

EXPERIMENT #AM-2: INTERFEROMETRIC SPECTROSCOPY

Experiment AM-2A: The Confocal-Spherical-Mirror Fabry-Perot Interferometer, and Laser Mode Structures

References: Preston and Dietz pp. 255-263.

Spectra Physics Laser Technical Bulletin #6--"Scanning Spherical-Mirror Interferometers for the Analysis of Laser Mode Structure" [a copy of this is placed in the laboratory on the third floor]

Hecht and Zajac, Optics -- a good reference for optical interference effects, including the Michelson interferometer, Fabry-Perots, and also multilayer dielectric films (which are used extensively in this experiment--for laser mirrors and F-P mirrors)

J.T. Verdeyen, Laser Electronics, second ed. (Prentice Hall, 1989) for laser mode structures, Fabry-Perot resonators, etc.

Overview--In this experiment we shall use two different Fabry-Perot (F-P) interferometers -- a confocal, spherical mirror system and a plane-parallel mirror system. Both of these F-Ps are research grade systems and you should treat them with great respect! For example, the mirrors in the plane-parallel system are 1" or 2" in diameter, multilayer dielectric coated on optical flats which have been polished to a flatness of at least $\lambda/200$! The set of mirrors alone originally cost about \$1000. You should never touch the mirrors or allow any hard object to touch them. In addition, you will be using some low power lasers. There is not much danger of eye damage at these intensities but nevertheless use good common sense not to look directly into the laser beam even after it reflects off several mirrors, etc.

The F-P allows you to do very high resolution spectroscopy. With the grating spectrometers you were able (presumably) to achieve resolutions of about 0.2 Å. A resolution of 0.2 Å at a wavelength of 5000 Å corresponds to a frequency width of $\Delta\nu = -c\Delta\lambda/\lambda^2 = 24 \times 10^9 \text{ Hz} = 24 \text{ GHz}$. Check this calculation...

The confocal mirror F-P has a "free spectral range" of 8 GHz and a resolution of about 8 GHz/200 or 0.04 GHz = 40 MHz, which is almost three orders of magnitude higher resolution than the grating spectrometer! With this type of instrument you will be able to examine carefully the "mode structure" of lasers to see that their output is not really monochromatic. In addition you will be able to examine the width (envelope of the laser modes) of spontaneous emission lines of the laser gases.

Note that the resolution of the Fabry-Perot is related to its "free spectral range" ($\Delta\nu_{\text{FSR}}$) mainly through the reflectivity of the mirrors. For the plane-parallel system, assuming the mirrors have the proper parallelism, the (reflectivity) finesse gives the ratio of the full width at half maximum of a perfectly monochromatic line:

$$F \equiv \Delta\nu_{\text{FSR}}/\Delta\nu_{\text{FWHM}} = \pi R^{1/2}/(1-R), \text{ where } R \text{ is the mirror reflectivity.}$$

Experiments:

1. Your studies will begin with the use of the confocal-mirror F-P (often called a "spectrum analyzer") since this is easily used as a stand-alone device. You should become intimately familiar with the terminology and definitions:

"free spectral range, finesse, longitudinal mode structure (of lasers), etalon"

2. Set up the spectrum analyzer. There are two BNC connections to the Fabry Perot itself. The side BNC is the driving voltage for the piezoelectric cylinder which holds one of the mirrors. It requires about a 100 Volt sawtooth which we obtain from the Tektronix Type 585 oscilloscope. See also Appendix XVI, "Quick Start: the Spectra Physics Model 470 Spectrum Analyzer."

WARNING--NEVER CONNECT THIS 100 VOLTS TO THE REMOVABLE DETECTOR ON THE BACK OF THE SPECTRUM ANALYZER!! YOU WILL DESTROY IT INSTANTLY!!

The BNC connector on the back of the spectrum analyzer is the output from a photodiode which detects the light transmitted through the F-P. This signal should be fed to the vertical axis input of the Type L Plugin Unit on the Tektronic Type 585 oscilloscope. Terminate with $\sim 10\text{-}20\text{ k}\Omega$, not the $1\text{M}\Omega$ scope impedance, to avoid too long an RC time constant (see Fig. 3 below for what the generally correct trace appearance). When the triangle waveform is properly driving the spectrum analyzer (at e.g., 2 or 5 ms/cm) you should be able to hear a "clicking" sound when you put your ear to the F-P. This is just the normal sound of the mirror movement.

