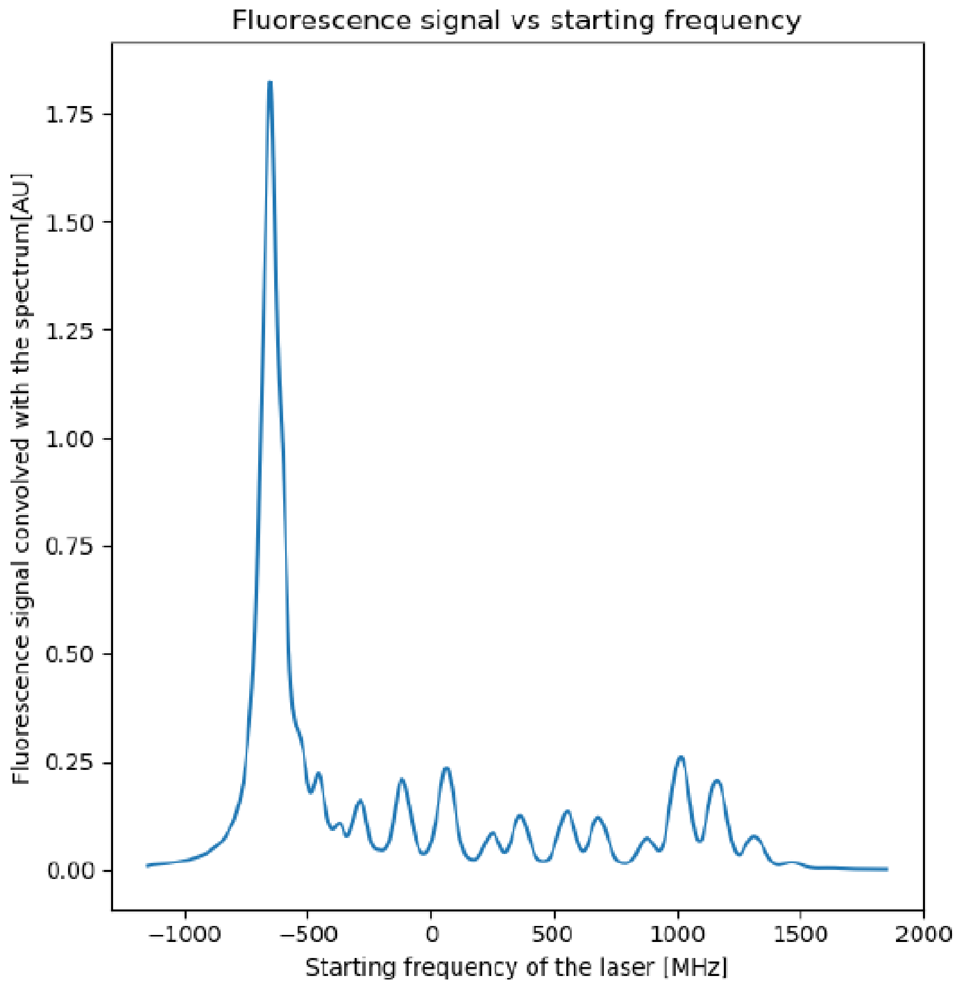
- ES ← COMSOL

Benchmarks against Experiments



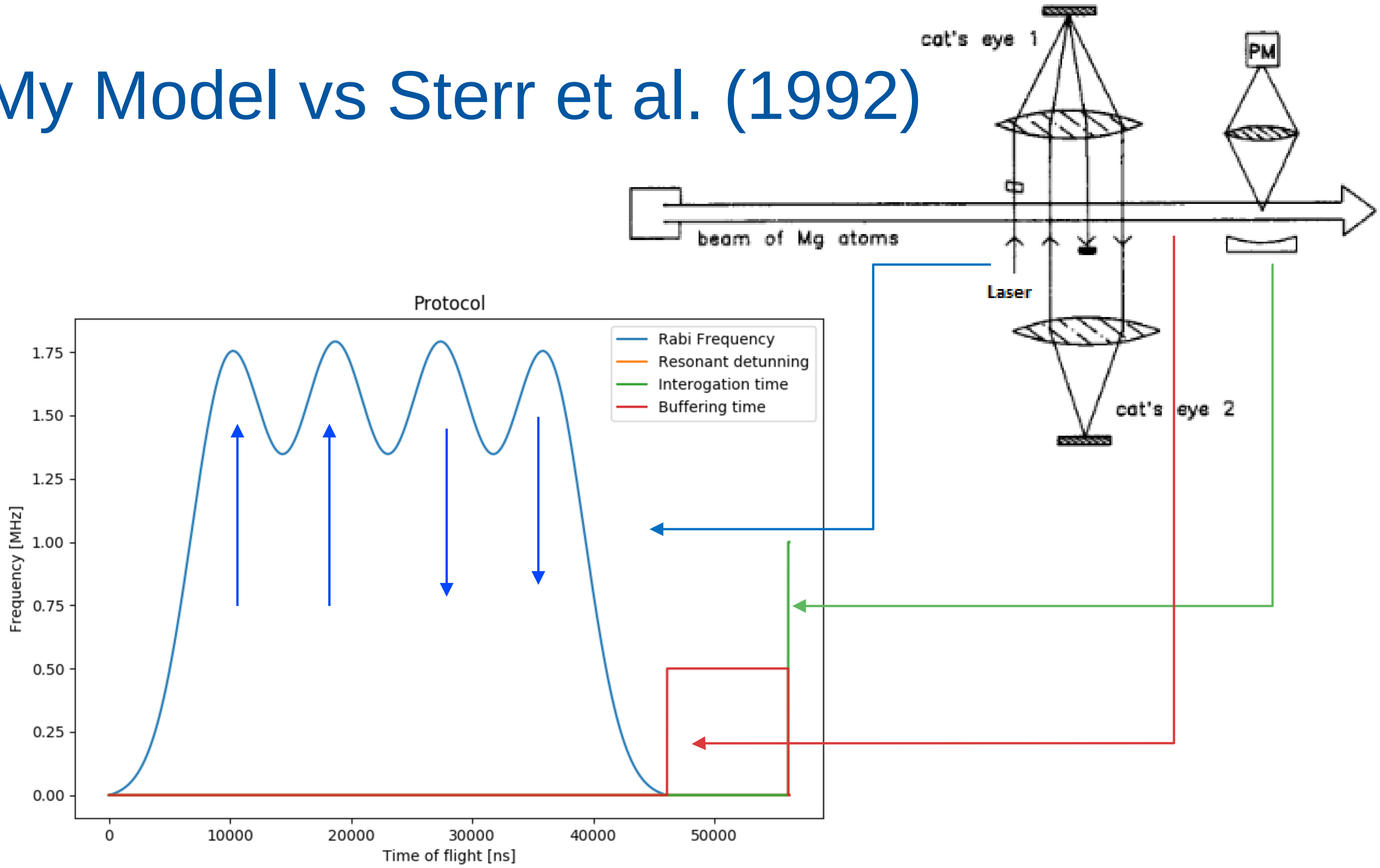
RE Silverans et al. Physics Letters A, 82(2):70–72, 1981.

Benchmarks against Experiments



Benchmarks against Experiments

- My Model vs Sterr et al. (1992)



Sterr, U et al. *Applied Physics B* 56.2 (1993): 62-64.

