Optogalvanic spectroscopy of the Zeeman effect in xenon

Timothy B. Smith,

Bailo B. Ngom,

and

Alec D. Gallimore

ICOPS-2006 10:45, 5 Jun 06

Executive summary

<u>What are we reporting?</u>

- Xe I optogalvanic spectra @ 834.911 nm (vacuum)
- Hyperfine structure (hfs) model for 834.911 nm
- Zeeman splitting of Xe I line at 152 gauss
  - – π-component (laser polarization **E** || **B**)
  - – σ-component (laser polarization **E** perp **B**)

<u>Why is this worth doing?</u>

- Laser-induced fluorescence (LIF) useful in electric propulsion (EP)
  - – Bulk velocity from Doppler shift
  - – Full velocity distribution f(**v**) from deconvolution
- Near-field LIF may involve significant **B** magnitudes
- Zeeman LIF has been on EP ‘future work’ slides since 1992

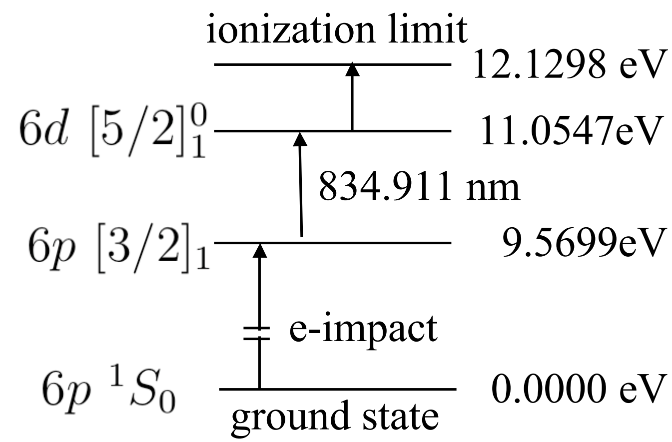
Overview

- Background
- Zeeman splitting
- Hyperfine structure
- Experimental setup
- Results
- Conclusions

What's optogalvanic spectroscopy (OGS)?

Process:

- Steady-state discharge
  - -electron-impact excitation to lower state
- Photon absorption at $h\nu = E_{upper} - E_{lower}$
  - - populates upper state
- Upper state more easily ionized
  - - increased discharge current

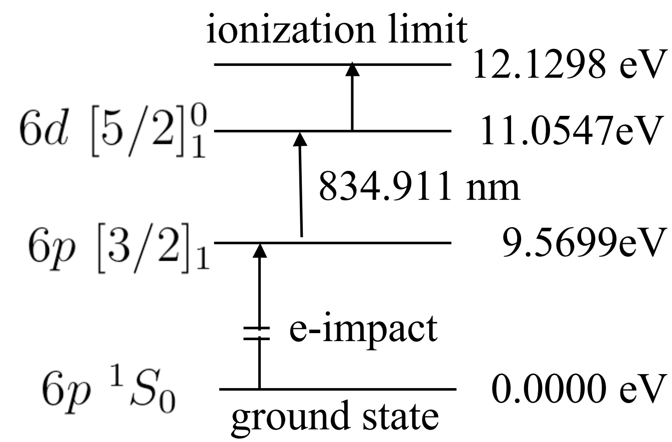


Xe I optogalvanic effect

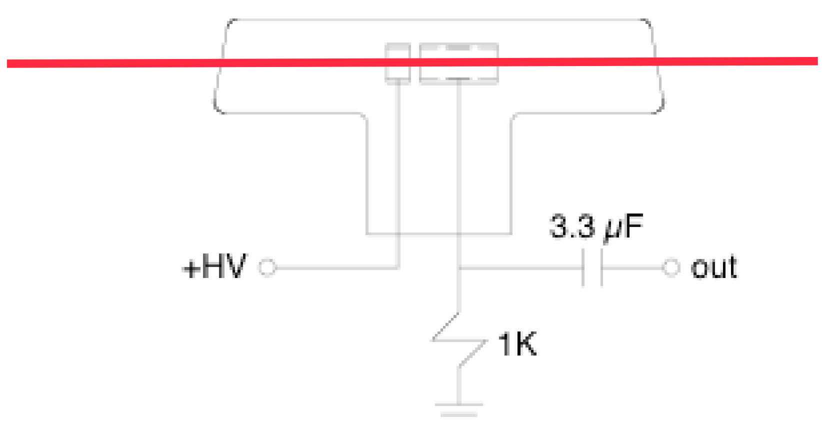
How do you do optogalvanic spectroscopy (OGS)?

<u>Process:</u>

- Steady-state discharge
  - -electron-impact excitation to lower state
- Photon absorption at $h\nu = E_{upper} - E_{lower}$
  - - populates upper state
- Upper state more easily ionized
  - - increased discharge current



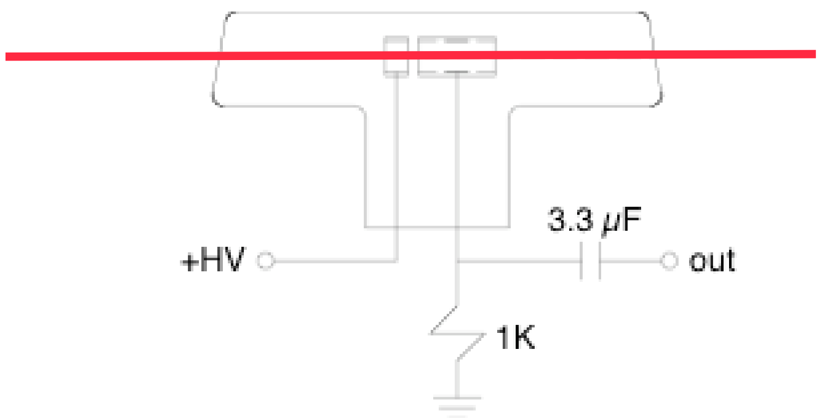
Xe I optogalvanic effect



<u>Application:</u>

- Hollow-cathode discharge
- Tunable laser
  - - swept through absorption line
  - - chopped at known frequency
- Lock-in amplifier
  - - recovers ac component at chopping frequency

Why bother with optogalvanic spectroscopy (OGS)?



