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RESEARCH PAPERS

A small hollow cathode arc as an optical line source

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Abstract. A small, versatile and bright emission source for line radiation has been developed. The source requires only a small rotary vacuum pump and a power supply of 1 kW; it employs a permanent magnet.

The source emits neutral lines and singly ionised lines of several elements including noble gases (e.g. Ar I, II lines), superimposed on a weak free-bound and free-free continuum spectrum. The lines are only Doppler broadened, so the source can be used to determine Stark shifts in other high density plasmas.

Results and characteristics of the source for hydrogen, neon and argon are given.

1. Introduction

In atomic and plasma physics there is often need of optical line sources which emit light of the ion spectrum. The lines have to be sufficiently narrow and with an unshifted wavelength. This requires operation at low pressures to avoid pressure broadening and shifting of the line.

In the following such an ionic line source based on the principle of a hollow cathode arc in a magnetic field is described. With this hollow cathode arc (HCA) source ionic emission of even noble gases has been achieved.

Ionic line emission of several other elements, typically metals, is usually obtained from hollow cathode discharge (HCD) lamps (Sawyer 1945, Willet 1974, Freeman and King 1977). These are also used for spectrochemical analysis and absorption spectroscopy.

Though the name of this type of line source is similar, as both types employ a hollow cathode, the HCA-lamp is quite different from the HCD-lamp both in operating principle and spectral emission possibilities. The hollow cathode discharge is basically a glow discharge usually operated at higher pressure (typically a few Torr) and without magnetic field. As the voltage drop near the cold cathode is large, sputtering causes also the element of the cathode material to be present. Commonly the medium of the HCD-lamp consists of a carrier gas with a high ionisation potential, usually a noble gas (He, Ne, Ar), and other materials, which may be metals.

Because of charge exchange of the noble gas ion and a metal neutral, excited ions are produced of the secondary element. Excitation of the carrier gas ion is hardly present. Consequently, ionic line emission is produced of the secondary element only and hardly of the noble gas. For the present HCA-lamp the situation is different. Ion excitation of the noble gas itself is produced, so the freedom of material is much larger and includes e.g. noble gases such as argon and helium. Also the neutral density is at least a factor of ten lower, which is favourable in view of the avoidance of inhomogeneous broadening and shift effects.

Existing low pressure spectral line sources of noble gases emit usually only neutral lines, as these plasmas are relatively poorly ionised. To obtain strong ion-line emission the ionisation degree has to be large. To avoid significant Stark effects, the electron and thus the ion density must be at maximum 10^{20} m^{-3} . The neutral density must be lower than 10^{22} m^{-3} . So the operating pressure is limited to values below 1 Torr ($\approx 133 \text{ Pa}$) at the prevailing neutral temperature of 1000 K. At these densities collisional confinement is ineffective, so a magnetic field is required to reach sufficiently high electron densities and temperatures. In regard of the strong radiation losses a relatively large specific power input is needed, which is most easily supplied by dissipation of a plasma current.

A plasma heated hollow cathode arc in a magnetic field is an ideal source. It can be operated at relatively low pressure and has the desired electron density and temperature. In the design we have aimed at simplicity, immediate availability and minimised power requirements.

2. The design

The source is a simplified version of various sources in use at the Eindhoven University of Technology (van der Sijde 1972a, b, c, Pots *et al* 1981, Theuws *et al* 1977, 1982, Theuws 1981). These plasmas are used for the investigation of plasma transport and radiation, and as a particle source. The source consists of a plasma heated hollow cathode, a ring anode, end anode, a magnet and a very simple vacuum system. Through the hollow cathode the gas is supplied (see figure 1).

A ring anode is used for three reasons. First, in earlier studies (van der Sijde 1972a, b, c) it has been shown that in this configuration the plasma is hotter and more dense. Second, it is possible to operate with a current-free end anode, which serves as a sampling plate if the source is used as a particle source. Also the electrode configuration can be inserted from one side, which is advantageous from the viewpoint of construction and serviceability. A third point of merit is that the ring anode can be used to screen the bright thermal emission from the cathode surface. The cathode material is tantalum or tungsten. The diameter of the cathode and thus of the plasma channel has to

Figure 1. The design of the source.

be small enough to allow for a sufficient current density. For plasma currents up to 1 A, cathode diameters of 1 mm internal and 2 mm external are ideal. The anodes are made of copper. The cathode, ring anode and end anode are water cooled. Cathode lifetimes of 10 h for hydrogen and 50 h for argon are obtained, using a tantalum cathode and a current of 0.2 A.