WARNING -- THE F-P SHOULD NEVER BE SCANNED FASTER* THAN 2 ms/cm TO AVOID TEARING THE MIRROR FROM THE PIEZOSTACK

*So 5 ms/cm or *larger* values (since this is the inverse speed) are acceptable – generally you'll want 2 or 5 ms/cm.

3. Now proceed with the optical alignment. I recommend setting the two HeNe lasers parallel to each other and perpendicular to the optical rail and using a mirror to reflect the beams into the F-P. The angular control of the mirror gives the needed flexibility for centering into the F-P. The laser beam should be brought into the F-P so that it focuses at the confocal point of the internal mirrors. Note that the F-P has a built-in lens to do the focusing; you only need to bring the laser beams into the F-P at the correct angle and properly centered. You will be able to tell this from observing the reflected beam coming directly back into the laser. It will help to use the "auxiliary pinhole aperture and the circular polarizer to avoid feedback into the laser. Fine tuning of the alignment should be done while looking at the spectrum on the scope. Adjust the orientation of the F-P to get the sharpest peaks.

Included with the F-P is a small aperture and a polarizer/quarter wave plate combination which fit in on the front of the F-P. The polarizer- $\lambda/4$ combination prevents feedback into the laser. However, you should try rotating the polarizer system to check the polarization of the laser modes. Note that this is a nominally unpolarized laser since the mirrors are mounted on the plasma tube perpendicular to the tube axis. Unfortunately there is a small damage spot on the plastic polarizer so that using the aperture is disadvantageous! Avoid the damage spot by keeping the beam slightly off center. See the included notes for a

sketch of the system and further tips.

4. Begin with a study of the properties of the short Uniphase He-Ne laser. Align the F-P and observe the interferogram without use of the polarization analyzer. Wait a few minutes for the laser to stabilize a bit. Note that there may still be significant laser drift due to changes in the cavity length caused by thermal effects. As the laser drifts there will be times when one will see two closely spaced peaks in the spectrum due to two adjacent longitudinal (axial) cavity modes of the laser. At other times only one peak will be seen. Adjust the oscilloscope trace to show two peaks (or two sets of closely-spaced peaks) -- i.e. just over one free spectral range. (You will be asked to discuss this phenomenon later).
 - a) The FSR of the F-P is 8 GHz; what does this tell you about the plate spacing?
 - b) From the scope trace, estimate the spacing in GHz between the adjacent longitudinal modes.
 - c) Insert the rotatable polarization analyzer (watch out for the bad spot) and verify that the two longitudinal modes are polarized perpendicularly.
 - d) Assuming that the gain profile of the He-Ne laser is dominated by Doppler broadening, you should be able to estimate $\Delta\nu_{\text{FWHM}}$ from the fact that only two or three axial modes are observed. In fact, if you watch the mode frequencies drift while the laser warms up you can see the modes sweep through the Doppler profile of the 633nm Ne transition.
 - e) The competing source of broadening of the gain profile is likely to be collisional. From the information provided in Appendix VIII, estimate Γ , the FWHM of the Lorentzian collision profile. Assume that $P = 0.01$ atm. Since there is 5-10 times as much He in the tube as there is Ne, you may make a first approximation by considering only collisions of He on Ne (the radiating atom).

To get more precise information, use the Tektronix TDS 1002 oscilloscope to digitize the analog signal from the photodiode. That is reconnect the BNC from the 585 scope to the TDS 1002 scope; you can then use the "Acquire" feature to record data and save it to the integrated CompactFlash memory card. You can save the data as a .csv file for later analysis, and also get a decent reading right off the scope using the "Cursors" option to measure the FSR, adjacent mode spacing, and FWHM, for example.