Application:
- Hollow-cathode discharge
- Tunable laser
  - swept through absorption line
  - chopped at known frequency
- Lock-in amplifier
  - recovers ac component at chopping frequency

Advantages:
- Simple setup
  - single optical axis
  - no collection optics
  - no spectral filtering
- Compact, inexpensive apparatus
  - commercial galvatron

Disadvantages:
- Needs electrode in plasma
  - loses non-intrusiveness
  - line-integrated measurement
- Not all lines have strong OGS

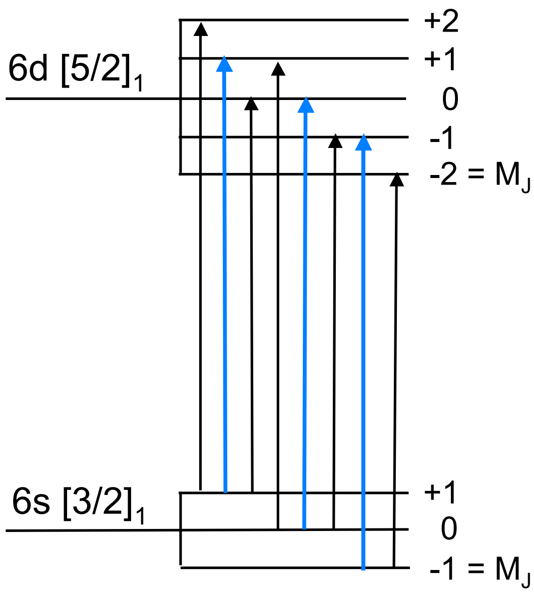
Overview

- Background
- Zeeman splitting
- Hyperfine structure
- Experimental setup
- Results
- Conclusions

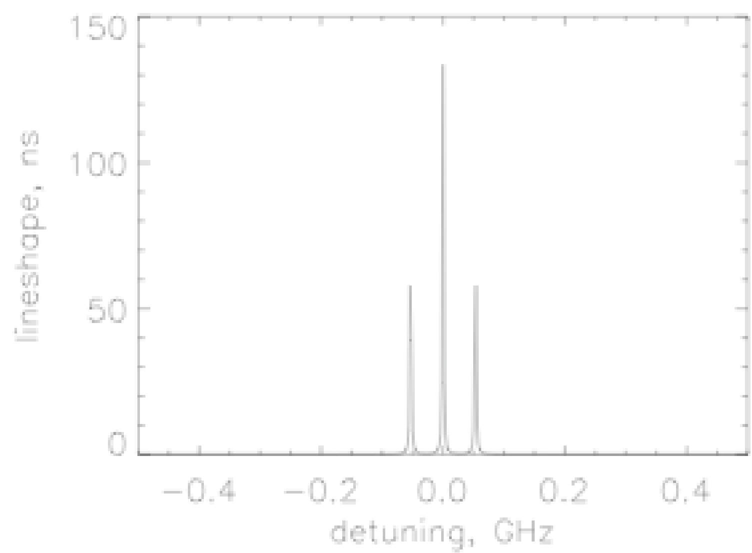
Zeeman splitting of the fine structure

Magnetic field B perturbs energy level:

- 2J+1 Zeeman splittings M_J per state
- Energy shift proportional to |**B**| (for weak B)
- Three $M_J \rightarrow M_J$ transitions (π-component, **E** || **B**)



Zeeman splittings

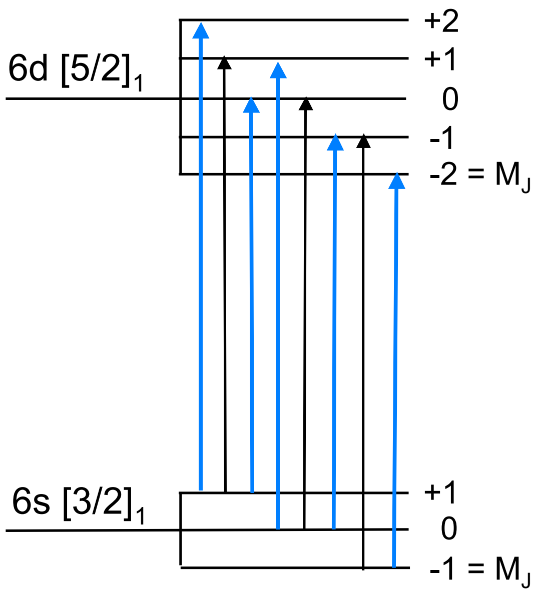


π-component at 152 gauss

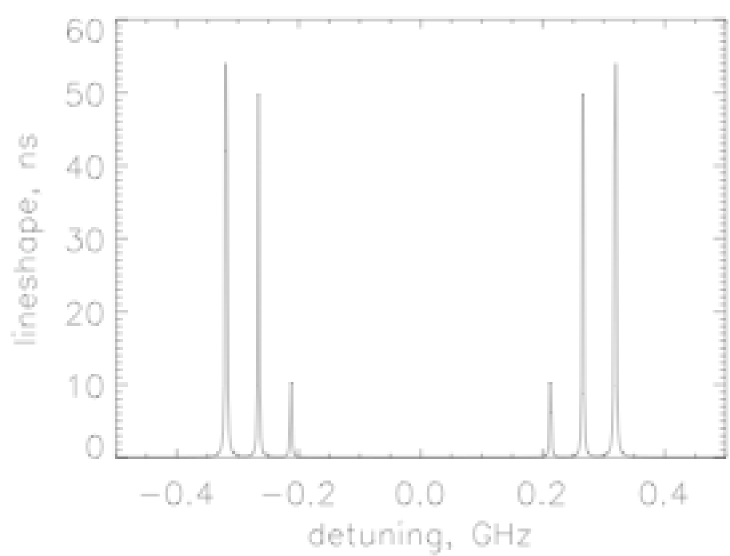
Zeeman splitting of the fine structure

<u>Magnetic field B perturbs energy level:</u>

- 2J+1 Zeeman splittings M_J per state
- Energy shift proportional to |**B**| (for weak B)
- Three $M_J \rightarrow M_J$ transitions (π-component, **E** || **B**)
- Six $M_J \rightarrow M_J \pm 1$ transitions (σ-component, **E** perp **B**)



