Department of Physics: MSc in Fusion Energy

ICF Data Laboratory

Week 3: "Back in the office" analysis

Aims

In week 3 we will aim to take a closer look at some of the data from weeks 1 and 2 of the lab with the aim of

1. Investigating the effectiveness and limitations of the "first look" analysis already completed.
2. Advancing the analysis and discussion of the data, with reference to external literature. This will entail you looking up additional material from the internet or other primary resources.

These are activities you would normally undertake after the experiment is complete, and it can take weeks, or months of work before data and analysis reaches a format suitable for publication. We don't expect you to complete work to this level in the lab, but would like to see

- A more detailed analysis of the self emission and spectroscopy data, with use of research papers.
- At least one critical attempt to improve on the basic analysis methods described in the weeks 1 and 2 scripts

By the end of this week you should therefore have written up the results of your analysis, a discussion of those results, and discussion of the techniques used to acquire them.

Sections 1 and 2 should be completed in their entirety. ***We do not expect you to address all of the questions in section*** 3. You should select a subset of topics which interest you (and write them down in your lab book as we need to know which points you are addressing). Plan your time to ensure you address both of the bullet points above, and meet the criteria set out in the marks scheme.

- Script Updated: October 2017

1 Self-Emission Further Analysis

In week 1 you analysed a data point from the WAX data set. The data from all members of the MSc/CDT is now on the VLE. Using this data, plot graphs estimating capsule diameter, density and pressure (assuming uniform density/pressure) against time. You will need information from the pre-reading script, and you may assume the ideal gas equation of state.

Once complete, you should try to fit a sigmoid trend line to each set of data, and include the influence of errors on the data (you will need to modify your python curve_fit command - look up how to do this).

Finally, look back at your spectroscopy data and determine what part of the capsule is glowing at each stage during compression. Based on this information, comment on what kinds of information you can reliably extract from the GXI, and whether any of your analyses are unjustified.

2 Spectroscopy Further Analysis

In this section you will use your spectroscopy data to infer two key plasma parameters: the electron density, n_e, and ion Temperature, T_i.

There are two approaches to extracting n_e. The first approach, see Griem [1, 2], is to compare your results with a suitable plasma atomic kinetics model, and the second approach is to compare spectra directly to atomic kinetics simulation. The first step is to determine which model is appropriate, ICF core plasmas are dense and it is worth checking whether LTE is valid and the optical depths are small.

The theory sections below give you some of the tools necessary to start to explore the consistency of your data under various assumptions. Take a moment to think about how you can apply them (not necessarily in the order presented), to interpret your results.

a) Local Thermal Equilibrium (LTE)

ICF core plasmas tend to dense and hot, thus it is possible that local thermal equilibrium (LTE) holds. For complete LTE, including the ground state, the approximation demands that collisional rates exceed radiative rates by at least an order of magnitude. Given this, LTE allows the use thermal equilibrium relations for level populations (Saha equation), particle distributions (Boltzmann) whilst the radiation field is much weaker than the blackbody temperature at the electron temperature, T_e. The condition for LTE in optically thin hydrogenic (one-electron) ions is

$$n_e \gtrsim 3.9 \times 10^{17} z^7 \sqrt{\frac{kT_e}{z^2 E}} \ \left[\mathrm{cm}^{-3}\right] \tag{1}$$

where E is the ionisation energy of Hydrogen, and Z the atomic number of Argon. Many plasmas do not approach complete LTE yet there still might be a partial LTE (PLTE) between the ground and upper state.

b) Opacity

In these experiments the argon concentration was chosen to ensure sufficient emission to deliver robust measurements whilst the diagnostic lines remain optically thin and effects of including a dopant on the implosion is minimised. You might want to check that this is true for the compressions attained.

The optical depth is given by

$$\tau \sim \frac{F_{He} b}{M_D} \left[\frac{\pi e^2}{mc} f \phi(E)\right] \rho R \tag{2}$$

where b is the dopant fraction by number, F_{He} is the fraction of He-like ions, M_D is mass of a deuterium atom and ρR is the areal density. The expression in square brackets is the absorption cross-section, this is 2.9×10^{-19} cm^2 and 2.3×10^{-19} cm^2 for the Ly-β and He-β respectively [5].

c) Spectral line profiles

Spectral lines are modified by Doppler, pressure broadening mechanisms and if present magnetic fields [2, 3]. In general there is no simple functional description for line shapes as they result from a combination of broadening mechanisms. You should estimate Doppler broadening to assess what impact this has on your measurements, assuming a Maxwellian distribution of non-relativistic ions.

d) Stark broadened line widths

Methods for inferring plasma densities from spectra include measurement of absolute line intensities and Stark broadened line widths. Stark broadened line widths give the density of ions in a specific ionisation state, by using an appropriate model plasma densities are inferred. Stark broadening results from the influence of micro-fields from surrounding ions (which principally affect the line centre) and electrons (which principally affect the line wings) on an emitting ion. As ions are heavy, fluctuations in these fields tend to be slow compared to transition rates, and are quasi-static. In hydrogenic ions this quasi-static field results in a linear Stark effect and gives a 2/3$^{\text{rds}}$ power dependence on density. Fields associated with electrons fluctuate rapidly leading to an impact approximation. This scales roughly weakly with electron density. The combination of ion and electron broadening suggests,

$$n_e = C(n_e, T)\Delta\lambda_S^{3/2} \tag{3}$$

where $\Delta\lambda_S^{3/2}$ is the full Stark width and $C(n_e, T)$ depends weakly on n_e. Values for $C(n_e, T)$ are usually extracted from line shape calculations. By using the information in Reference [4], which discusses the argon Ly-β and He-β line width as a function of n_e, you can estimate n_e for your measurements.

e) Ion temperatures from line ratios

It is possible to extract temperatures from Ar K-shell spectra by taking ratios of the integrated intensity in the He-β and Ly-β transitions. The integrated intensity is the area enclosed by the curve fit to each transition. The graph below shows the integrated intensity ratio is density dependent. The density must be first extracted from the line-widths (gives n_e) and then converted to ion density (n_i) by assuming an average ionisation.