A permanent magnet of a magnetron with annular pole shoes and 16 bar magnets gives a magnetic field of 0.06 T. The vacuum system consists only of a two-stage rotary roughing pump. This simple type of mechanical pump is adequate to give a stable working pressure of 0.1–10 Torr. This system is time saving since it allows for operation after a few minutes of pumping.

The power requirements are 0.2 A at 1 kV to start and 0.2–1 A at 400 V to operate the discharge. The arc is stabilised by a loading resistor.

3. Measurements of line intensities

The optical line source is suitable for several elements; in this paper measurements for the elements H, Ar and Ne are presented. The line intensities are measured absolutely with an optical system of three lenses, a diaphragm and a monochromator. The solid angle of observation is 1.3×10^{-3} sr.

The argon and neon lines are predominantly Doppler broadened with a half width of 3–5 pm ($\lambda_0 = 400$ nm) for the estimated ion temperature of 0.5 eV (Pots *et al* 1981). The corresponding Doppler broadening of H lines is 21 pm while the Stark broadening of H for electron temperatures between 1 and 4 eV is 9 pm for $n_e = 10^{19} \text{ m}^{-3}$ and 42 pm for $n_e = 10^{20} \text{ m}^{-3}$ (Griem 1974). To measure the total intensity of a spectral line the apparatus width of the monochromator (Jarrell Ash, model no 25-101) is chosen to be 82 pm for argon and neon and 160 pm for hydrogen.

The observed side-on area of the plasma is $0.1 \times 1 \text{ mm}^2$ for argon and neon and $0.2 \times 1 \text{ mm}^2$ for hydrogen. This results in an étendue of the system of $1.5 \times 10^{-3} \text{ sr mm}^2 \text{ nm}^{-1}$.

The system is calibrated with a tungsten ribbon lamp, so that the total line-integrated intensity is absolutely measured. The local emissivity ϵ_λ ($\text{J m}^{-3} \text{ s}^{-1} \text{ sr}^{-1}$) of the spectral line on the axis of the arc is obtained by Abel-inversion of the lateral profile of the line-integrated intensity, which has a half width of 2–4 mm.

With the well known expression for the emissivity,

$$\epsilon_\lambda = h\nu A(m, q) \frac{n_m}{4\pi} \quad (1)$$

where $A(m, q)$ is the transition probability of the line from level m to level q , one can deduce the population density n_m of the upper level of the transition used. The measured densities can be compared with those of collisional radiative models. From these models also information on the electron density and temperature can be obtained.

It is known that for $n_e > 10^{19} \text{ m}^{-3}$ and $T_e = 2\text{--}3 \text{ eV}$ the excited Ar I and Ar II levels are in the so-called excitation saturation phase (ESP) (van der Mullen *et al* 1980, van der Sijde *et al* 1983). This phase is an intermediate stage between corona and partial local thermal equilibrium (PLTE). In the ESP the electron excitation is balanced by electron de-excitation rather than by radiative decay as in the corona phase.

It has been shown that for ionising plasmas in the ESP the excited state density n_m can easily be related to the ground state density n_0 by:

$$\frac{n_m}{g_m} = \frac{n_0}{g_0} r_m^{(1)} \exp\left(\frac{E_m}{kT_e}\right) \quad (2)$$

where g_m and g_0 are the statistical weights of level m and the ground level; E_m is the excitation energy of excited state m .

The collisional radiative coefficient $r_m^{(1)}$ scales as

$$r_m^{(1)} \propto p_m^{-6} \quad (3)$$

where p_m is the effective main quantum number defined by

$$p_m^2 = \frac{Z^2 Ry}{E_{\text{ion}} - E_m} \quad (4)$$

Z is the charge of the continuum ($Z = 1$ for the neutral system and $Z = 2$ for the ion system), Ry is the Rydberg energy and E_{ion} is the ionisation energy of the ground state.

The population densities for excited states of Ar, Ne and H are shown in figure 2. For the Ar 4p level ($p_m = 2.37$) the $r_m^{(1)}$

Figure 2. The population densities per statistical weight of excited states against the excitation energy.