Zeeman splittings



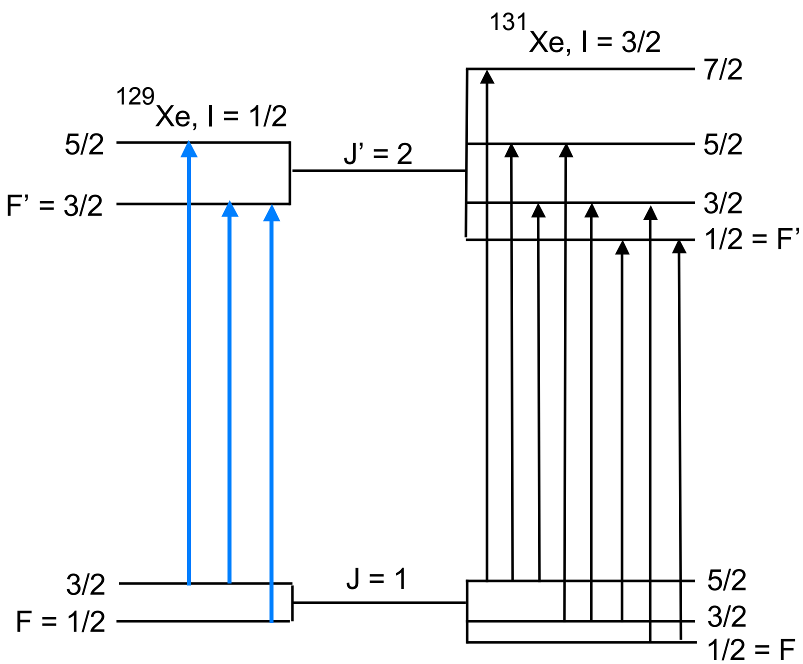
σ-component at 152 gauss

Overview

- Background
- Zeeman splitting
- Hyperfine structure
- Experimental setup
- Results
- Conclusions

What determines Xe I hyperfine structure at 834.911 nm?

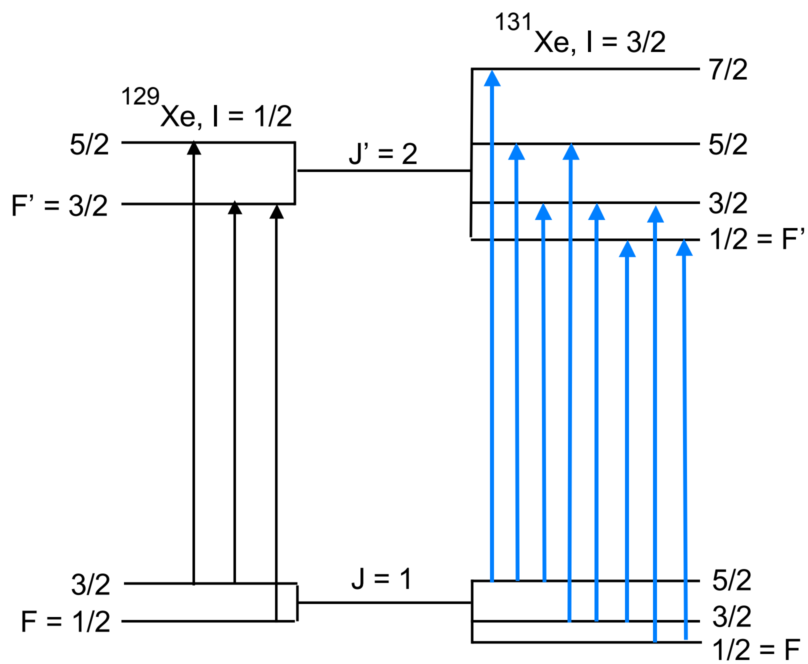
- Xenon has 9 isotopes → 9 isotope shifts
- For J = 1 → J'= 2, ^{129}Xe has 3 nuclear-spin splittings



(a) Nuclear-spin splittings

What determines Xe I hyperfine structure at 834.911 nm?

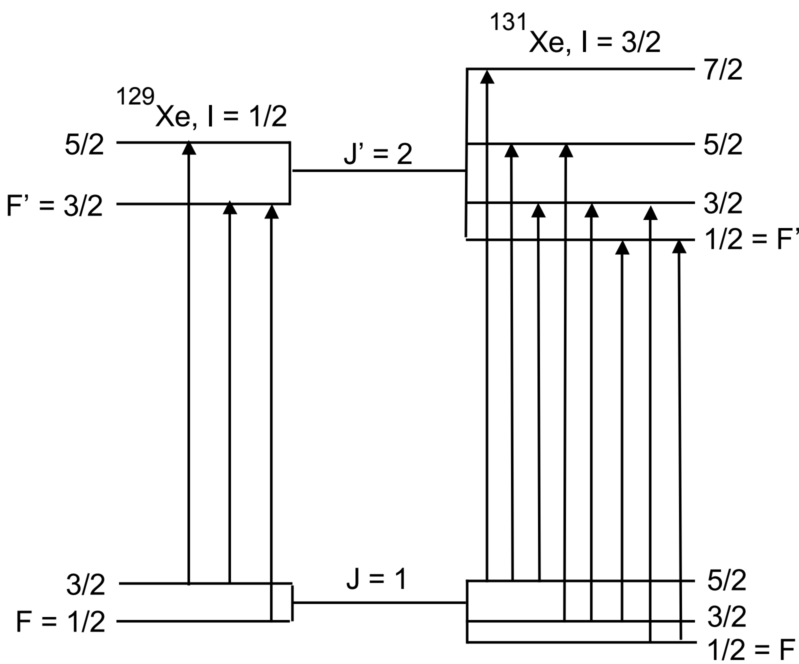
- Xenon has 9 isotopes → 9 isotope shifts
- For J = 1 → J’= 2, ^{129}Xe has 3 nuclear-spin splittings
- For J = 1 → J’= 2, ^{131}Xe has 8 nuclear-spin splittings
- Absorption line has 9 - 2 + 3 + 9 = 18 hyperfine splittings.



