Techniques for Using Emission Spectroscopy as a Plasma Diagnostic

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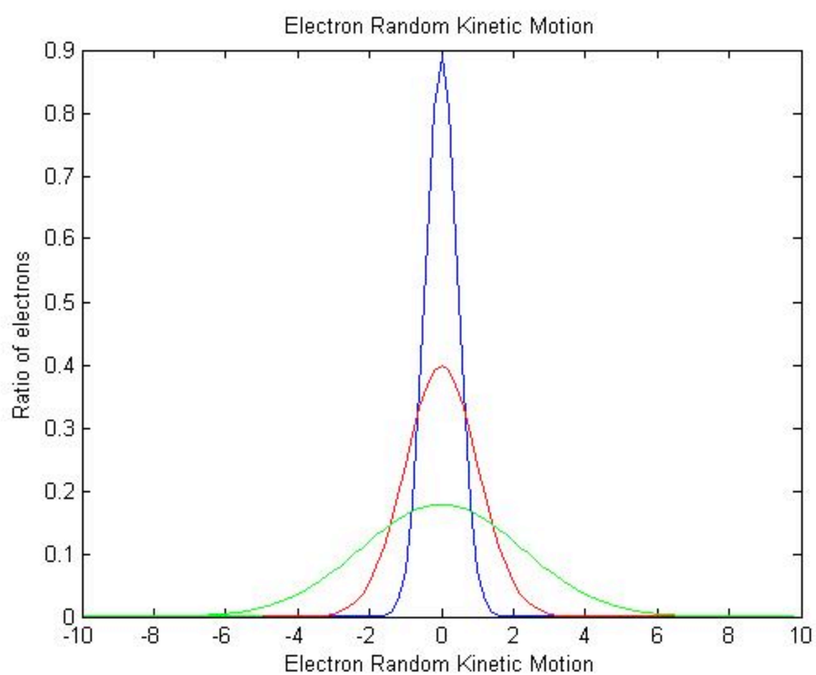
Motivation

- Emission spectra useful for determining electron temperature
  - Needed for efficiency model
    - How does the electron temperature change in different operating modes?

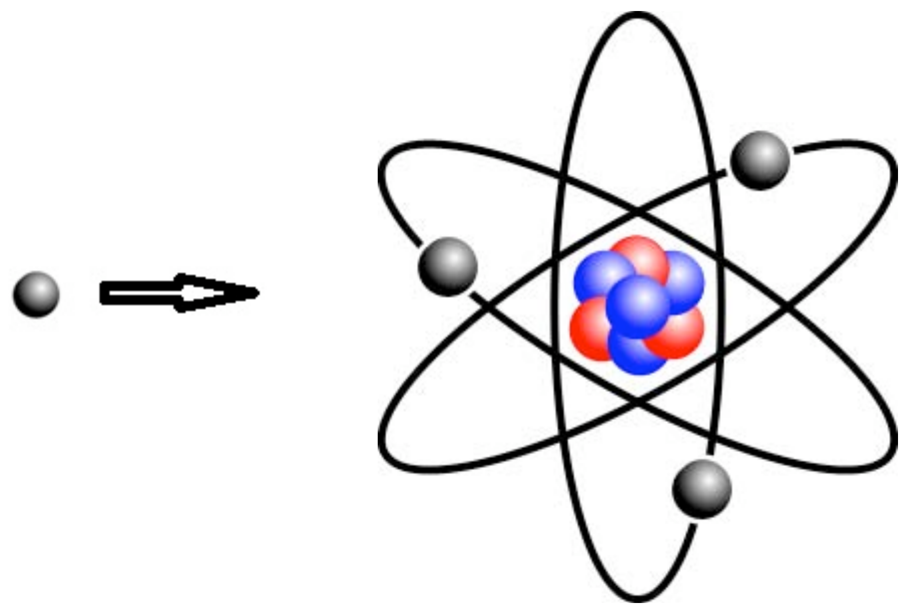
Theoretical Analysis

- Temperature of electrons in the plasma is the random motion of the electrons
  - Follows a regular distribution
    - Higher electron temperature means that there are more electrons farther from 0 random motion



