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A high-current hollow cathode as a source of intense line radiation in the VUV

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Abstract. The VUV line emission of a high-current DC hollow cathode was investigated in the wavelength region 10 nm to 100 nm. Spectra of quadruply ionised atoms could be observed. The radiance in the Al IV lines at 13 nm and 16 nm and in the He II Lyman-series was determined by a comparison with the spectral concentration of radiant intensity of the synchrotron radiation emitted by the electron storage ring BESSY. We found the radiance of the lines to be reproducible within ±25%.

1. Introduction

In the last decade the use of VUV radiation has steadily been growing. Today radiometric techniques are well established with calibrated transfer standard sources for wavelength $\geqslant$115 nm, such as the deuterium lamp (Einfeld *et al* 1978, Key and Preston 1980), and the wall-stabilised argon mini-arc (Bridges and Ott 1977, Einfeld *et al* 1979). In the wavelength region below 115 nm, reliable and easy to use transfer standard sources are still missing. It seems possible that laser-produced plasmas can be used for this purpose (Kühne 1982), but as these are pulsed sources, there still will be a demand for a continuous source. Of special interest are line radiation sources which close the gap between the long wavelength limit of soft x-ray sources of approximately 10 nm and the comparatively easy to produce He I resonance line at 58.4 nm (Paresce *et al* 1971, Warden and Moos 1977).

Hollow cathode discharges are known to produce significant densities of highly excited atoms and ions (Falcone and Pedrotti 1981). We have therefore investigated the VUV emission of a high-current DC hollow cathode in the region between 10 nm and 100 nm. In this paper we report measurements of the line-integrated radiance of selected Al IV, He II, and He I lines performed as a radiometric comparison with the electron storage ring BESSY as a primary standard source.

2. Hollow cathode discharge

We used a modified version of the hollow cathode as described by Danzmann and Kock (1980). The construction is shown schematically in figure 1. It consists of two cylindrical anodes symmetrically opposing one cathode, which contains an exchangeable hollow

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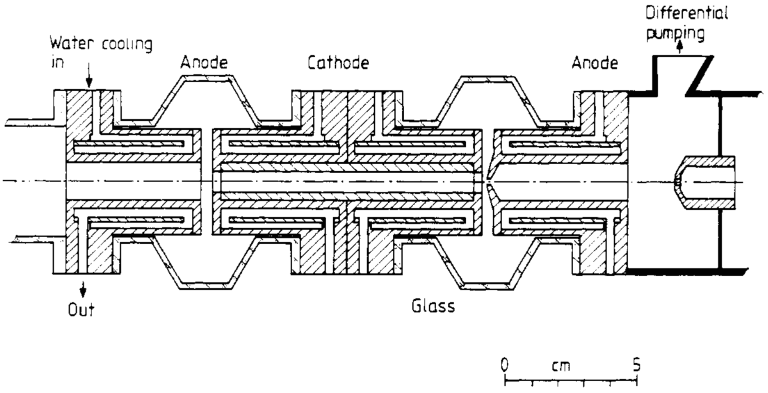

Figure 1. Longitudinal section of the hollow cathode and the differential pumping system.

metal cylinder with a straight bore of 8 mm diameter and 100 mm length. The electrical insulation of the water-cooled stainless steel electrodes is by glass tubes. The components are held together by O-ring seals and clamps.

Reabsorption of the VUV radiation in cool boundary layers is prevented by a two-stage differential pumping system. One of the anodes holds an exchangeable aperture with a free diameter of 1 mm at a distance of 4 mm from the cathode. While the

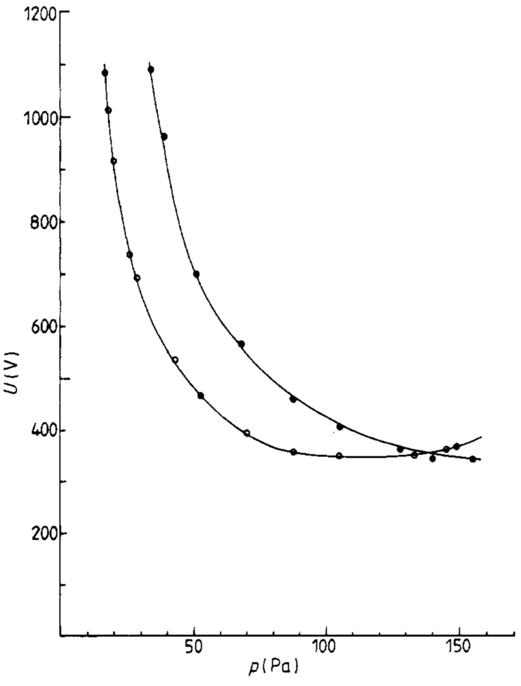

Figure 2. Operating voltage as a function of buffer gas pressure for an aluminium–argon hollow cathode. Parameter is the discharge current I(A): ○, 1; ●, 2.