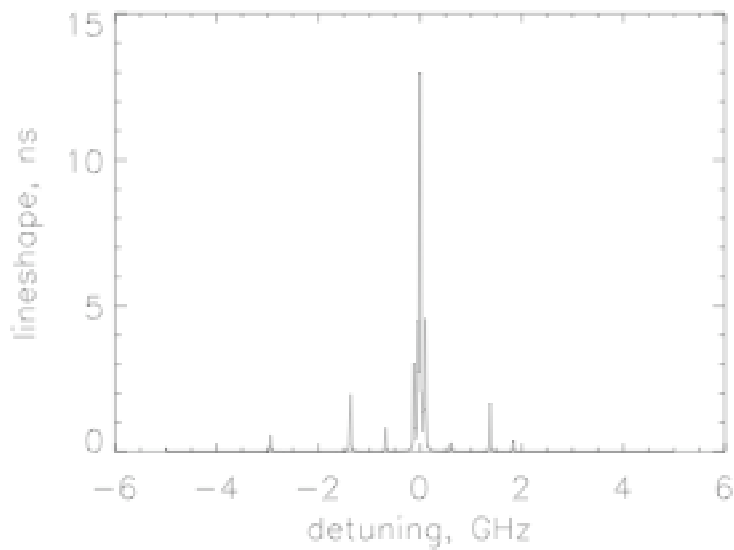
(a) Nuclear-spin splittings

What determines Xe I hyperfine structure at 834.911 nm?

- Xenon has 9 isotopes → 9 isotope shifts
- For J = 1 → J'= 2, ^{129}Xe has 3 nuclear-spin splittings
- For J = 1 → J'= 2, ^{131}Xe has 8 nuclear-spin splittings
- Absorption line has 9 - 2 + 3 + 9 = 18 hyperfine splittings.



(a) Nuclear-spin splittings



(b) Hyperfine structure, h(ν)

Cold-plasma spectrum

- Natural broadening l(ν) is a Lorentzian
  - based on Heisenberg Uncertainty Principle
  - linewidth inversely proportional to upper state lifetime,

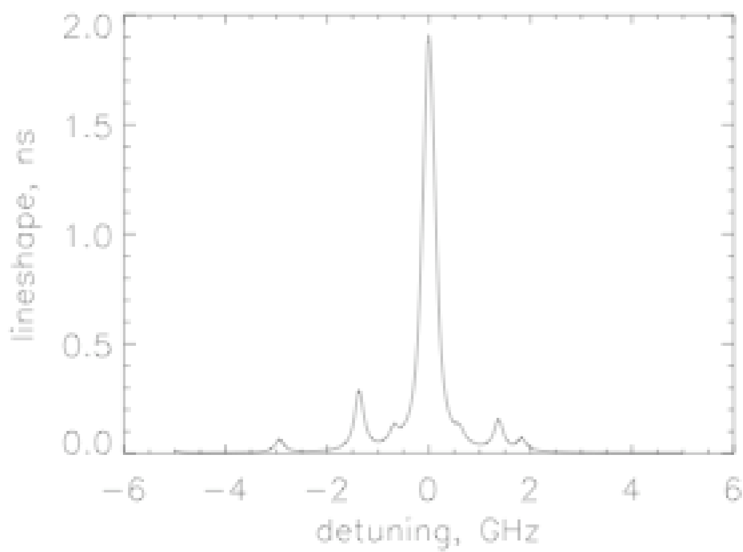
$$\Delta \nu_n = A_i / 2\pi$$

- Cold Xe II LIF spectrum c(ν) is convolution of
  - hyperfine structure, h(ν)
  - natural broadening, l(ν)

$$c(\nu) = h(\nu) \otimes l(\nu)$$

- Simulates spectrum for a stationary population at absolute zero (T = 0 K),

$$f(\underline{\mathbf{v}}) = \delta(\underline{\mathbf{v}})$$



cold-plasma spectrum, c(ν)

Warm-plasma spectrum

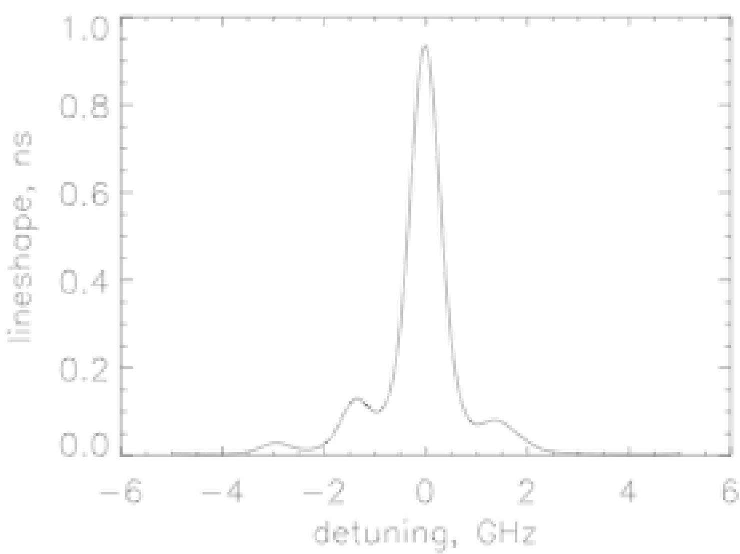
- For ion velocity distribution f(v), Doppler broadening

$$d(\nu) = \frac{c}{\nu_0} f\left(\left[1 - \frac{\nu}{\nu_0}\right] c\right)$$

directly transforms f(v) from velocity to frequency space.

- Unsaturated warm-plasma spectrum (or “lineshape”) i(ν) is convolution of
  - cold-plasma spectrum, c(ν)
  - Doppler broadening, d(ν)