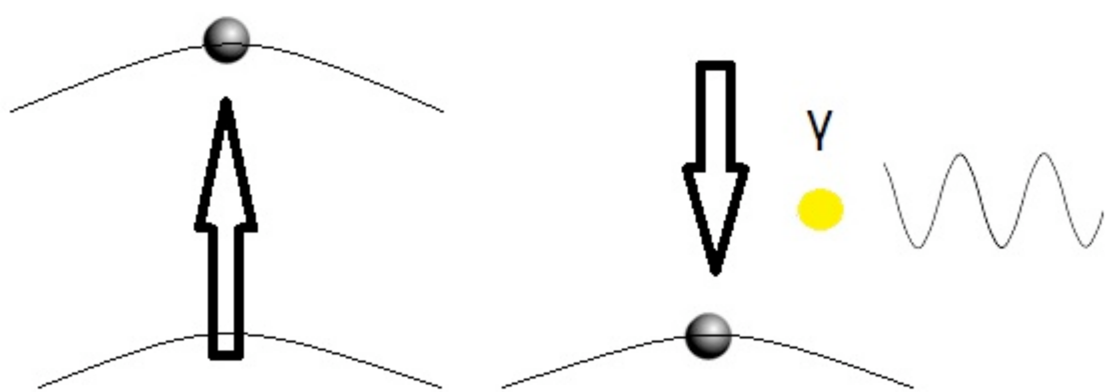
Theoretical Analysis

- Collisions of electrons with ions and with atoms in the plasma transfer energy among electrons



Theoretical Analysis

- Collisions can excite electrons to a higher energy state
  - When electrons return to a lower energy state, they release photons
    - Wavelength of emitted light depends on energy
    - Intensity depends on the amount of photons emitted



Theoretical Analysis

- Lithium has strong ionized lines at 17.8 nm, 19.9 nm, 548 nm, and 958 nm
  - With our spectrometer, can observe the intensity at the last two strong lines
  - If necessary, can use non-ionized lines as well
- Tungsten has a strong ionized line at 400.8 nm
  - Interested in Tungsten
    - Indication that the cathode and anode are being eroded by lithium flow

Theoretical Analysis - Continued

- Finding the electron temperature
  - Necessary assumptions
    - Plasma at Local Thermal Equilibrium (LTE)
      - Leads to Boltzmann distribution

$$\frac{n_m}{n} = \frac{g_m}{Z_{(T_e)}} \exp\left(-\frac{E_m}{kT_e} \right)$$

    - Optically thin plasma
      - Spontaneous emission dominates stimulated absorption

$$I_{mn} = l_{op} \frac{hc}{4\pi} \frac{1}{\lambda_{mn}} A_{mn} n_m$$

Theoretical Analysis - Continued

- Manipulating the above expression gives an equation for the intensity of one spectral line

$$I_{mn} = l_{op} C \frac{f_{nm}}{\lambda_{mn}^3} \frac{g_n}{Z_{(T_e)}} n \exp\left(-\frac{E_m}{kT_e} \right)$$