pressure in the discharge is typically between 10 Pa and 300 Pa (0.1 mbar and 3 mbar), a turbomolecular pump evacuates the first stage to a pressure below 5×10^{-2} Pa (5×10^{-4} mbar). The first aperture protrudes into the negative glow region and prevents the formation of dense boundary layers. The second aperture at a distance of 100 mm from the first has a free diameter of 2 mm. Behind this aperture the pressure is kept at less than 2×10^{-4} Pa (2×10^{-6} mbar). We operated the discharge with cathode cylinders made out of iron, copper, vanadium, or aluminium in helium, neon, or argon as buffer gases. The voltage drop across the electrodes at constant current is dependent on the buffer gas pressure. Lower pressures require higher voltages, as can be seen from figure 2. We used a current-regulated power supply (1500 V/50 A) with an RMS ripple $\Delta I/I = 10^{-3}$. The discharge voltage was adjusted by varying the buffer gas pressure. Both anodes were at earth potential. At cathode voltages larger than 1200 V sudden current disruptions would extinguish the discharge. Arcing limited the maximum stable currents to about 10–15 A with new electrodes.

3. Experimental set-up

The experiment was performed at the laboratory for VUV radiometry of PTB at the electron storage ring BESSY. The radiances of the emission lines emitted by the discharge in the hollow cathode were determined by comparison with the calculable spectral concentration of radiant intensity of an electron storage ring (Schwinger 1949). An ellipsoidal mirror images the tangent point of the storage ring or the hollow cathode into a toroidal grating monochromator in such a way that the radiant flux is not limited by the entrance slit size (figure 3). For both the sources the same surface element of the mirror, the same angle of incidence and a common aperture stop A is used. To allow for corrections due to the different degree of polarisation of the two sources (synchrotron radiation is highly polarised near the electron orbit plane), the monochromator can be rotated around its optical axis defined by the centre of the entrance slit and the centre of the grating. A detailed description of the calibration procedure can be found in Fischer *et al* (1984). The spectral concentration of radiant intensity of the hollow cathode is then converted into radiance by integrating over the line profile and averaging over the source size (aperture with 1 mm diameter).

An angle of incidence of 86° was chosen for the ellipsoidal mirror. The distance from the storage ring tangent point to the mirror was 15000 mm, and the distance from the 1 mm aperture in the differential pumping system of the hollow cathode to the mirror was 5000 mm. The corresponding images were formed in 930 mm and 1060 mm respectively.

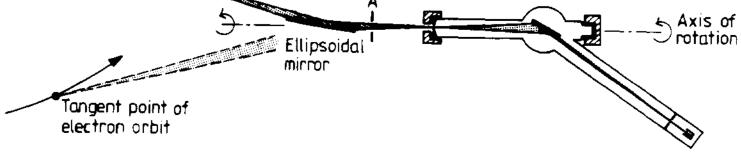

Figure 3. Instrumentation for comparing the unknown spectral concentration of radiant intensity of a source with the calculable spectral concentration of radiant intensity of an electron storage ring.

The distance between the monochromator and the mirror could be adjusted to compensate for the different image distances. Gratings with 200 lines/mm and 600 lines/mm were used with corresponding exit slit widths of 40 μm and 200 μm respectively to insure a bandwidth of <0.1 nm for all wavelengths. The VUV signal was detected by a fast linear focused EMI D233B electron multiplier.

4. Results and discussion

Depending on the combination of cathode material and buffer gas pressure the whole range from 13 nm to 100 nm can be covered by intense line radiation. We observed lines from ionised noble gas atoms in ionisation stages up to Ne IV and Ar V. When operated at high current and low pressure, cathode material will be sputtered off the cathode wall and lines from metal ions up to Al V and Cu V are visible. The simplest spectrum is provided by an aluminium hollow cathode operated in helium. It mainly consists of the intense Al IV doublet ($2p^6$-$2p^5\,3s$) at 16 nm, the He II Lyman series and He I lines. If argon is used as a buffer gas an additional Al IV line ($2p^6$-$2p^5\,3d$) appears at 13 nm as can be seen in figure 4. The cluster of lines at 17 nm consists of the Al III satellite lines to the Al IV lines at 16 nm. The upper levels of these lines arise from the doubly excited configurations $2p^5 3s 3l$ in sodium-like Al III. Harris *et al* (1984) have recently noted the existence of a subclass of quartet levels of these configurations in alkali-like atoms and ions that retain relative metastability against auto-ionisation and are radiatively allowed. They discuss these states as possible upper levels of XUV lasers. It may be interesting to mention that in our DC discharge the intensity of the satellite lines is greater than that of the parent lines. The structure of the satellite cluster is dependent on the buffer gas used. If we operate our hollow cathode in neon at least nine lines are clearly visible, whereas only three lines can be distinguished when helium or argon are used. These satellite lines have been observed by Warden and Moos (1977) in a Penning discharge, but in their case the satellites were much weaker than the parent lines.