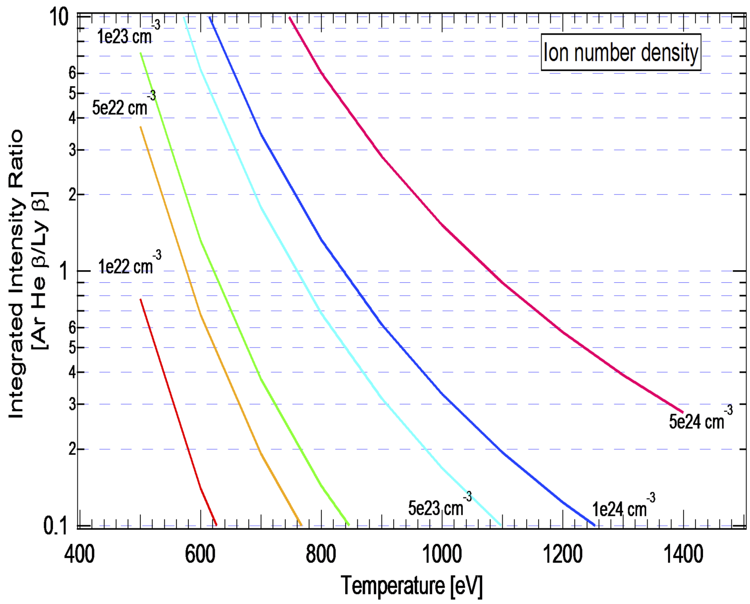

Figure 1: Relation between He-β and Ly-β intensity ratio, temperature and total ion density. This data was produced by the FLYCHK code.

3 Advancing your analysis

This section will pose a few questions which would be addressed either in the planning or analysis stages of the experiment. We expect to see a solid attempt at addressing ***at least one*** of these questions, or a similar investigation of your own choosing. This should include some quantitative analysis, and some discussion of the implications of your results.

1. Does fitting using a non constant baseline (i.e. background radiation) in the WAX data affect your FWHM measurements, and if so, to what extent?
2. Is the assumption of spherical implosion reasonable? Do asymmetries exist in the data, and if so, what are the likely causes?
3. A WAX analysis dataset using full width at 90% maximum (referred to as FWNM) is available on the VLE. Use this and the corresponding FHWM analysis to confirm or contradict your conclusions from section 1.
4. To what extent does continuum radiation from the hohlraum affect your spectroscopy data?
5. Is ideal gas a suitable equation of state for this data?
6. Hydrogen and Helium like lines typically have weak satellites due to physics such as double excitation or inter-combination of spin states (which are dipole forbidden)[7]. These satellites may not be visible as distinct peaks, but lead to a skewed peak which may not be fit accurately. Determine whether these satellites fall on the red or blue (low or high energy) side of the main peak, and use a masking technique to refit the data. Compare results with and without masking to assess its importance. An example of masking in python is provided on the VLE.

4 Writing Up

Your laboratory notebook should contain details of all the analysis undertaken. This includes recording estimates, stating what images were used, the position of the cross-sections, width of the cross-sections, the parameters used for cross-section reduction etc. You should include appropriate images of the steps taken. In short, your laboratory notebook must contain a record of all the important experimental details to enable a reproduction of analysis.

Your final results should include an estimate of the electron density. Be sure to quote errors and make an assessment of your error analysis. In addition, you should comment on the quality and how robust your fits are. This is your opportunity to discuss parts of your analysis that requires further investigation (if you had the time).

References

[1] H. R. Griem, Plasma Spectroscopy, McGraw-Hill (1964)

[2] H. R. Griem, Principles of Plasma Spectroscopy, CUP (1997)

[3] I. H. Hutchinson, Principles of Plasma Diagnostics, 2nd ed., CUP (2002)

[4] B. A. Hammel et al., K- and L-shell x-ray spectroscopy of indirectly driven implosions, Rev. Sci. Instrum. 63, 5017 (1992)

[5] B. A. Hammel, C. J. Keane, M. D. Cable, D. R. Kania, J. D. Kilkenny, R. W. Lee, and R. Pasha, X-ray spectroscopic measurements of high densities and temperatures from indirectly driven inertial confinement fusion capsules, Phys. Rev. Lett. 70, 1263 (1993)

[6] H.-K. Chung, M.H. Chen, W.L. Morgan, Yu. Ralchenko, and R.W. Lee, FLYCHK: Generalized population kinetics and spectral model for rapid spectroscopic analysis for all elements,, High Energy Density Physics v.1, p.3 (2005)

[7] U. Feldman et al. Satellite Line Spectra from Laser-Produced Plasmas, The Astrophysical Journal, 192, 213–220 (1974).