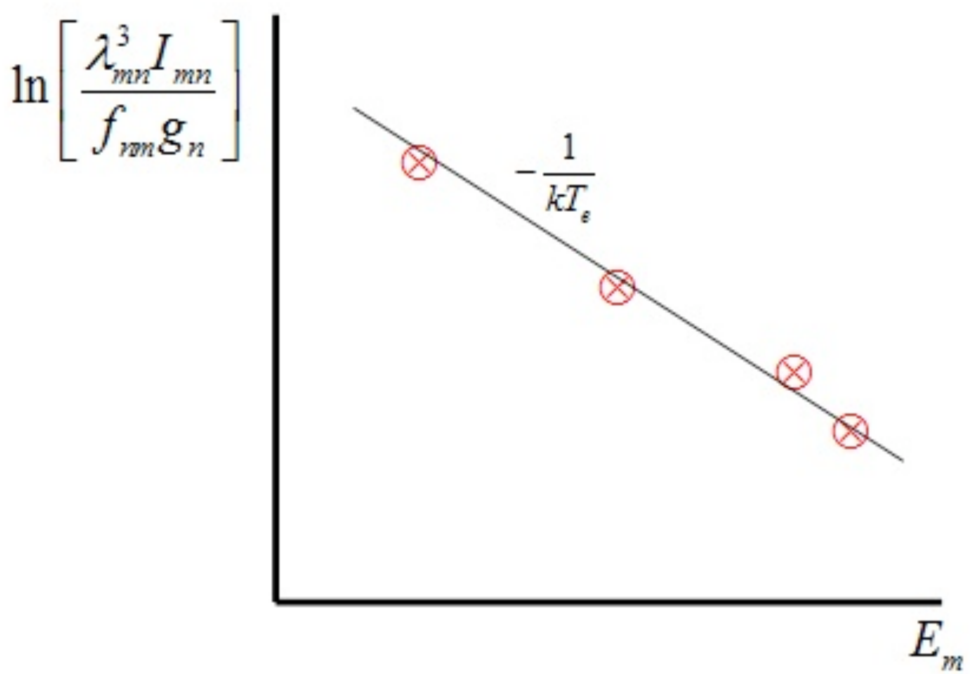
- Further manipulation leads to

$$\ln\left[\frac{\lambda_{mn}^3 I_{mn}}{f_{nm} g_n} \right] = -\frac{1}{kT_e} E_m - \ln\left[\frac{Z_{(T_e)}}{l_{op} C n} \right]$$

Output Slope Input y - intercept

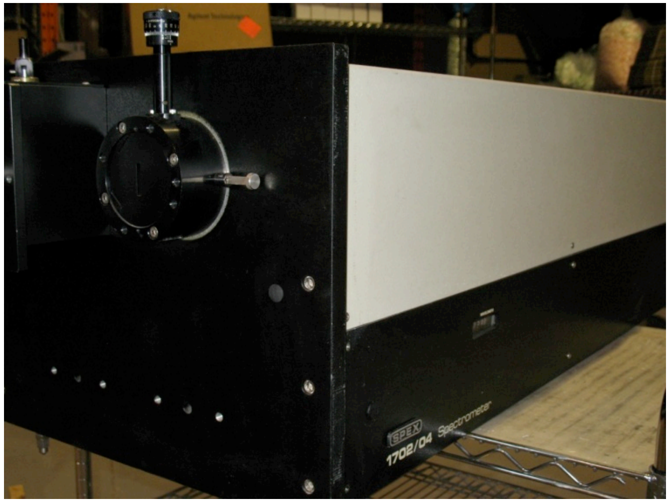
Theoretical Analysis - Continued

- Can plot experimental data, and from slope of line, find the electron temperature



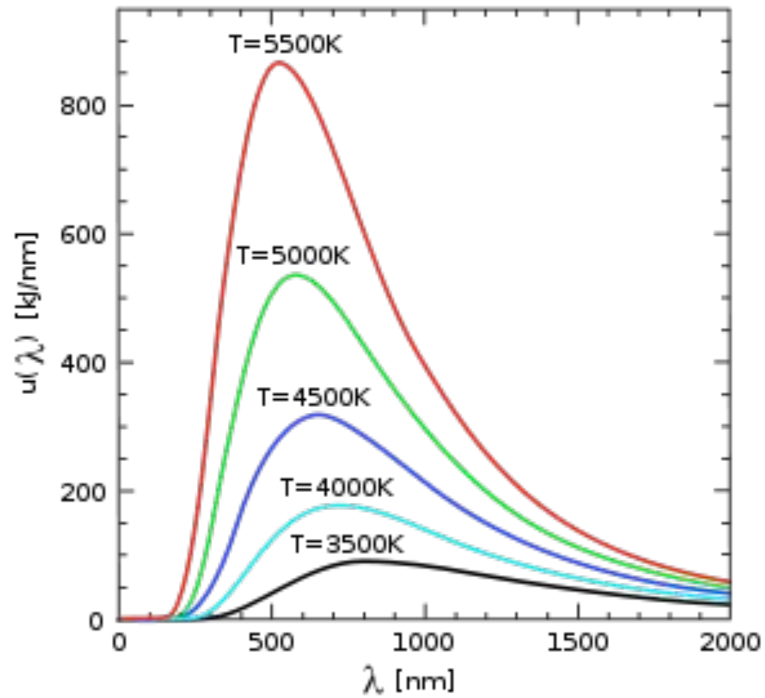
Experimental Setup – Common

- 1702/1704 Spex Spectrometer
  - ¾ meter focal length
  - Compudrive keyboard and controller