Benchmarks against Experiments

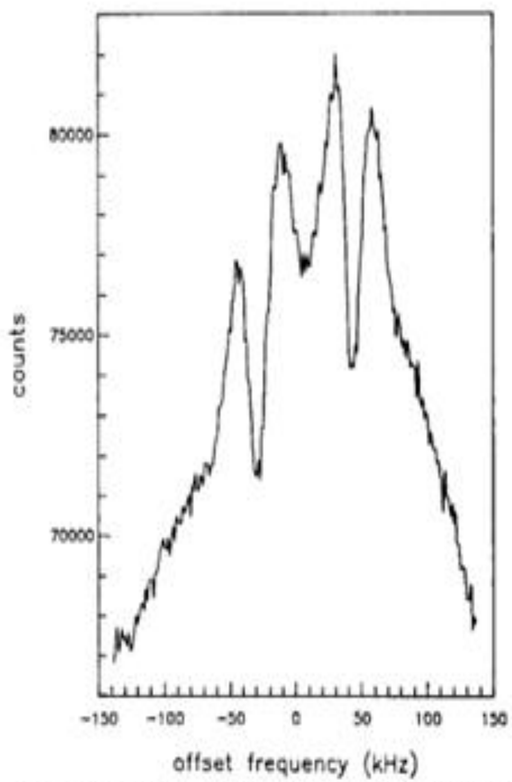
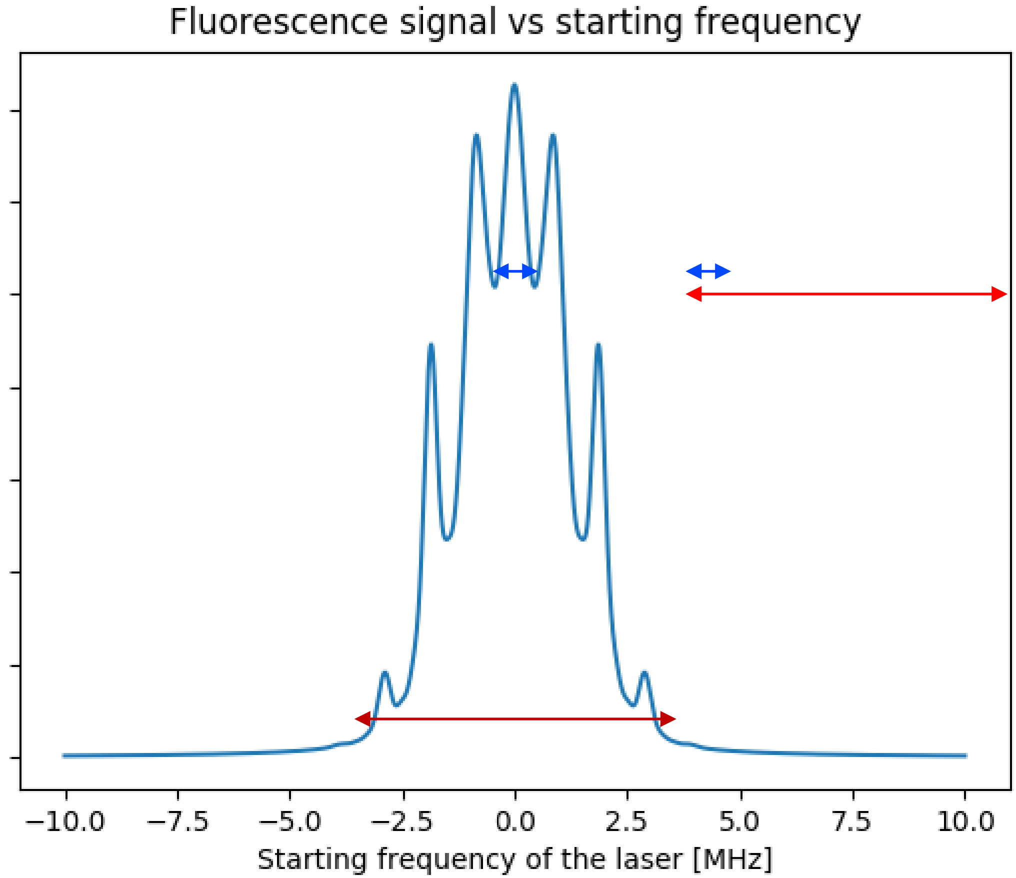


Fig. 2. Scan of the central part of the ^{24}Mg intercombination line, showing the Lamb dip with superimposed Ramsey fringes

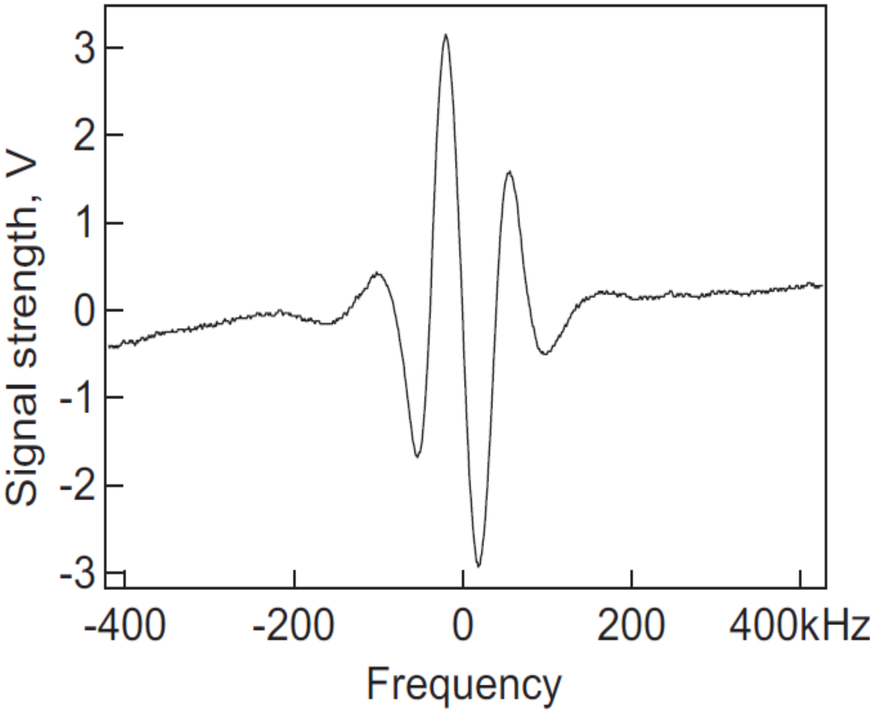
Scales are not crucial.