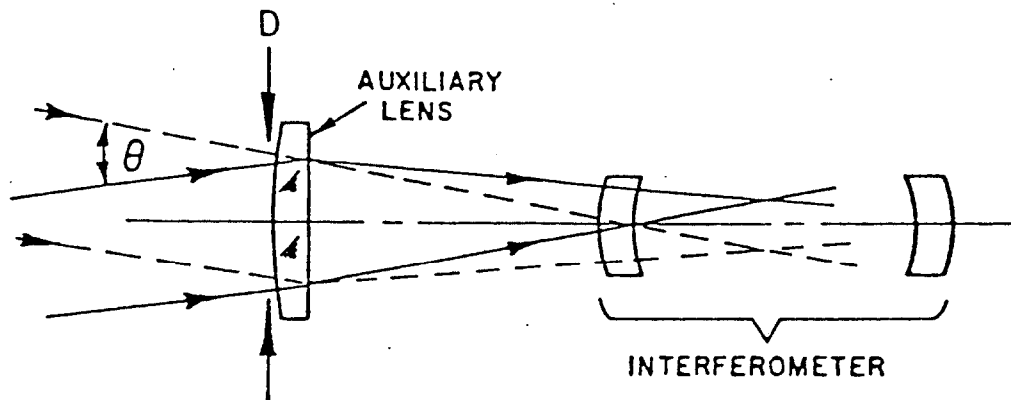
Use this method to do the following:

- f) Measure the adjacent mode spacing more accurately; use it to compute the laser cavity length-- is the value reasonable?
- g) Refine your measurement of $\Delta\nu_{\text{FWHM}}$ and Γ .
- h) Estimate the FWHM of one of the modes. The width is due to a combination of the inherent laser line width and the instrumental resolution of the F-P. Assuming that

your observations are solely due to this latter factor, compute the finesse from the FWHM; if this were entirely due to transmission losses, what would the F-P reflection coefficient R have to be? Is this value reasonable?

- i) From the value of the laser cavity length determined earlier, estimate p -- the number of wavelengths between successive reflected rays in the laser; use this and your observations to estimate the rate at which the cavity length is changing in time. Can you now explain why sometimes one and sometimes two modes are observed? For a discussion of applications which need a stabilized lasing frequency and techniques for accomplishing this, see any good book on lasers.
5. Replace the Uniphase HeNe laser with the longer Spectra-Physics He-Ne laser. Make similar measurements. What is/are the main difference(s) between the two sources?

N.B.: It is not necessary to draw fancy pictures of apparatus, oscilloscope traces, etc. Just make photocopies from the sketches you have in your notebook, where everything should be labeled anyway.



INCIDENT BEAM DIAMETER AND ANGULAR DIVERGENCE WITH AUXILIARY LENS.

Fig. AM2-1: Optical layout of the Spectra Physics model 470 spectrum analyzer

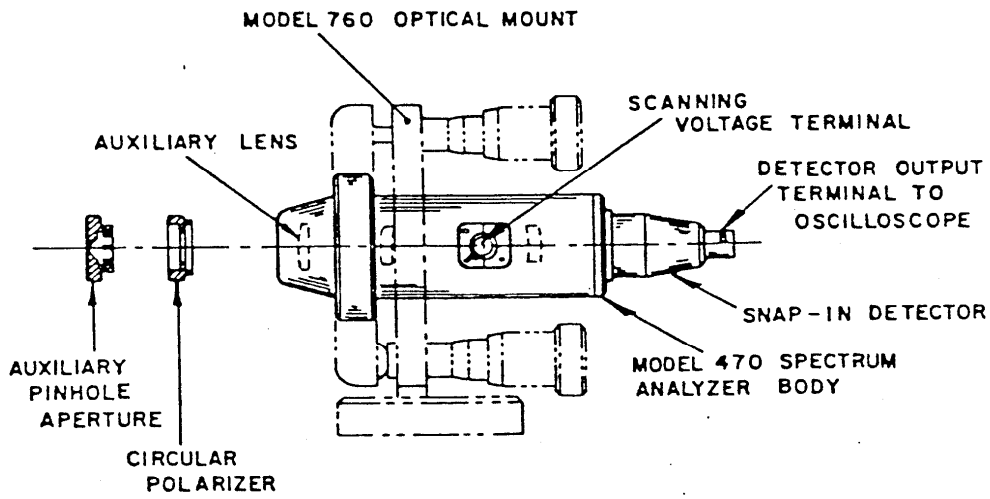
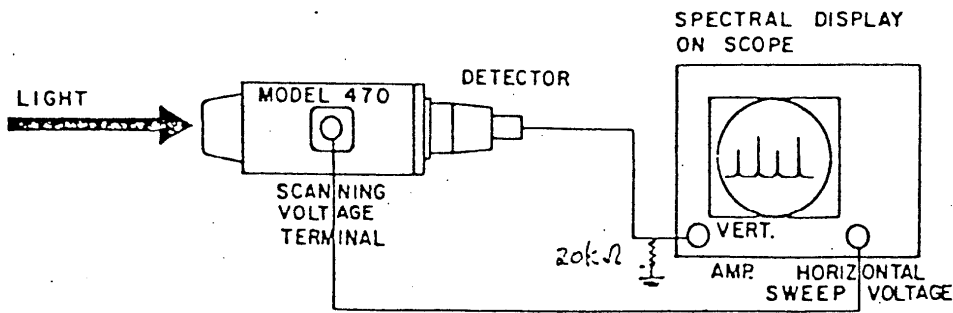