Experimental Setup - Common

- Calibration
  - Blackbody source
    - Electromagnetic radiation intensity dependant on temperature of source and wavelength
      - Theoretically known from Planck's Law

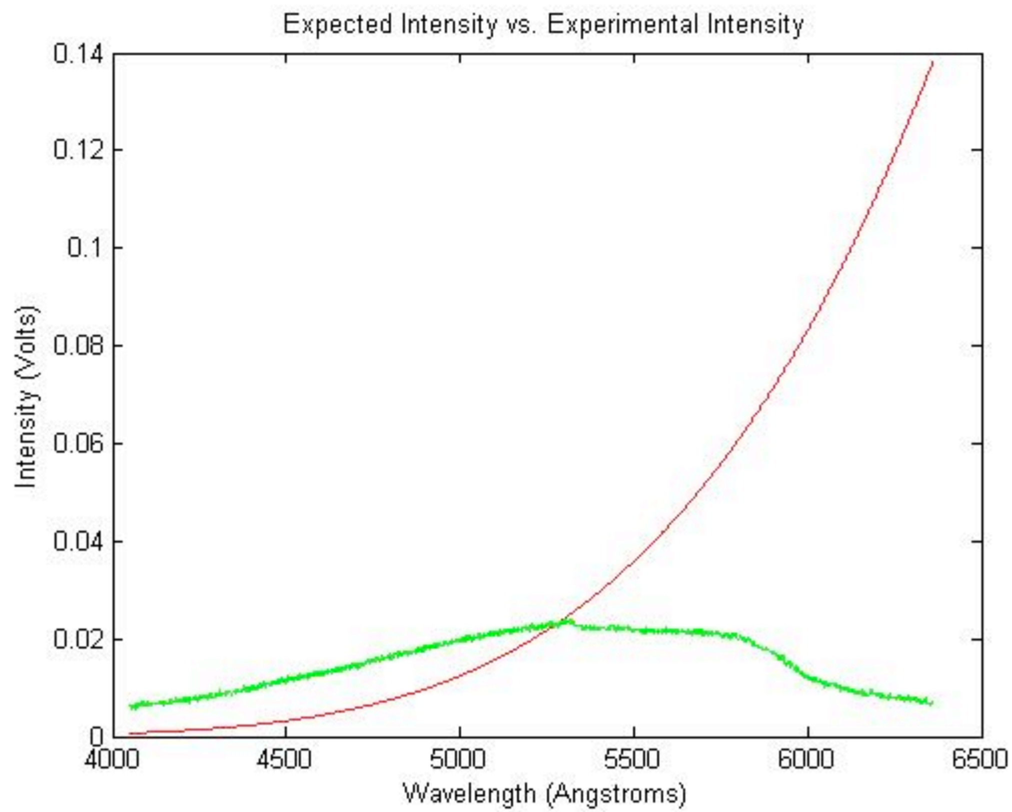


$$I'(\lambda, T) = \frac{2hc^2}{\lambda^5} \frac{1}{e^{\frac{hc}{\lambda kT}} - 1}.$$

