Plasma temperature measurements using black-body radiation from spectral lines emitted by a capillary discharge

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Abstract

Optically thick spectral line emssion from plasmas is often difficult to use for the diagnosis of plasma parameters. We demonstrate a technique for temperature measurement using the peak intensity of optically thick lines as their intensities approach a black-body distribution. Recording optical emission in the wavelength range 300 - 1000 nm from a plasma formed by radio-frequency heating and electrical discharges in a 0.2 m long capillary plasma, we show that the high wavelength Rayleigh-Jeans form of the black-body emission can be fitted to the most intense spectral lines to give a measurement of plasma temperatures in the 1 - 1.5 eV range. The temperature measurement technique should have wider applicability in diagnosing plasmas with optically thick spectral lines.

Keywords: opacity, Rayleigh-Jeans, black-body, plasma

1. Introduction

Capillary discharge plasmas have several potential and realised applications. The plasmas produced in a capillary discharge are very uniform along the capillary length, enabling, for example, basic studies of atomic kinetics and radiation transfer without the complications of non-uniformity as occurs in, for example, many laser-produced plasmas [1]. Capillary discharge plasmas have been proposed as appropriate plasmas for the propagation and guiding of injected laser pulses with the aim of generating wake-fields suitable for the acceleration of electrons with acceleration gradients > 100 GeV m^{-1} [2], [3], [4]. Plasma escaping along the axis of the capillary has been proposed for medical applications, including sterilization [5]. With tailored high current discharges, plasmas with peak electron temperatures of 350 eV have been produced in capillary discharge plasmas [6].

Lasing at wavelength 46.9 nm in the extreme ultra-violet has been achieved using capillary discharge plasmas [7], [8], with several applications of the laser output now being developed (for example, see [9], [10]). Amplified spontaneous emission occurs along typically 0.2 m of argon plasma ionised and excited by sequences of radio-frequency heating and electrical discharges. The physics of a capillary discharge plasma is similar to more conventional Z-pinch designs, but with a solid capillary acting as a physical guide for the electrical current [11]. Electron temperatures in the pinch plasma can approach 80 eV for times of several nanoseconds and enable the production of population inversions in Ne-like argon leading to lasing at 46.9 nm [7], [8]. However, the spatially and temporally averaged emission from the argon plasma in the visible/near infra-red spectral range is dominated by a much longer lived, much lower temperature plasma not associated with the plasma pinching effect.

In this paper, we measure the electron temperatures associated with the unpinched plasma for a capillary discharge. The visible/near infra-red emission from the capillary arises from plasma formed without significant pinching, while the pinched plasma temperature (up to 80 eV) produces emission from ions such as Ne-like argon in the extreme ultra-violet and soft x-ray spectral regions.

2. Background: emission from uniform optically thick plasmas

For the capillary discharge used for the present study, plasma is formed by a radio-frequency discharge in argon gas of pressure 0.3 Torr contained in the bore of a ceramic capillary of inner diameter 3 mm. Singly ionised argon (Ar II) is created with emission of neutral and singly ionised argon occuring for durations up to a millisecond. For a much shorter duration of several nanosec-

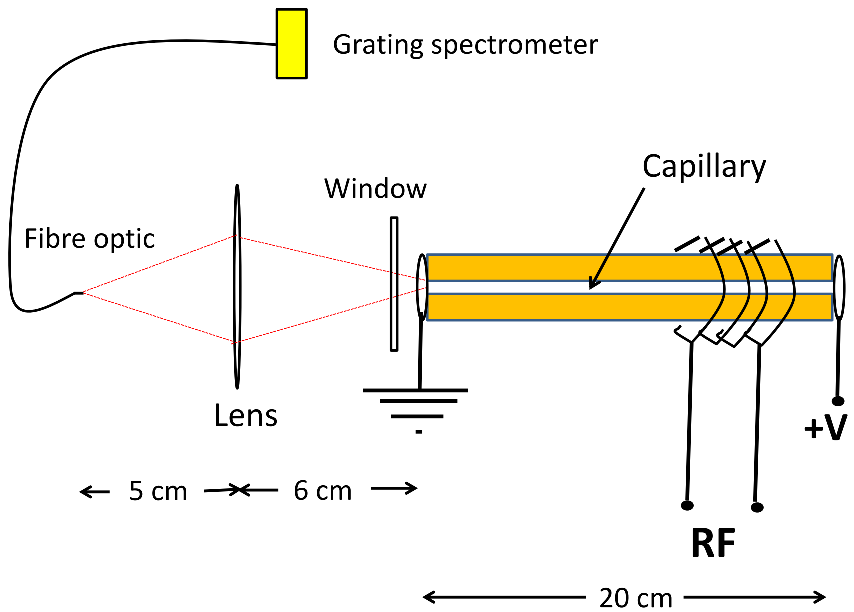

Figure 1: A schematic of the argon filled (0.3 Torr) capillary with radio-frequency (RF) heating coil and electrodes for high voltage direct current discharge down the 3 mm diameter bore of the capillary. Optical spectra are recorded by focusing the plasma emission onto an optical fibre connected to a 300 lines/mm grating spectrometer with CCD detection. Vacuum and electrical pulse forming components are not shown. The glass window separates the argon gas and atmospheric air.