Fig. AM2-2: Mechanical mounting of the Model 470 optical spectrum analyzer



(a) WITH OSCILLOSCOPE DISPLAY.; SCOPE PROVIDING SCAN VOLTAGE.

Fig. AM2-3: Electrical connections for the Model 470 optical spectrum analyzer

EXPERIMENT AM-2B: THE PLANE-PARALLEL F-P AND THE ZEEMAN EFFECT

References: Preston and Dietz, Expt 14: pp 241-262.

Objectives: *The application of a magnetic field produces a change in the electron orbits in an atom and therefore it also affects the electronic energies. However, the Coulomb field and the internal magnetic field of the atom are still the predominant effects (at least until one reaches fields much larger than we can produce in this lab! The 1 meter grating spectrometer is barely able to resolve these electronic energy changes; however, the Fabry Perot is ideal for the high resolution needed for studies of this Zeeman effect. We seek to master the tandem technique of the F-P plus a small spectrometer and to understand the various aspects of the Zeeman Effect.*

INTRODUCTION:

A. The Zeeman Effect

Note that Preston and Dietz have a very good and extensive discussion of the Zeeman effect with some application to the case of multielectron atoms having Russell-Saunders (L-S) coupling. This discussion includes an introduction to the Fabry-Perot -- at least for fixed spacing F-Ps. This section has been referenced already in Expt. AM-2A above.

We have an electromagnet which can generate, for small pole separations, fields up to 7 kGauss (0.7 Tesla). We will use a tandem arrangement for the Zeeman effect, namely a plane-parallel Fabry-Perot in series with the Heath spectrometer. The plane-parallel F-P has high quality 1 inch and 2 inch diameter mirrors (not metalized, but rather dielectric coated which results in minimal absorption) so its light-gathering power is much larger than the confocal spherical-mirror F-P you used earlier.

The discussion of Preston and Dietz on the Zeeman effect is essentially self-contained and the theory needs really no additional remarks. Keep in mind throughout this experiment that Doppler broadening in the gas discharge will usually limit the detail you can observe.

Landé g-factor: The energy in a magnetic field of a particular atomic state goes like:

$$E_z = \mu_0 g_j m_j B$$

where μ_0 is the Bohr magneton $\mu_0 = eh/m_e$, m_j is the magnetic sublevel of the state with total angular momentum j , and g_j is the Landé g-factor:

$$g_j = 1 + \frac{j(j+1) + s(s+1) - l(l+1)}{2j(j+1)}$$

Therefore if you know precisely the spectroscopic state (s , l , and j), you can calculate g_j .

Before coming to this lab you should calculate the g_j for all the lines you plan to study. Note that to calculate how the wavelength or frequency of the **transition** will change with magnetic field strength B , you need to calculate how the energies of both upper and lower states of the transition change with magnetic field. Predict qualitatively, for each case, what the spectrum would look like for photons emitted perpendicular to the direction of \mathbf{B} , observed

- 1) through a linear polarizer oriented parallel to **B**, and
- 2) through a linear polarizer oriented perpendicular to **B**.

(You will need to recall the connection between the polarization properties and the selection rules. Preston and Dietz have a good discussion of this starting on p. 252.)