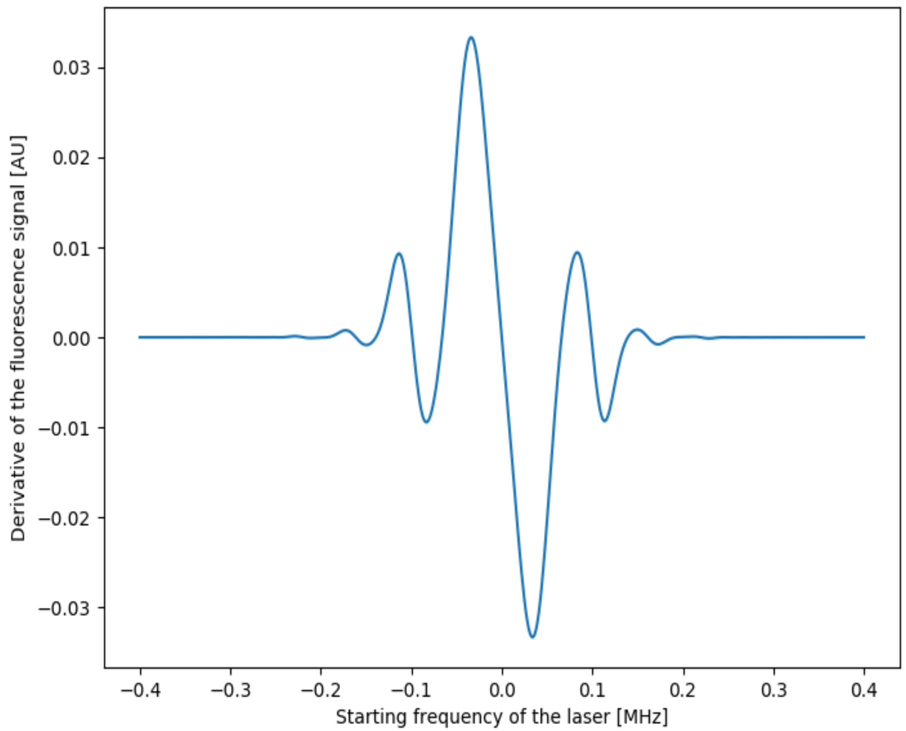
Around 8x reduction w/r to the natural linewidth



Benchmarks against Experiments

- Mc Ferran et al. (Similar Cross Geometry as in Sterr et al.)