$$i(\nu) = c(\nu) \otimes d(\nu)$$

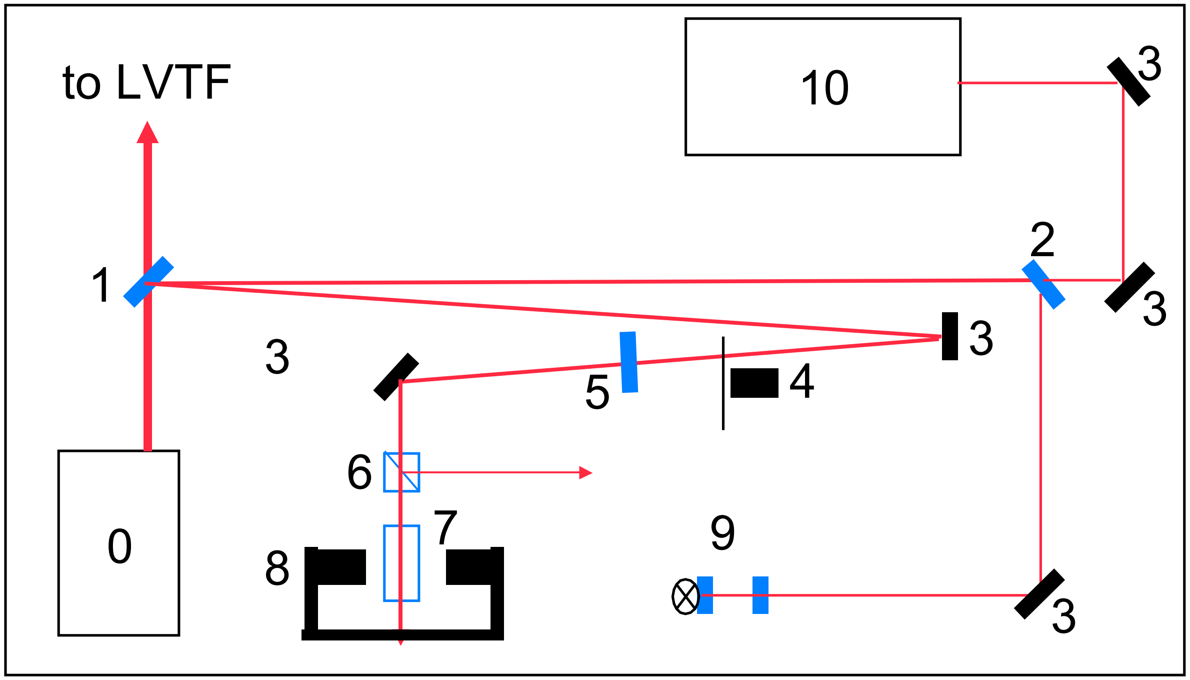


warm-plasma spectrum (600 K), i(ν)

Overview

- Background
- Zeeman splitting
- Hyperfine structure
- Experimental setup
- Results
- Conclusions

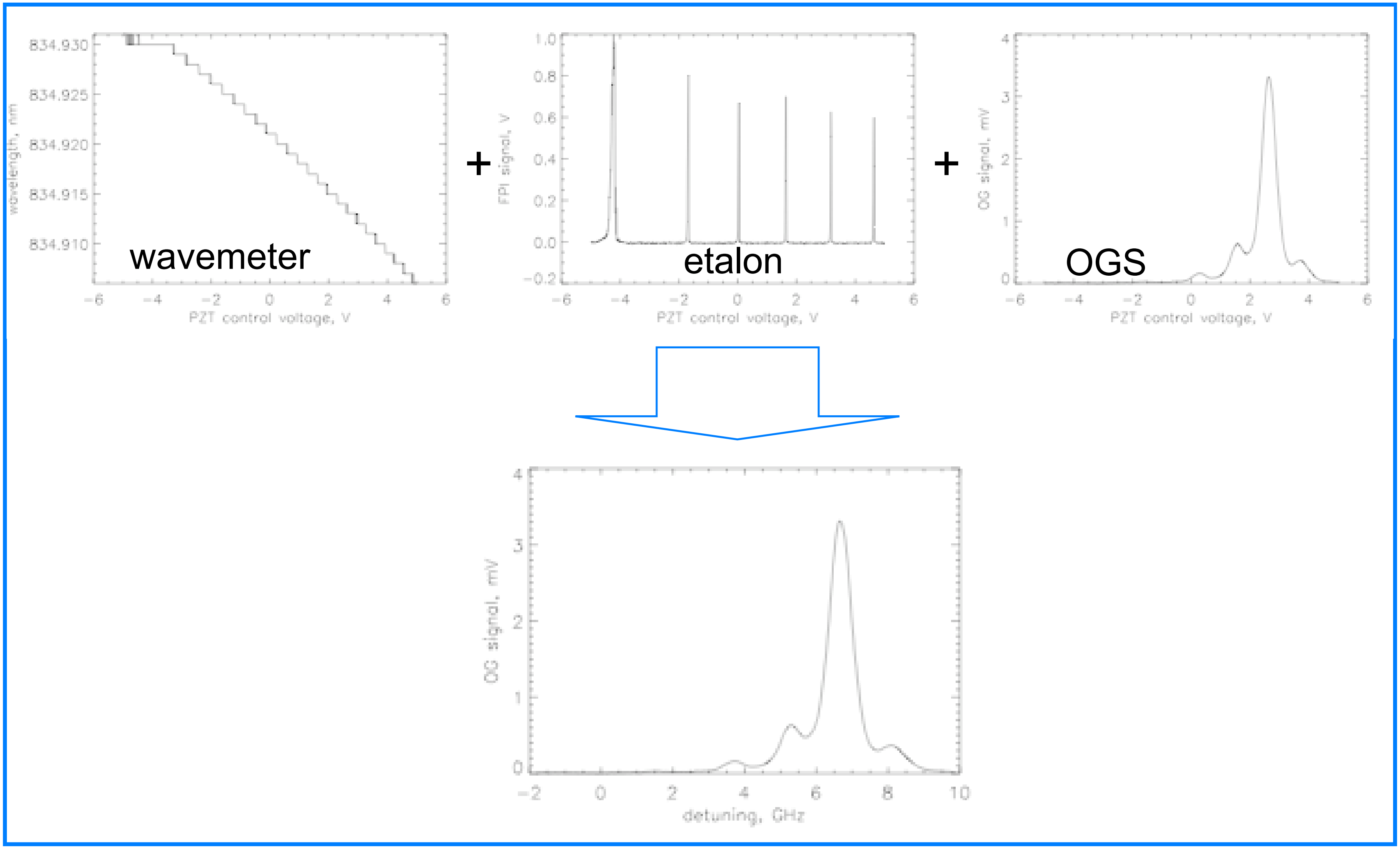
Optical schematic



Index:
0. Tunable diode laser
1. Beam pickoff
2. 50/50 beamsplitter
3. Steering mirror
4. Chopper
5. Half-wave plate
6. Polarizing cube beamsplitter
7. Optogalvanic cell
8. Electromagnet
9. Etalon (2 GHz FSR)
10. Wavemeter