onds, a current flow of up to 40 kAmpgs creates a plasma pinch with electron densities $\approx 10^{19}$ cm^{-3} and diameter $\approx 100\,\mu$m. The capillary discharge plasma is approximately uniform along the capillary axis for a distance of ≈ 0.2 m (see figure 1).

For a plasma with a constant source function S_0 along a line of sight, the intensity I of radiation escaping the plasma is given by

$$I = S_0(1 - \exp(-\tau)) \tag{1}$$

where τ is the optical depth along the line of sight. Kirchhoff's law states that the source function S_0 is equal to the Planck black-body radiation intensity I_p

with the radiation temperature equal to the electron temperature [12]. Consequently following equation 1, the maximum value of the intensity I at any wavelength approaches the black-body intensity I_p as the optical depth τ increases. On a line of sight along the axis of a capillary discharge plasma, the optical depth at the line centre of optical spectral line emission is high, whereas the optical depth of continuum emission between the spectral lines is close to optically thin. The most optically thick spectral components of plasma intensity at spectral line centres will approach the black-body intensity.

Utilising the intensity of the strongest spectral lines, we show that the plasma electron temperature in a capillary discharge plasma can be deduced using the high wavelength Rayleigh-Jeans limit [12] of black-body emission fitted to the most intense spectral line intensities. The diagnostic technique is applicable to determining the electrons temperatures in capillary discharge plasmas at times where significant pinching of the plasma column is not occurring and should be generally useful for measurements of temperatures < 10 eV in uniform plasmas with large optical depth.

3. Experiment

The capillary discharge used was manufactured by 'XUV lasers' (see [13]) and is partly described by Heinbuch et al [14]. Emission along the axis of the 0.2 m long, diameter 3 mm capillary discharge plasma passed through a glass window and was imaged onto a fibre optic cable leading to a Maya Ocean Optics spectrometer with dispersion using a 300 lines/mm diffraction grating and a measured spectral resolution of ≈ 1 nm (see figure 1 for a schematic of the experimental set-up). Spectra arising from the argon fill gas and some impurities were recorded and interpreted for the different stages of plasma heating.

The plasma is heated by radio-frequency (RF) waves for a total duration of 1 ms, a small current pre-ionisation pulse over a much shorter time of $\approx 15\mu$s after $2 - 4\mu$s of RF heating and a large current induced by a driving pulse of 30 - 40 kV stepped up by a Blumlein arrangement to ≈ 0.3 MeV potential

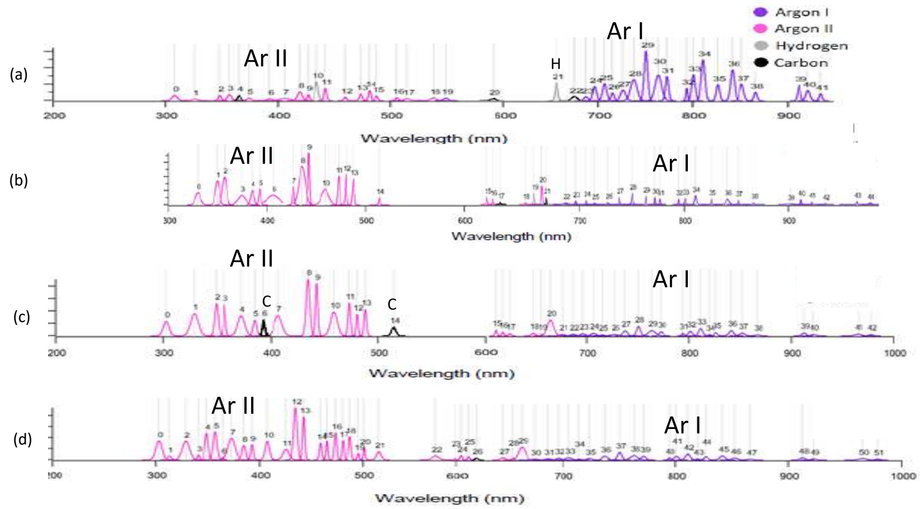

Figure 2: Spectral intensities emitted from the capillary discharge plasma: (a) radio-frequency (RF) heating only, (b) RF heating and a low current pre-ionisation pulse, (c) RF heating, low current pre-ionisation and a high current pulse with driving potential (before Blumlein compression) of 30 kV, (d) as for (c), but with driving potential of 40 kV. The spectral lines are identified as labelled as arising from mainly Ar I or Ar II, with some hydrogen and carbon lines identified.