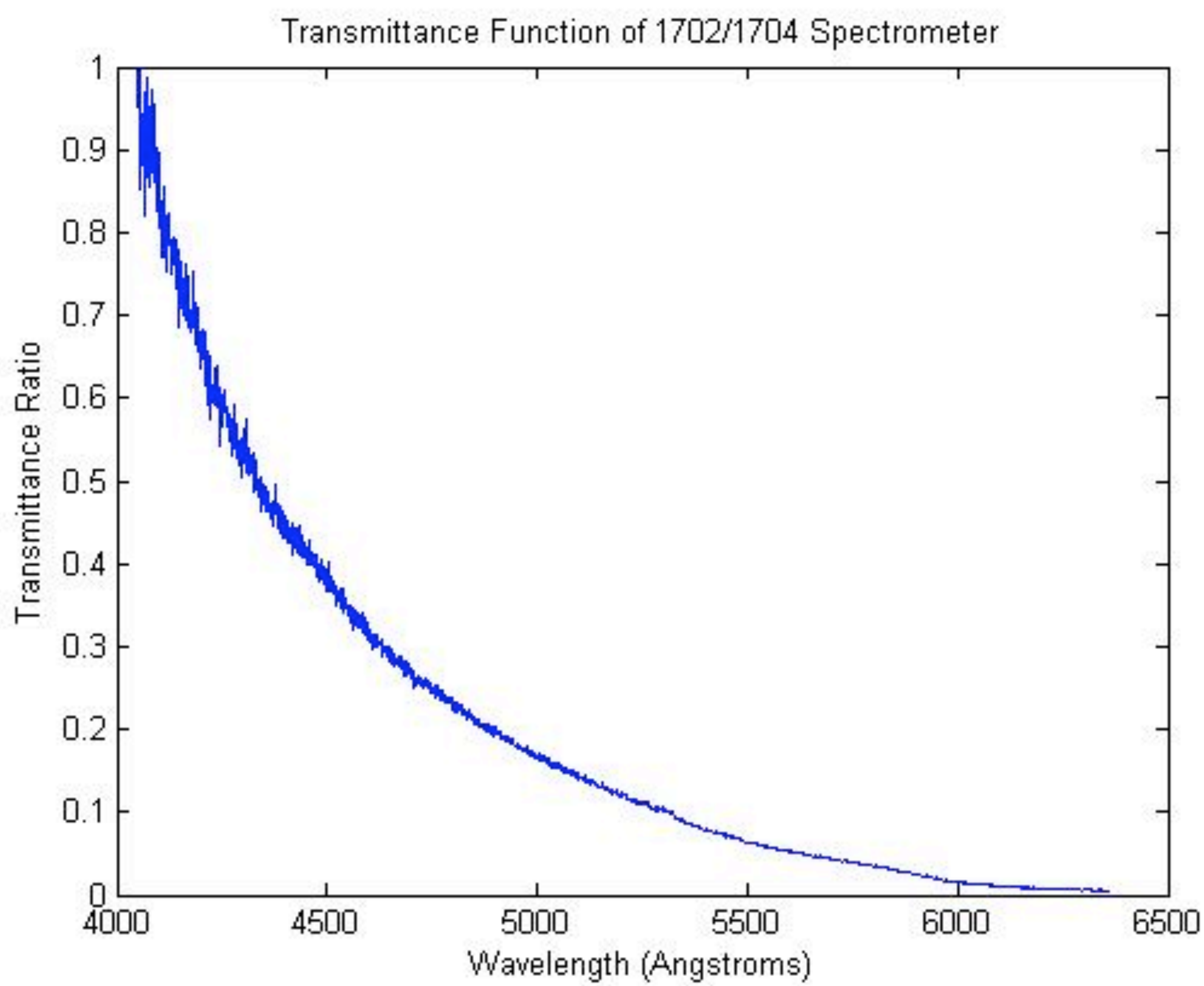
Experimental Setup - Common

- Calibration
  - Spectrometer attenuates radiation of certain wavelengths
    - Calibrate by comparing known theoretical value of blackbody source and experimental results of blackbody radiation
  - Code for analysis written