- TA-100 tapered-amplifier diode laser
  - ~2 MHz linewidth, up to 500 mW output
- WA-1000 wavemeter, ± 1 pm accuracy
- Etalon, 2-GHz FSR
- Hamamatsu galvatron, Xe-Ne mix, Mo electrodes

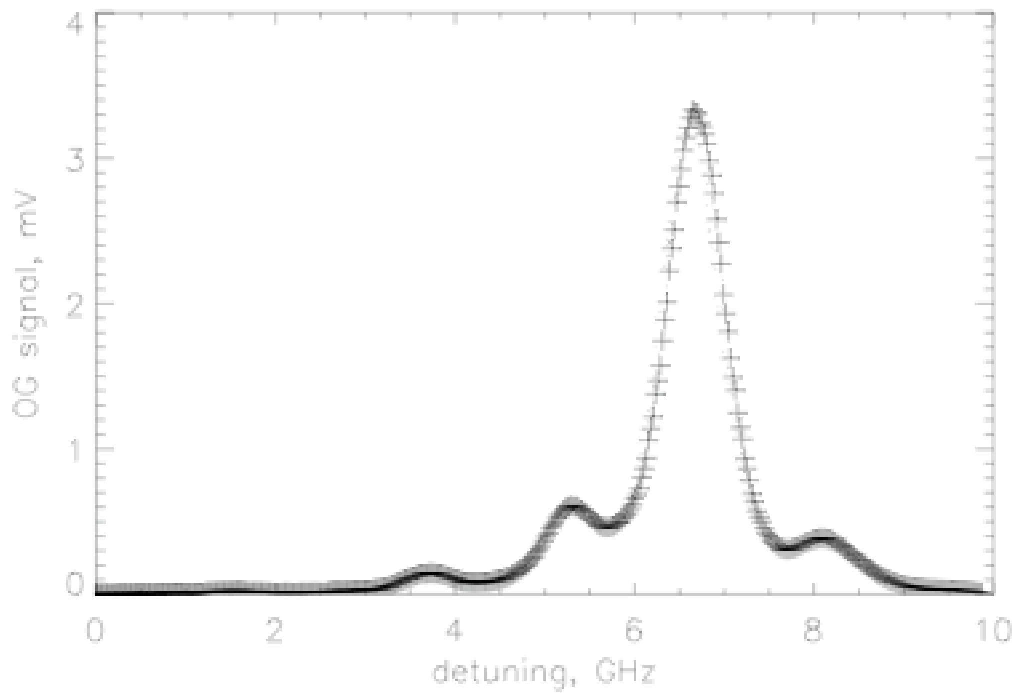
Data reduction



Overview

- Background
- Zeeman splitting
- Hyperfine structure
- Experimental setup
- Results
- Conclusions

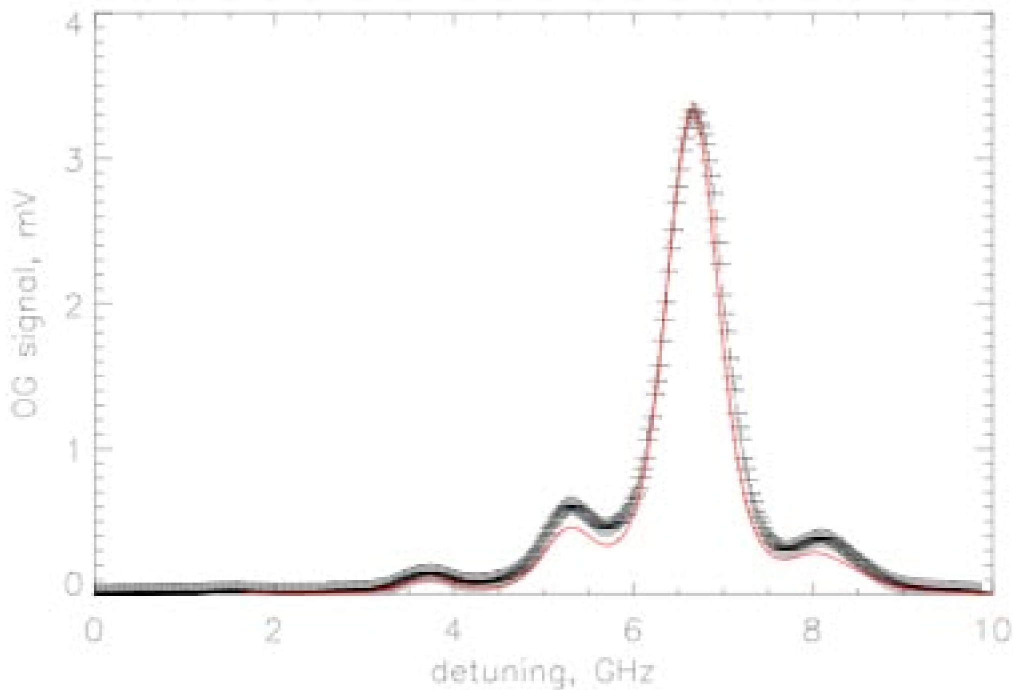
Xe I OGS @ 834.911 nm
B = 0 gauss



Data set:

- Ensemble average of 10 reference cell scans
- Laser input 5.3 to 3.7 mW over ~ 50 mm^2