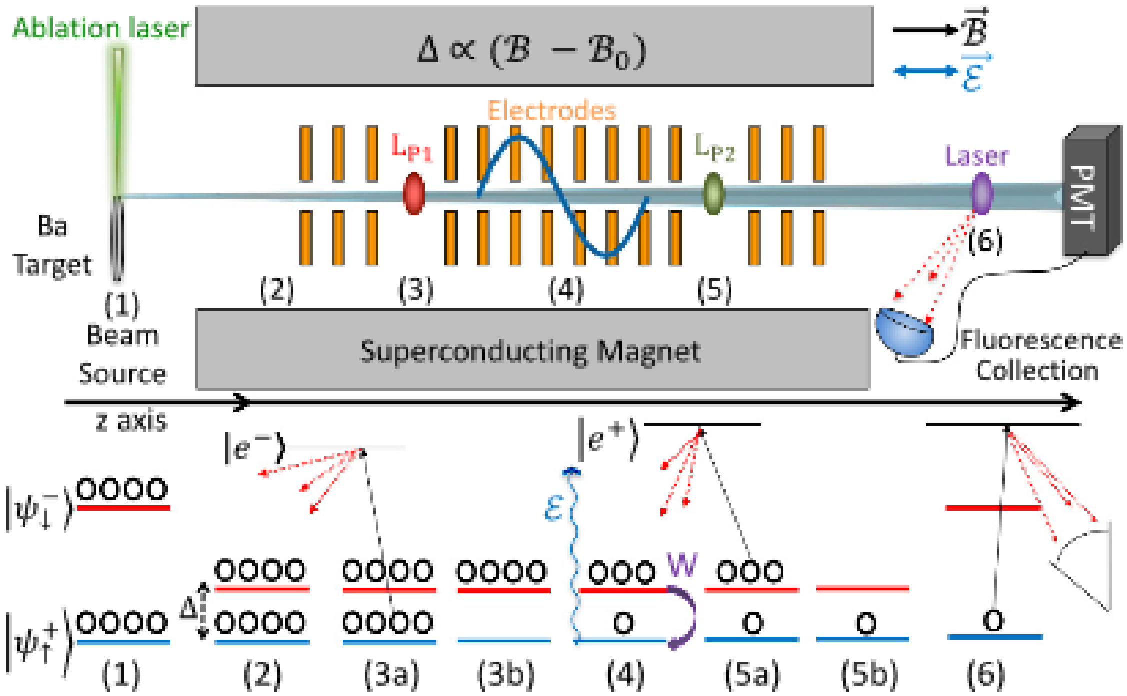




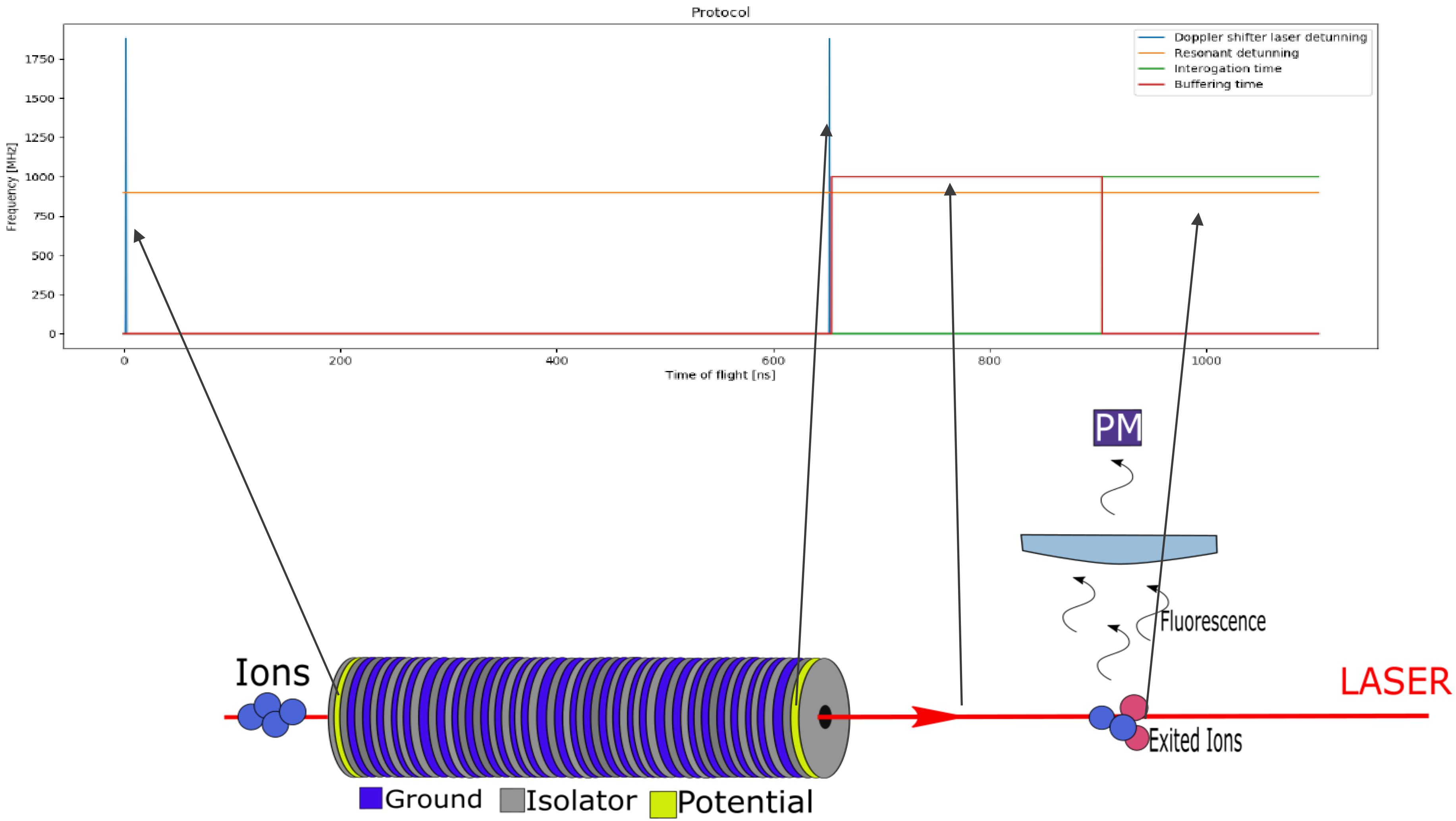
John J. McFerran and Andre N. Luiten,
J. Opt. Soc. Am. B **27**, 277-285 (2010)