Specimen	I_{arc} (mA)	p (Torr)
● Ar I	200	0.2
× Ar II	200	0.2
○ Ne I	200	0.2
+ Ne II	200	0.2
△ H	200	5.0
□ H	500	0.7

coefficient is 5×10^{-5} (Abu-Zeid 1982); with a value of $n_0/g_0 = 2 \times 10^{21} \text{ m}^{-3}$ derived from the ideal gas law, and with the pressure $p = 0.2$ Torr and neutral particle temperature $T_0 = 1000$ K, the electron temperature, T_e , for Ar according to equation (2) is 2.8 eV. Since T_e depends logarithmically on n_0 this value for T_e is insensitive to the actual value of n_0 .

For hydrogen the electron temperature is 1.1 eV if $T_0 \approx T_i \approx 5000$ K, $p = 5$ Torr, $r_m^{(1)} = 7 \times 10^{-5}$ for $p_m = 4$ (Drawin and Emard 1976), and 2.7 eV if $T_0 \approx T_i \approx 5000$ K, $p = 0.7$ Torr, $r_m^{(1)} = 3.5 \times 10^{-5}$ for $p_m = 4$. The electron density for argon is $5 \times 10^{19} \text{ m}^{-3}$ using equation (2) with $T_e = 2.8$ eV and $r_m^{(1)} = 3 \times 10^{-4}$ for $p_m = 2.62$ of the Ar II system (Abu-Zeid 1982).

So if the pressure is low ($p < 1$ Torr) the electron temperature is about 2–3 eV, and since the calculated value of n_e is larger than the quoted minimum electron density, the plasma is indeed in ESP as presumed. A plot of $(n_m/g_m) \exp(E_m/kT)$ against p_m shown in figure 3 indicates also that $r_m^{(1)} \propto p_m^{-6}$ as predicted for the ESP.

Figure 3. The population densities per statistical weight of excited states against the effective quantum number p_m .

Δ : Ar I	$T_e = 2.8$ eV
$\square$: Ne I	$T_e = 2.8$ eV
$\circ$: H	$T_e = 1.1$ eV
$\bullet$: H	$T_e = 2.7$ eV

Figure 4 shows that the densities of the excited ion states increase with the arc current, but decrease with the pressure. To get strong ion lines, low pressure and high arc current are preferable. At present stable operation is possible above a minimum pressure of 0.1 Torr for Ar and Ne and 0.5 Torr for H. The arc current is limited by the heat dissipation of the arc and the evaporation rate of the cathode. Because the emissivity of a spectral line depends on the distance between the observed area and the cathode tip, this length is kept constant to 7 mm during our measurements.

The densities of the excited states of the noble gas ions in the HCA-source are appreciable and, especially at low pressures and high currents, strong ion line emission is obtained. This is the major merit of the HCA-lamp over the HCD-lamp, which has practically no noble gas or carrier gas ion line emission. Of course HCD-lamps do show ion line emission of the secondary (metal) element. Since the excitation energies of these secondary ions are much lower than for noble gas ions, the population densities are higher (Van Veldhuizen 1983, Van Veldhuizen and De Hoog 1984). Therefore, at least comparable line emissions would be expected in the HCA-source if these elements were

Figure 4. The population densities per statistical weight of the Ar II 4p excited state derived from the Ar II 488 nm spectral line against the arc current (I_{arc}) for different gas pressures.

introduced. Nevertheless the primary use of the HCA-source would be the emission of ion lines with large excitation energies.

4. Conclusions

The small hollow cathode arc is a simple and adequate source for line radiation. It gives sufficient emissivity of ionic lines for most applications, e.g. for the Ar 488.0 nm ion line, the line-continuum ratio is about 500, when the apparatus width of the monochromator is 82 pm. Only spectral lines with high lying upper levels are too weak to be observed.

For most gases the lines are narrow and unshifted because the ion temperature is at maximum 0.5 eV for these types of arcs, and the electron density lies between 10^{19} and 10^{20} m^{-3} . Only for hydrogen and helium are the Stark and Doppler effects measurable.

For argon, neon and hydrogen the plasma is proven to be in the excitation saturation phase, with an electron temperature of about 2–3 eV if the pressure of the gas is lower than 1 Torr. The same behaviour is expected for other atomic species. So knowing the population density of one of the levels in ESP a first value of the population densities of the other levels in ESP can be obtained from the p_m^{-6} scaling.

The present HCA ion line source can be operated with any element which can be introduced in gaseous form, including noble gases. In this it differs from the HCD-lamp in which ion lines are produced of comparable strength of a secondary element, usually the metal of the cathode material, which can be high-melting-point metals, and not of the primary element of the carrier gas.

The two types of line source, HCA and HCD, should be seen as complementary and not as competing. The HCA source has the additional advantage of possible operation at lower pressure.

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