Example: Consider the He transition at 5016 Å. This arises from the states $(1s3p)^1P_1 \rightarrow (1s2s)^1S_0$. You should be able to verify that for the upper state $g_j = 1.0$ and for the lower state g_j is undefined since $j = 0$ and the state does not split in a magnetic field. Thus only the upper state splits into a triplet in the magnetic field and the light emission also should show three lines. When observed at right angles to **B**, two lines are linearly polarized perpendicular to **B** while the third is linearly polarized parallel to **B**.

Other examples are discussed in Preston and Dietz.

B. The plane-parallel mirror Fabry-Perot (with adjustable plate spacing):

In Experiment 2A you mastered the use of the confocal mirror spectrum analyzer; Experiment 2B utilizes the plane-parallel F-P. [Please consult Appendix XX for Quick Start instructions.] Again, this is a piezo-electrically scanned device -- i.e., one of the mirrors is mounted on three "stacks" of piezoelectric crystals which physically move the mirror. However, in this plane-parallel system the mirrors are exposed and mounted on three invar (a steel alloy with almost zero coefficient of expansion) rods. The plate spacing d can be adjusted from 0 to ~10 cm to change the free spectral range ($\Delta \nu_{FSR} = c/2d$) to suit the needs of the experiment. Whereas alignment of a spherical mirror F-P is trivial (once the mirror separation is adjusted to be exactly $d =$ radius of curvature and the orientation is adjusted mechanically to let the incoming beam cross the common focus), the plane-parallel F-P must be frequently "tweaked" to maintain the parallelism to within $\sim \lambda/200$. Hence the following procedure:

1. ALIGNMENT

- a. Determine the free spectral range by measuring the plate spacing. (BE VERY CAREFUL NOT TO TOUCH THE MIRRORS!! A CAREFUL ESTIMATE IS GOOD ENOUGH! (The F-P should be set (already) for a plate spacing of about 5 mm for this Zeeman experiment.)
- b. Arrange for an extended source by diverging the HeNe beam, before entering the F-P, with a short focal length lens (or by placing two layers of tissue paper in the laser beam). Now look through the plates directly with your eye. You should see a "bull's-eye" pattern of concentric rings. Move your eye from right to left and up and down and you will see the pattern expand or collapse. This is caused by the plates being closer together at one edge than at the other. You need to adjust the differential micrometer screws until the pattern does not change as your eye moves across in any direction. Note that one of the three screws can be treated as a pivot so that one of the other will give a horizontal adjustment and the last a vertical correction. Make an adjustment; check with an eye scan; make another adjustment; check with an eye scan; etc, etc.... When the alignment is perfect, you should be able to move your eye from side to side, or top to bottom, and see the center spot remain either a bright or dark spot, and the size of the first (and all) concentric rings, won't change with your eye's motion. Continue adjusting until you've perfected the

alignment.

c. Final adjustment is usually made as with the confocal system by adjusting to get the sharpest peaks using some sort of detector, but as yet you do not have one on this system. However, your eye is really quite sensitive to movement of fringes. You should be able to adjust parallelism to within $\lambda/50$ at least by "eyeball". Note that the central fringe is most sensitive to plate spacing.

d. Remove one layer of the scattering paper and use a mirror to direct the expanded HeNe beam through the F-P. You should now see the "bulls-eye" pattern on paper a foot or so behind the F-P. For highest resolution, the pattern should be observed in the "far field"-- either by using a very distant screen or (better) by using a long focal length lens and placing the screen or detector exactly at the focus of this lens -- see Fig. 9.47 from Hecht-Zajac. We have in the lab a lens of approximately 25 cm focal length. Use this to obtain a very sharp image of the ring pattern on the entrance aperture of the Heath spectrometer. The slits of the Heath should be set very wide (about 1 mm) since you only need to isolate each atomic transition from the next nearest one. A piece of white paper in front of the entrance slit improves the visibility of the fringes.

e. Now set the F-P scanning with the switch on the back of the power supply and observe the pattern change. Note that when you use the F-P for the Zeeman experiment you will be using an aperture to select only the central spot. The brightness of this central spot will be determined by the range of angles of the light which passes through the F-P plates. If you have a point source of light, you can use a collimating lens to collect the light so that most of the light on the other side of the F-P can be focussed into the central "bulls-eye" of the concentric fringes. If you want to scan the HeNe laser fringes with the PMT, remember to protect the PMT! You will probably need more than two layers of tissue paper as diffusers, and/or you need to attenuate by at least 1/100!