Benchmarks against Experiments

- Altuntas et al. (2018) – not modelled yet

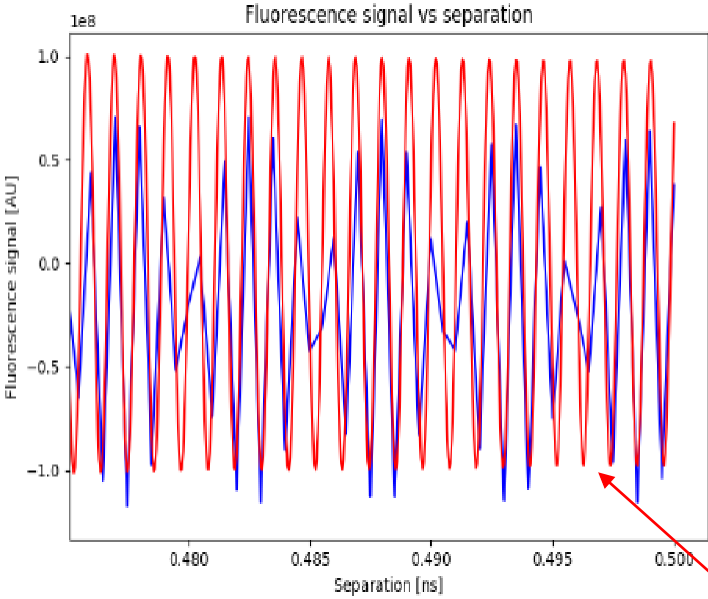


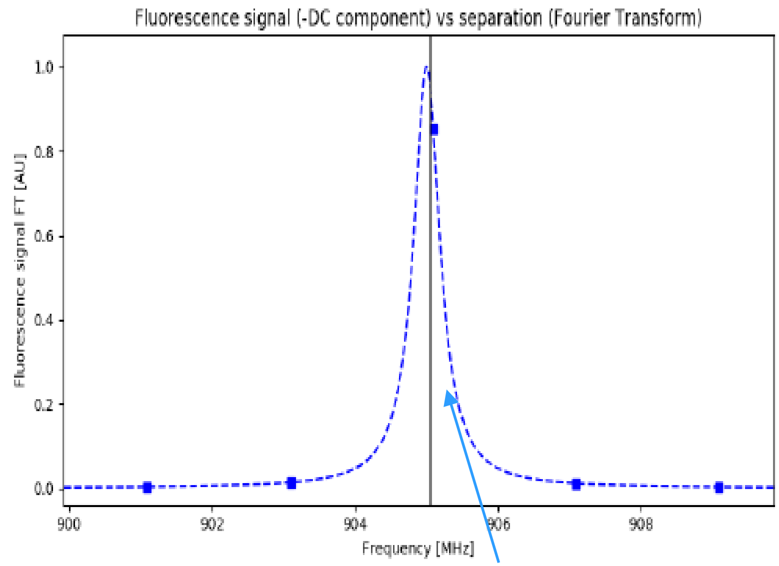
Double Switch: Design and Scanning Protocol



Doppler Switch

- Experimentally Reasonable Setup Results:

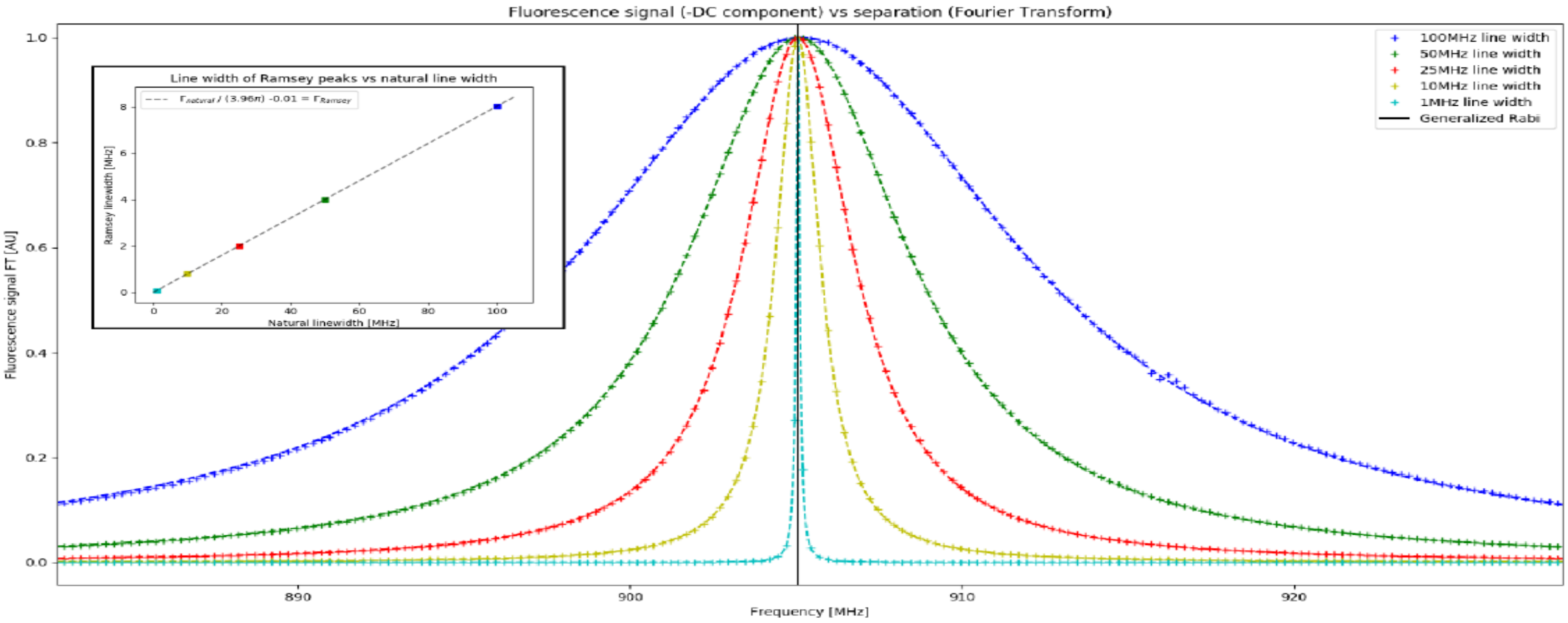




- EXP: 905051.9 kHz, FIT: 905051.5 kHz, FT: 905002.0 kHz
- Fitting in time domain: $Ex\ Pop \sim e^{-\Gamma t/2} \sin(\Omega' t + \phi)$

Doppler Switch

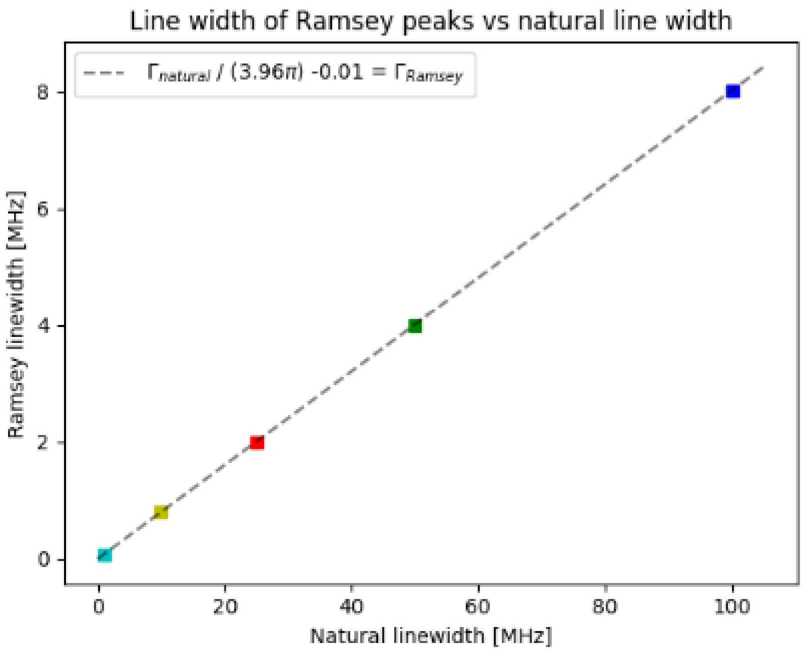
- Line Shape Analysis (Super Experiment):