creating a plasma current of 20 - 40 kAmps for $\approx 1\mu$s at a time 9μs after the start of the pre-ionisation pulse. The high voltage components of the electrical pulse forming network are enclosed in flowing and cooled MIDEL 1215 organic dielectric fluid. Spectra were recorded with RF heating only, RF heating plus low current pre-ionisation, and RF heating plus low current pre-ionisation plus high current electrical pulse (figure 2).

Recorded sample spectra are integrated over times (6 ms) longer than the times when plasma exists. The overall temporal plasma emission in the visible can be expected to be largely determined by the RF heating time which is constant for a duration of 1 ms, though significantly increased average ionisation is observed when there is also an electrical discharge through the plasmas (see figure 2). To aid the identification of lines and the measurement of the intensities of the lines, the continuum emission is removed from the plots shown in figure

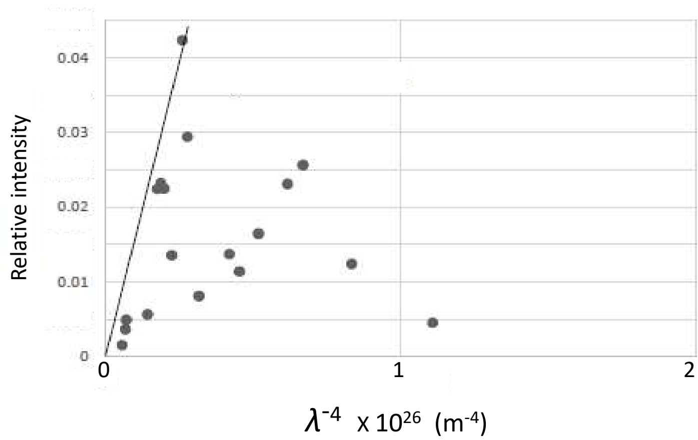

Figure 3: Spectral intensities for different spectral lines emitted from the capillary discharge plasma with a driving potential of 30 kV plotted as a function of the spectral line wavelength λ raised to the power -4. . The black-body emission for a temperature of 1.45 eV is shown as a straight line.

2. Lines are identified in figure 2 as arising from Ar I, Ar II, carbon or hydrogen using the wavelengths listed in the NIST database of spectral lines [15]. A numbering system and small vertical marker for each spectral line is included in figure 2 as a label. Under the same discharge conditions, the recorded spectral intensities were found to be reproducible for each stage of plasma heating to within 5 percent.

In the high wavelength limit, the Rayleigh-Jeans expression for black-body intensity I_p for a radiation temperature T at wavelength λ is given by

$$I_p = \frac{2ck_BT}{\lambda^4}. \tag{2}$$

Optical pyrometers use the Rayleigh-Jeans expression [12] to measure temperatures of hot solid objects radiating as black-bodies. However, in plasmas, it is unusual for radiation to interact sufficiently for the radiation to be black-body at all frequencies.

Intense spectral lines are the most likely components of the radiation spectrum to interact with matter, and consequently the maximum intensity for a spectral line approaches the black-body intensity with the radiation temperature equal to the electron temperature. Plotting the intensity I (in relative units per unit wavelength) of different spectral lines emitted from the capillary plasma as a function of $1/\lambda^4$ shows that the maximum intensity for any value of $1/\lambda^4$ is defined by a line corresponding to the maximum allowed value associated with the black-body intensity (see figure 3). The error in assigning the line of maximum intensity in figure 3 produces an error in the deduced relative temperature as shown by the horizontal error bars in figure 4. The error in a relative temperature measurement is not large because there is always an accurate point at zero intensity and zero value of λ^{-4} in plots of the form of figure 3.