Xe I OGS @ 834.911 nm
B = 0 gauss



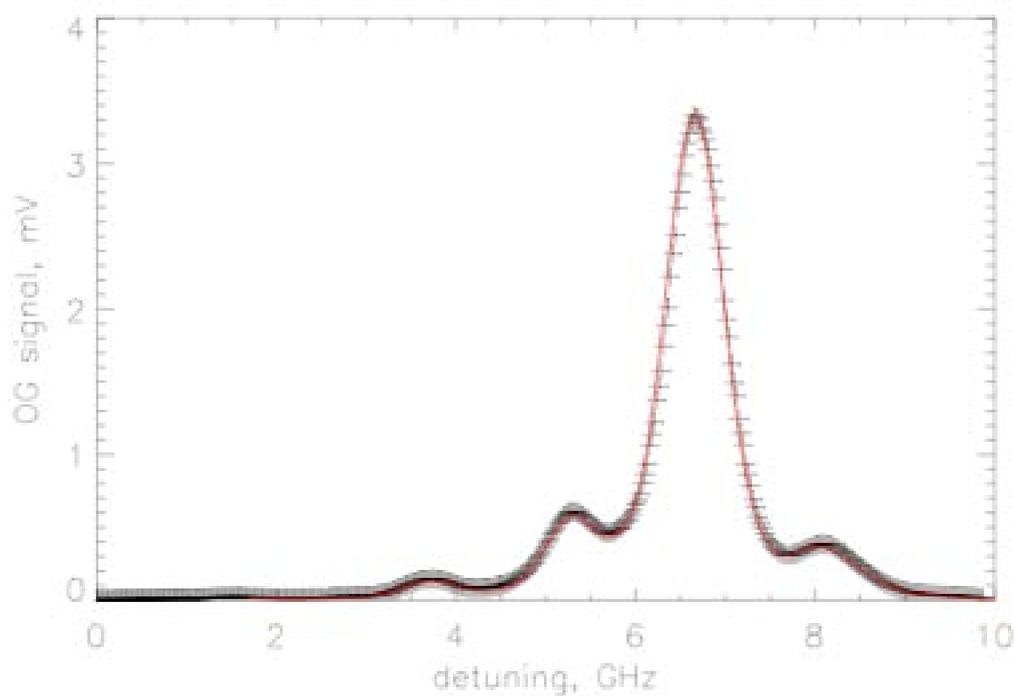
<u>Data set:</u>

- Ensemble average of 10 reference cell scans
- Laser input 5.3 to 3.7 mW over ~ 50 mm^2

<u>Model</u>:

- best-fit temperature 600 K; higher temps lose hfs structure

Xe I OGS @ 834.911 nm
B = 0 gauss



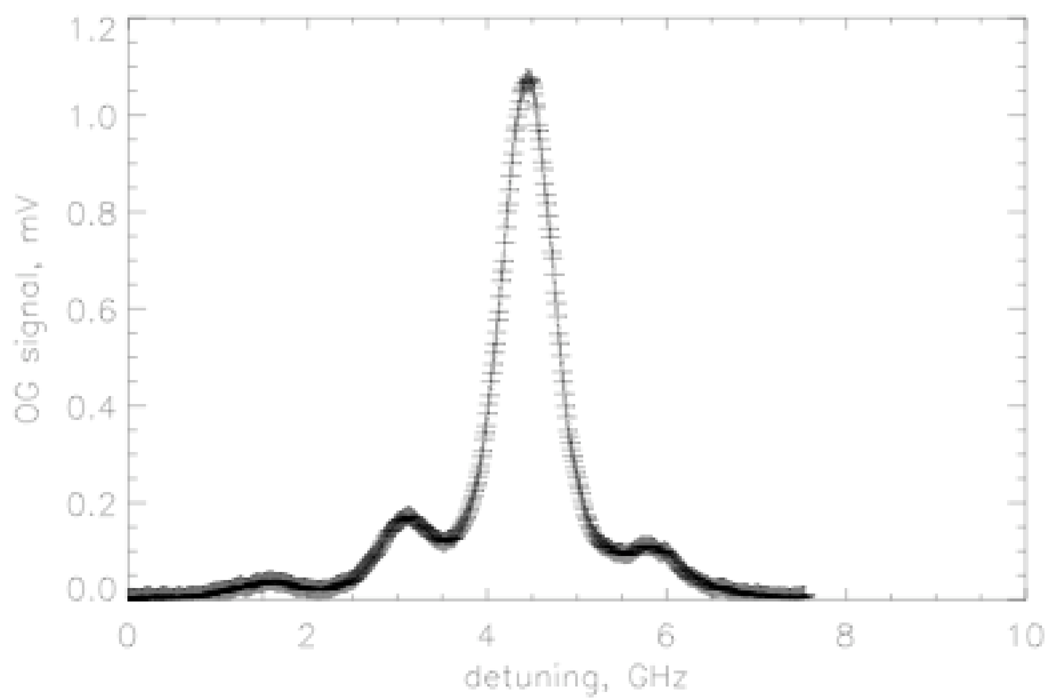
Data set:

- Ensemble average of 10 reference cell scans
- Laser input 5.3 to 3.7 mW over ~ 50 mm^2

Model:

- saturation correction at 600 K gives excellent fit

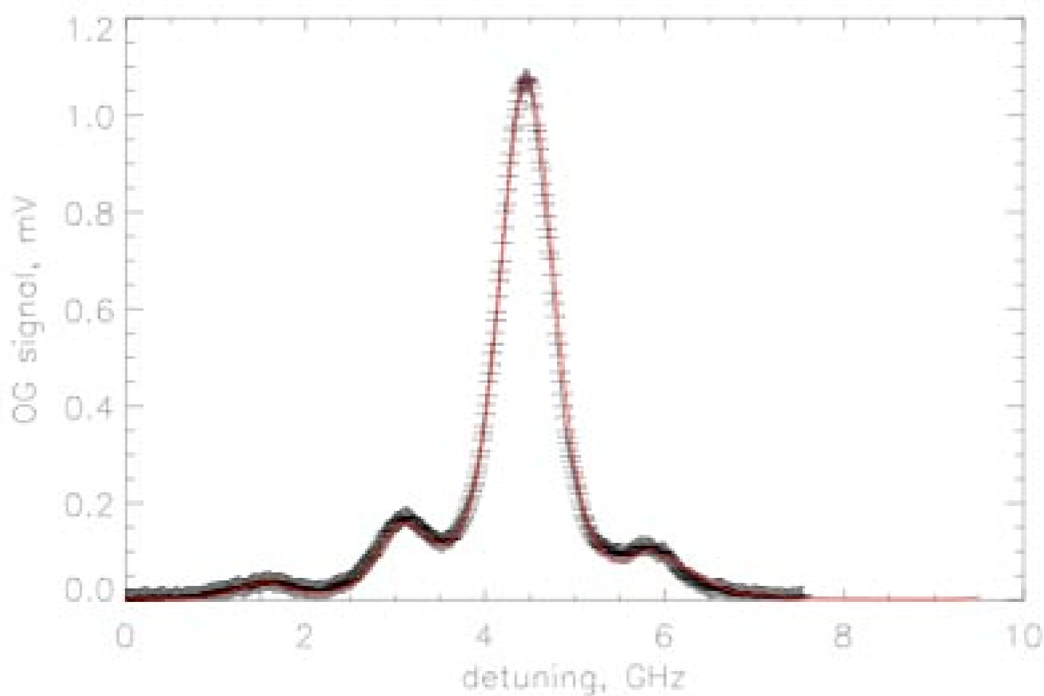
Xe I OGS @ 834.911 nm
B = 152 gauss, π-component