4. Finally, replace the HeNe laser with the spectral lamp supplied by your instructor placed between the pole pieces of the magnet. You should be able to observe fringes from the lamp easily with your eye by looking directly at the lamp through the F-P. (If possible, use an appropriate narrow band filter in front of your eye to isolate a single transition -- this step is best done with the focusing lens removed from the path.) You are now ready to do a quantitative measurement of linewidth using the pinhole and the PMT on the back end of the Heath spectrometer. Note that the spectrometer is just a convenient way to remove spectral lines other than the one you are interested in. Qualitative measurements, however, can be done with your eye just by looking through the F-P with your eye covered by a narrow band filter which passes the emission line of interest. If you cannot see fringes and splittings with your eye, don't bother to try the quantitative electronic measurement with the spectrometer, PMT, electrometers, and computers. Instead fix the optical problems!

Hints on set-up:

1. Optics: you should use a collecting lens to collimate approximately the light from the discharge lamp through the F-P. Then a focussing lens (of ~ 25 cm focal length is good) should be

used to image the far field F-P ring pattern on an aperture in front of the spectrometer. (I have assembled a tube with an 800 μm pinhole which fits partially into the entrance aperture to the spectrometer slit.)

2. You should think of the Heath spectrometer as a narrow band filter which isolates the atomic transition of interest. Therefore it will not need to be scanned automatically and the slits may be wide $\sim 1\text{-}2$ mm. *In fact, you should unplug the controller after you have set the Heath to the proper position. Sometimes an erratic discharge lamp will cause the controller to start the Heath scanning by itself (or so I have heard)!* The F-P can be used on a scan rate of ~ 10 s while acquiring data on the computer (every 20 ms or so).

3. Note that the plane-parallel F-P has a set of mirrors (1" diameter) with good reflectivity in the region from 480 to 580 nm. A copy of the transmission curve is attached. (Note: for these multilayer dielectric coated mirrors, $T = 1 - R$ to a very good approximation, since absorption is negligible.)

4. For the slender discharge tubes such as for Hg, He, Ne, etc we have found that the B-field will eventually quench the discharge unless a high discharge voltage is used. You should use the model 5000 "Spectrum Tube Power Supply" from Korea which supplies 5000V AC.

5. Pay particular attention to the polarization dependence of the Zeeman lines (See the discussion in Preston and Dietz on pp 252-254.) You may want to observe first without a polarizer in the beam and then observe the pattern for both σ and π configurations.

6. Table 14.1 in Preston and Dietz contains a list of some transitions and their identifications from which you should pick two if possible. Start with the He green line at $\lambda = 501.6$ nm since this is particularly simple. (See example above.) Then proceed to a more complex transition such as the Hg green line at $\lambda = 546.1$ nm.

7. Use the Lakeshore Gaussmeter to measure the magnetic field at the position of the lamp. The slender wand can be inserted into the space between the pole pieces. Note that the sensor is located in the tip and is about 1 cm long. The sensor operates on the principle of the Hall effect. You should review the basic idea of Lorentz forces and the Hall effect to understand how the probe operates.

8. To detect the signal, focus the ring pattern from the F-P onto the entrance slits of the Heath Monochromator. We're using the PMT (currently a 1P28 from Hamamatsu) in analog mode with the anode current converted to a voltage using a vintage Keithley digital multimeter. The high resolution spectrum is acquired by scanning the F-P synchronously with the channel advance in the computer multiscaler.

BE VERY CAREFUL NOT TO OVERDRIVE THE PMT! ALWAYS OBSERVE THE DIGITAL MULTIMETER FOR AN IMMEDIATE CLUE AS TO THE SIGNAL STRENGTH! REDUCE THE SIGNAL BY ADDING GREY NEUTRAL DENSITY FILTERS.

Now start the scan on the F-P controller (with the Heath fixed) and acquire data on the PC for the case of $B = 0$. *Remember that if you are not at a peak when you start, the signal may increase by a large factor!* The appropriate program is "**zeeman.exe**." See Appendix XX for details

on its operation. Parameters which work: integration time of 50 msec, step size of 0.1 Å (this is a dummy variable -- a hold over from using the Heath to scan spectra) and a range $\Delta\lambda$ of 50 Å. The combination of step size and range gives 500 points.