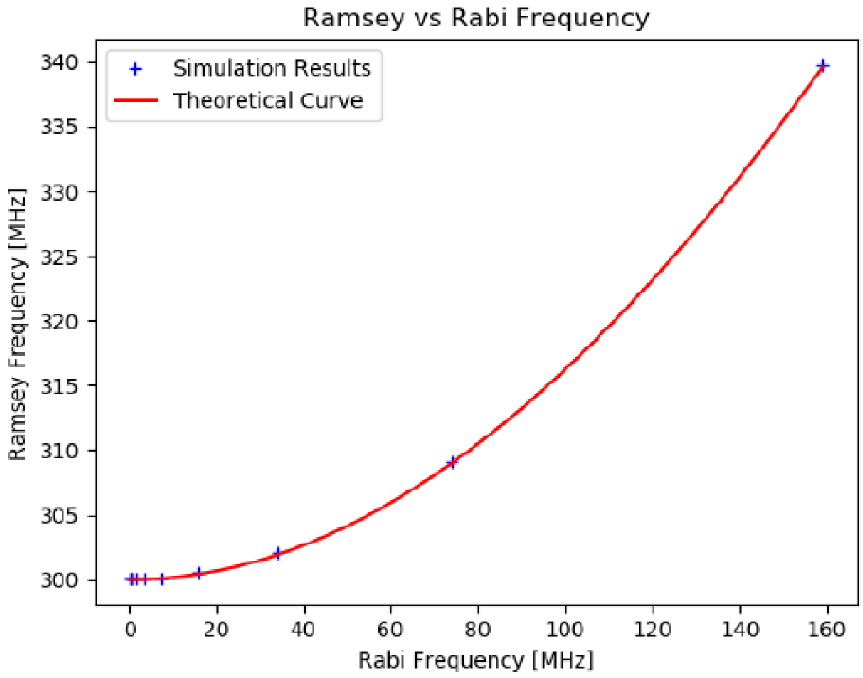


- Lorentzian Shape

Doppler Switch

- No Power Broadening

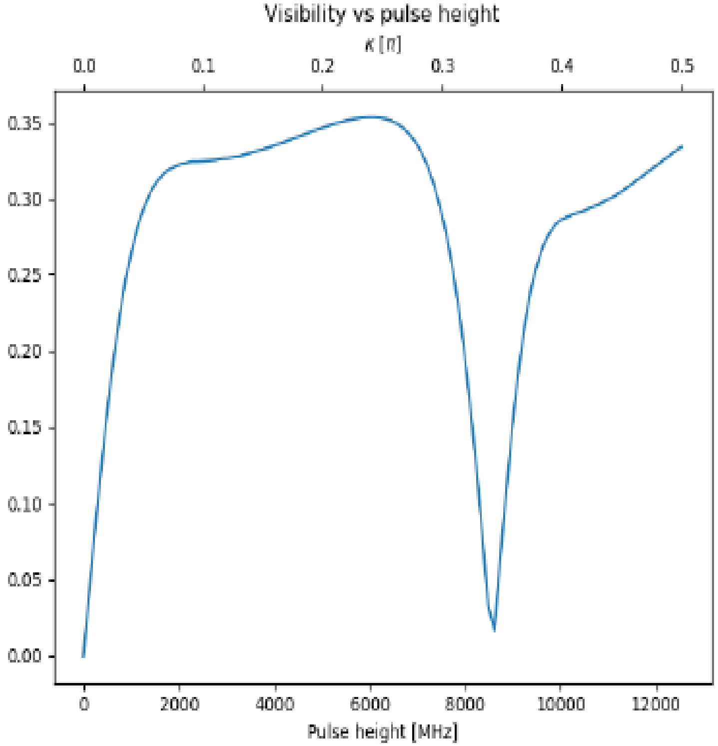


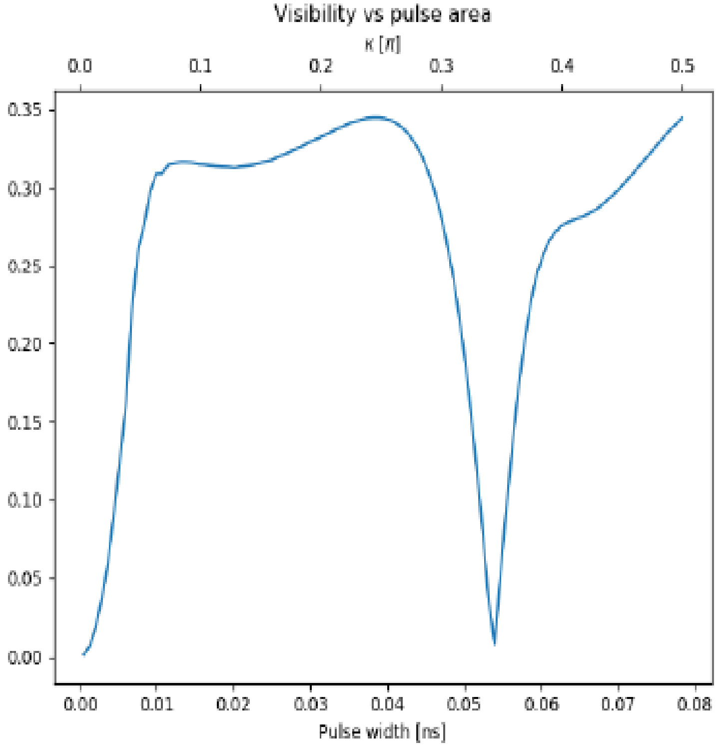


- Power factors in only as AC Stark Shift

Doppler Switch

- Pulse Shape Optimization
    - Only the Area factors in (Theoretically Understood)





Conclusions and Summary

- Line-shapes measured in the Reference Papers are now well understood and modelled well
- Even Low Quality Doppler Switch Setup Promises Sub-kHz Precision
- Works Only for Ions
- For Atoms One must use Cross Laser RS and for Molecules Near-Degenerate Probe

Future Plans

- Future Plan is to do the Same Analysis for the other Two Devices (Experimental Benchmark and Precision Analysis)
- For all Three Setups: Monte Carlo Simulations to take Thermal Broadening and Laser Linewidth into account

Thank you for your attention!

Acknowledgments

- Dr. Ronald Garcia Ruiz
- Dr. Adam Vernon

References

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