Data set:

- Ensemble average of 10 reference cell scans, same laser intensity
- Polarization rotated to **E** || **B**

Xe I OGS @ 834.911 nm
B = 152 gauss, π-component



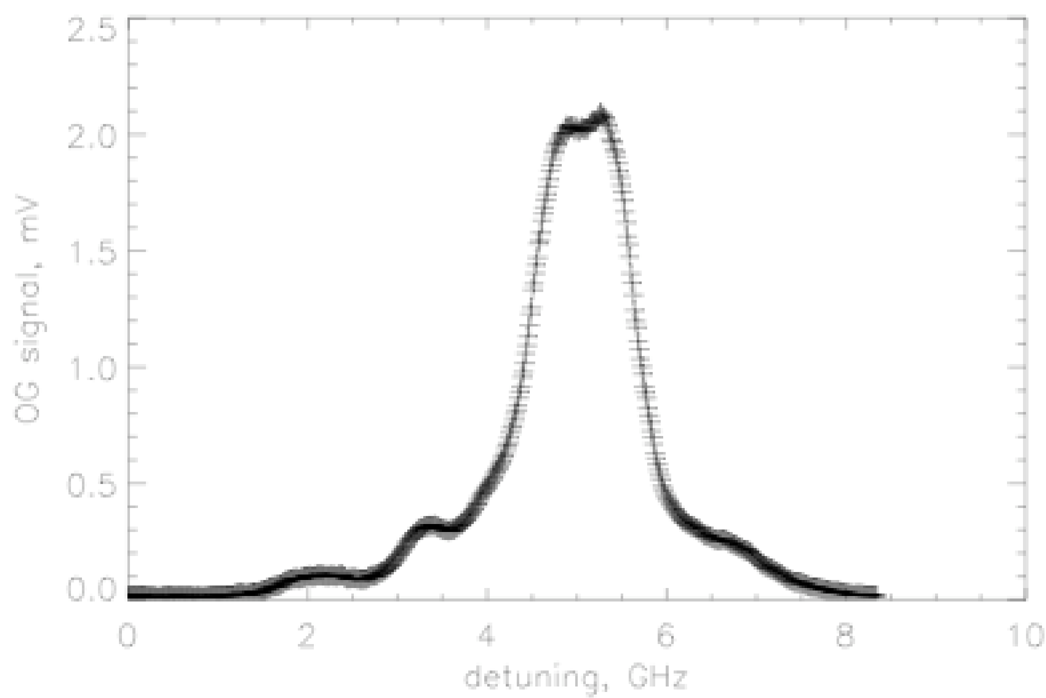
<u>Data set:</u>

- Ensemble average of 10 reference cell scans, same laser intensity
- Polarization rotated to **E** || **B**

<u>Model</u>:

- acceptable fit with no Zeeman terms, just hfs model at 600 K

Xe I OGS @ 834.911 nm
B = 152 gauss, σ-component



Data set:

- Ensemble average of 10 reference cell scans, same laser intensity
- Polarization rotated to **E** perp **B**

Model:

- none yet!

Overview

- Background
- Zeeman splitting
- Hyperfine structure
- Experimental setup
- Results
- Conclusions

Conclusions

Optogalvanic spectra:

•Xe I @ 834.911 nm has strong OGS; Xe II @ 834.953 nm not reported

• π-component at 152 gauss almost identical to 0 gauss

• σ-component at 152 gauss shows clear Zeeman splitting

Spectral modeling:

• good fit for Xe I hfs model @ 834.911 nm

• small saturation correction required

• σ-component Zeeman model: need one!

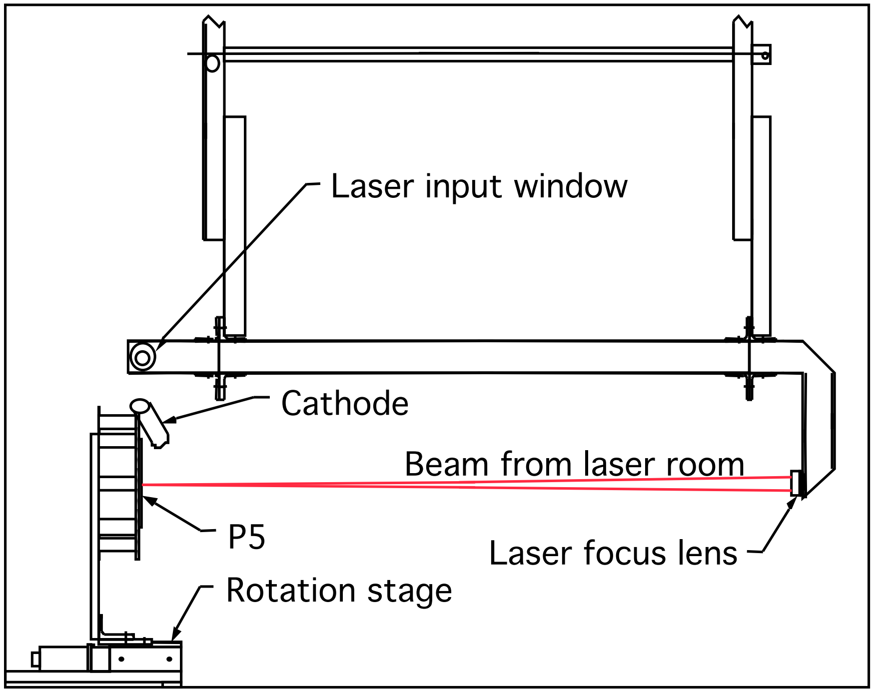
Future work

<u>Further validation:</u>

- improved Zeeman model w/ hfs
- application to Xe II at 834.953 nm

<u>Application to LIF:</u>

- Hall thruster plume & internal LIF
  - Zeeman correction to f(v)
  - polarization LIF for Hall current
- Ion engine internal LIF
  - Zeeman correction near cusps



Periscope & P5 (facing west)