Compare your observations with the expected width based on

- 1) the reflectivity finesse of these mirrors in the F-P (see refl. curves in Fig. IV-1),
- 2) the Doppler width expected for a gas (plasma) temperature of 300 K and 1000 K.

9. Turn on the magnet cooling water and the magnet power supply. Turn up the magnet current as high as possible without the discharge becoming erratic. Measure the magnetic field with the Hall probe. Again take a F-P spectrum (unpolarized). Insert a polaroid polarizer and take two additional scans -- one with the polaroid parallel to the magnetic field (π polarization) and one with the polaroid perpendicular (σ polarization) to the B field.

Explain your observations. Do they agree with theory? Use your zero field profile, your calculated g-factors, and the measured value of B.

Repeat for a second atomic discharge lamp such as Hg.

On the write-up:

1. For whatever lines you study, work through the calculation of the Landé g-factors for upper and lower state and calculate the magnetic field dependence--i.e., the splitting to be expected. Compare with your observations. [You should be able to do most of these calculations before you leave the lab!!]

2. Do the line widths you observe in the absence of magnetic field agree with what you expect for Doppler broadening?

3. Does the polarization dependence behave as expected? Is the number of components correct for each polarization?

4. You may observe in the Hg spectra, especially for the zero-field case, that there appears at least one weak line near the main Hg line. This is a line shifted due to the isotope effect. As you can see from Appendix XI, mercury has several naturally occurring isotopes. This small peak is likely due to ^{198}Hg , ^{199}Hg , or ^{201}Hg . Read Appendix XI for an estimate of the isotope shifts in Hg.

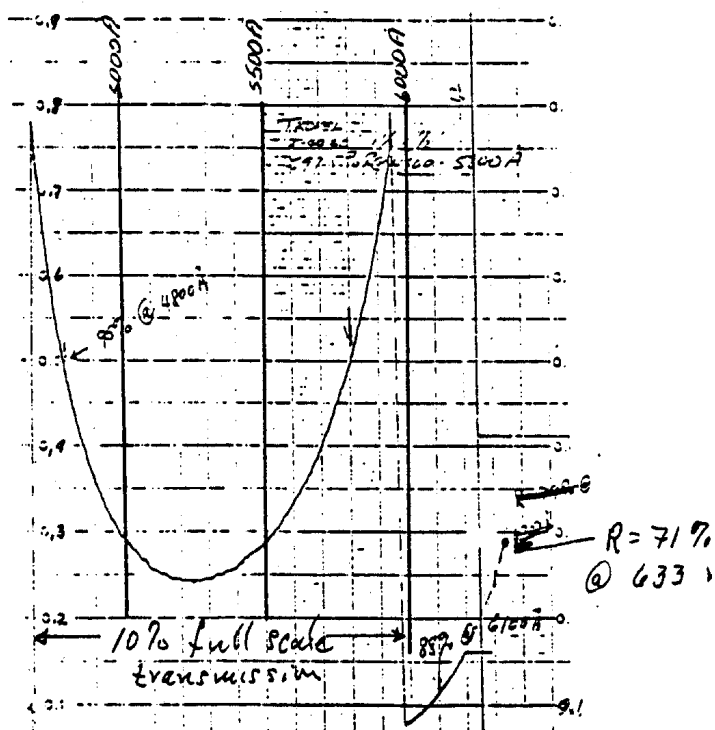


Fig. AM2-4. Transmission of a single mirror of the Fabry-Perot.

EXPERIMENT #AM-2 - CHECKLIST

Zeeman Effect

1. classical and quantum effects
2. selection rules
3. polarization of emitted radiation

Polarization of Electromagnetic Waves and Relation to Magnetic Substrates

1. linear
2. circular

The Fabry-Perot Interferometer

1. transmission formula and relationship to reflectivity of mirrors
2. free spectral range
3. finesse
4. resolution

Line Broadening

1. natural lifetime
2. collisional lifetime (pressure broadening)
3. doppler

Magnetic Field Measurements

1. the Hall effect
2. the Hall probe