Spectrometer Calibration

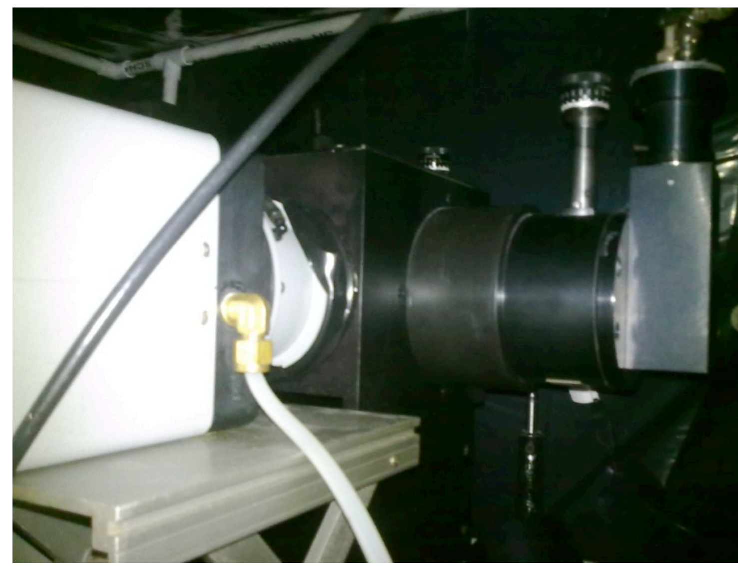


Spectrometer Calibration

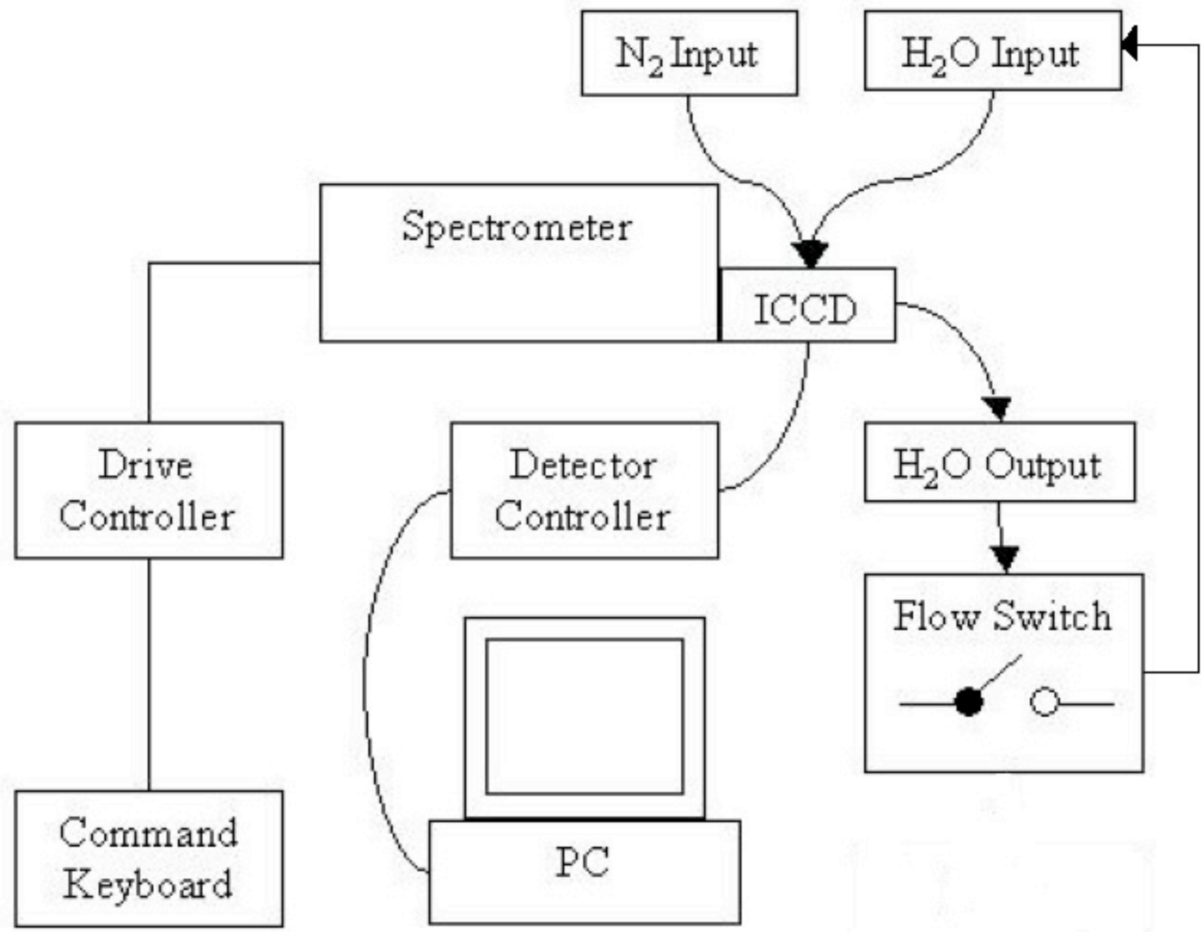


Experimental Setup – Common

- Ambient room light and other external light sources must be minimized.

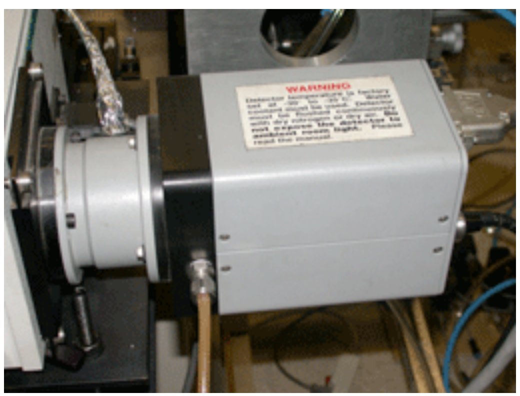


Experimental Set Up



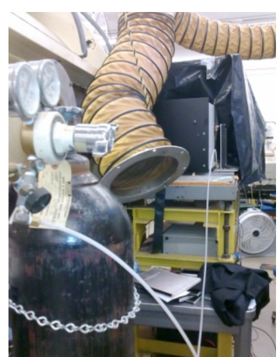
Experimental Setup - CCD

- CCD Camera, ST-138 Controller



Experimental Setup - CCD

- Temperature Control
  - Water Cooling
  - Operational range
    - Adjustable
- Nitrogen used to prevent condensation