An absolute temperature measurement requires an absolute calibration of the intensity I as a function of wavelength λ and was undertaken with the Ocean Optics LS-1-CAL tungsten halogen light source assuming emission occurs for the duration (1 ms) of the RF plasma heating. We used the following procedure to check the calibration of the absolute intensities I. Electron temperatures can be measured from the ratio of the intensity of optically thin spectral lines if the excited state populations are in equilibrium with each other. A Boltzmann ratio of populations causes the intensity I of spectral lines of photon energy E_p with the same final quantum state to vary in temperature T with proportionality such that

$$I \propto E_p g_p A_p \exp\left(-\frac{E_p}{k_B T}\right) \tag{3}$$

where g_p is the degeneracy of the upper quantum state and A_p is the spectral line transition probability [12]. Temperatures deduced in detailed analysis using equation 3 with less intense spectral lines likely to be close to optically thin were found to be in agreement with temperatures measured using equation 2. However, temperatures measured using equation 3 were found to have a greater relative error compared to the calibrated Rayleigh-Jeans method (equation 2) because (i) $E_p < k_B T$ and hence the intensity variation (equation 3) becomes insensitive to temperature for some spectral lines, (ii) there is a remaining uncertainty that the spectral lines are optically thin and (iii) the intensities of less intense lines are measured with greater relative error compared to the measured intensities of intense spectral lines.

For different discharges with increasing heating, we find that the measured temperatures increase (see figure 4). The spectral resolution of the spectrometer (≈ 1 nm) was verified as sufficient to resolve the emitted widths of Ar I and Ar II spectral lines. The more intense spectral lines are opacity broadened which ensures that measuring the peak intensity of a spectral line (as for figure 3) records the black-body intensity.

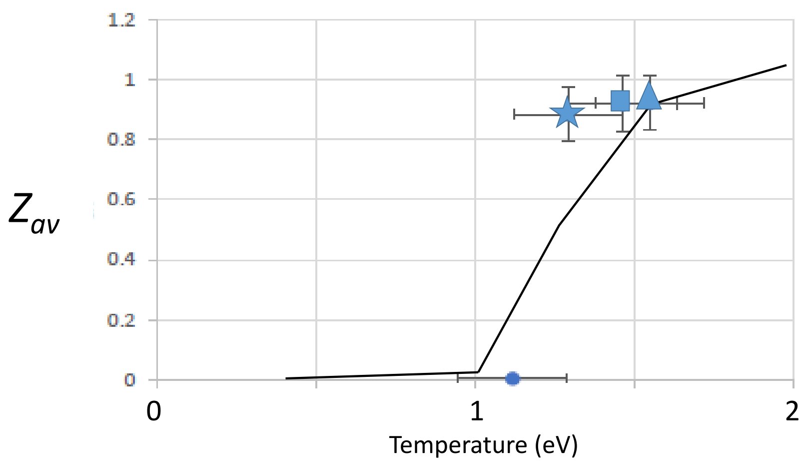

Figure 4: The average ionisation Z_{av} determined from the relative abundance of Ar II and Ar I spectral lines as a function of the temperature measured as described for figure 3. Different heating mechanisms are indicated by different data points (circle: radiofrequency (RF) alone, star: RF and pre-ionisation current, square: RF, pre-ionisation and 30 kV supplied to electrical pulse, triangle: as for the square with 40 kV). The solid curve shows the ionisation calculated with the FLYCHK collisional-radiative code.

An estimate of the average ionisation in the capillary discharge plasma was made by summing up the measured intensities of all recorded singly ionised argon (Ar II) emission and the intensities of all neutral argon emission (Ar I). In models of plasma emission [12], these intensities are proportional to the abundances (n^+ and n) of respectively singly ionised and neutral argon with a similar proportionality constant. We can write for the average ionisation Z_{av} that

$$Z_{av} = \frac{n^+}{n^+ + n}. \tag{4}$$

The values of average ionisation Z_{av} estimated in this way as a function of the temperature measured as outlined for figure 3 are shown in figure 4. For comparison, the average ionisation Z_{av} as calculated by the collisional-radiative code FLYCHK [16] at densities where coronal equilibrium is applicable is superimposed on figure 4. There is good agreement between the measured parameters and the collisional-radiative prediction (figure 4).

The presence of carbon and hydrogen spectral lines (figure 2) suggests that there is contamination of the organic dielectric oil in some of the argon plasma discharges. Such contamination can change the resistivity of the plasma and reduce the effectiveness of the plasma pinch. It is clearly useful to monitor the optical emission from the plasma to check for impurities and also to measure the average temperatures of the plasma.

4. Conclusions

We have demonstrated a technique for temperature measurement using the peak intensity of optically thick lines as their intensities approach a black-body distribution. Recording optical emission in the wavelength range 300 - 1000 nm from a plasma formed by RF heating and electrical discharges in a 0.2 m long capillary plasma, we have shown that the high wavelength Rayleigh-Jeans form of the black-body emission can be fitted to the most intense spectral lines to give a measurement of plasma temperatures in the 1 - 1.5 eV range. Optically thick spectral line emssion from plasmas is often difficult to use for the diagnosis of plasma parameters and the proposed procedure does not require any detailed atomic physics knowledge of, for example, transition probabilities. The temperature measurement technique should have wider applicability in diagnosing plasmas with optically thick spectral lines.

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