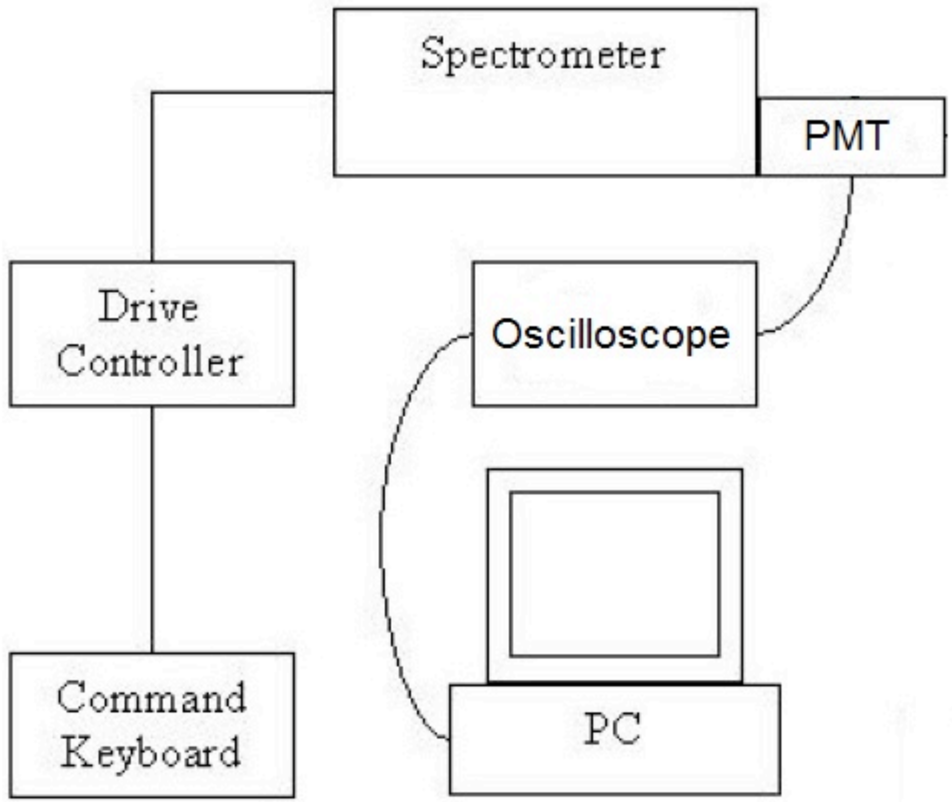
Experimental Setup - CCD

- CCD Calibration
  - Dark frames (thermal)
    - Accounts for accumulation of dark current (temperature noise)
  - Bias Frames
    - Zero-time exposure frames to account for the pre-charge and electronic noise
  - Flat Frames
    - Account for uneven illumination of CCD because of unwanted light sources, optical deformities, and dust

Experimental Setup - CCD

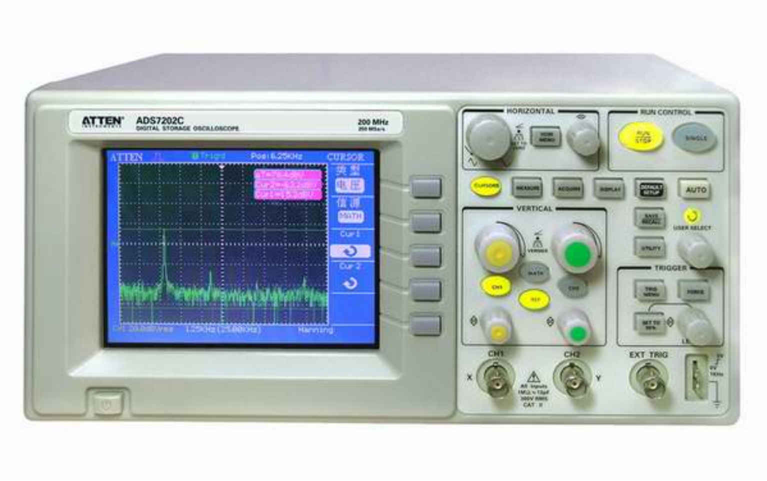
- Calibration procedure
  - Creation of master dark, master bias, and master flat frames, comprised of 10-20 frames
    - Dark frames should have long exposure time, 5-10 minutes each
    - Master frames should be made before every use of the CCD camera.
  - Code for transferring images to Matlab, and calibrating images using master frames written

Experimental Setup - PMT



Experimental Setup - PMT

- Photomultiplier tube, Oscilloscope



Procedure

- Same general procedure for both diagnostics
  - Turn on Compudrive keyboard and controller
  - Set current wavelength to wavelength stated on the side of the Spectrometer on the meter
  - Find strong lines for lithium and tungsten
  - Record intensity
  - Analyze intensity to find the electron temperature

CCD Procedure

- Turn on water cooling and nitrogen cleansing
- Turn on ST-138 Controller, and wait until it reaches thermal equilibrium
- Turn on WinSpec program and make sure it can connect to the controller
- Create calibration master frames, scanning from 300 nm to 1000 nm
- Take exposure frames of data
- Transfer files to Matlab using code, and analyze individual intensities for electron temperatures

PMT Procedure

- Turn on power for the PMT, and turn on oscilloscope
- Scan from 300 nm to 1000 nm, look for peaks in intensity
- Save from oscilloscope and transfer to computer
- Analyze strong lines to find electron temperature

Advantages and Disadvantages

- Using the PMT is a faster process
  - Easier to scan through a wide spectrum and save the data
- Harder to transfer data from the oscilloscope
- More detailed data received from CCD
  - Can differentiate between different regions of the plume
- Takes longer to scan and store intensities from entire spectrum

Conclusions

- 1702/1704 Spectrometer now a viable tool for use in diagnostics
- PMT and CCD diagnostics fully setup
  - Missing good power supply for PMT
  - Missing PCI control card for CCD controller
- Emission spectra from LiLFA experiment can now be analyzed
  - Find electron temperature
    - Theoretical analysis and code finalized

Further Exploration

- Use emission spectra to find ion temperature
  - Similar procedure, further theoretical analysis needed
- Use diagnostics during LiLFA firing

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