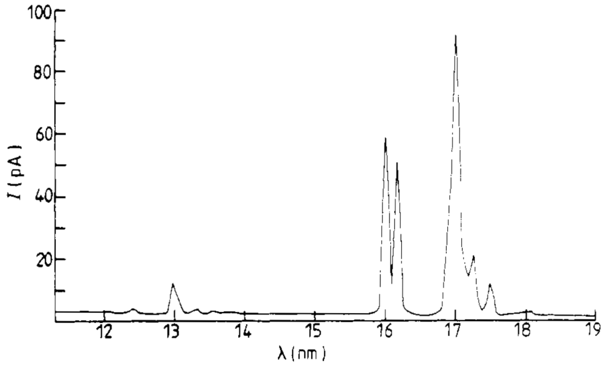

Figure 4. VUV spectrum of an aluminium–argon hollow cathode at a current of 4 A and a voltage of 600 V. The photocurrent is not corrected for the spectral sensitivity of our detection system.

Figure 5 shows the radiance of the Al IV doublet at 16 nm as a function of the voltage drop across the electrodes at constant current for a He–Al discharge. The

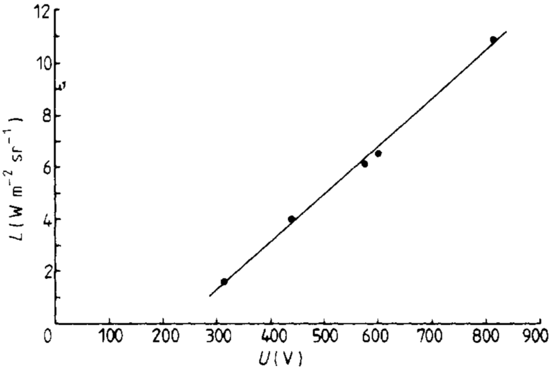

Figure 5. Radiant power of the Al IV doublet (16.0 nm, 16.2 nm) as a function of the discharge voltage for an aluminium–helium hollow cathode at a current of 4 A.

voltage drop was varied by changing the buffer gas pressure. The approximately linear dependency holds for all lines in the parameter range investigated, except for neutral transitions, the radiances of which tend to saturate above 600 V. Figure 6 shows the radiance of the Al IV doublet as a function of discharge current at constant voltage for a He–Al discharge. The approximately quadratic dependency holds only for metal lines: noble gas lines show an almost linear behaviour. The emitted radiances are stable to within 5% for several hours, but tend to decrease because the aperture protruding into the negative glow plasma gets clogged by a deposit of sputtered cathode material. After approximately 10 h of high current operation the radiances have typically fallen to about 50% of their initial value. Removing the deposit will restore the original radiance to within our uncertainty limits. After approximately 20 h of high-current operation the discharge tends to become critically unstable because the cathode cylinder is degrading by ion bombardment. Replacing the cathode cylinder by a new one will restore the original performance.

We found current and voltage drop to determine the discharge in a much more meaningful way than current and buffer gas pressure, because in the low pressure regime a very small pressure change corresponds to a large change in discharge voltage. Especially with slightly degraded cathodes we sometimes observed sudden changes in

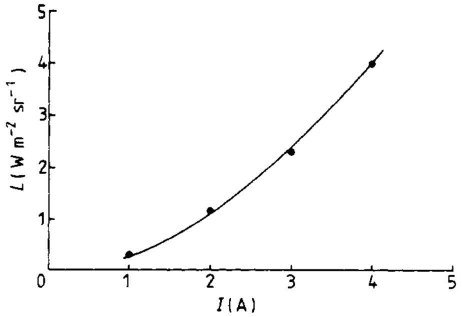

Figure 6. Radiant power of the Al IV doublet (16.0 nm, 16.2 nm) as a function of the discharge current for an aluminium–helium hollow cathode at a voltage of 440 V.

the line radiances and the voltage drop without any measureable pressure change. Adjusting the gas flow to restore the previous voltage would also restore the previous radiances.

Operating the hollow cathode at a current of 4 A and a voltage of 600 V proved to be a good compromise between high radiance and long lifetime. Under these conditions we have determined the radiance integrated over the respective line profiles for selected transitions emitted by an aluminium hollow cathode with helium or argon as buffer gases (table 1). The quoted uncertainty is the statistical uncertainty (standard deviation) evaluated from five hollow cathode runs combined with three synchrotron runs. For possible systematic uncertainties see Fischer *et al* (1984).

Table 1. Radiance of selected spectral lines.

Source:	Differentially pumped hollow cathode
Cathode:	Aluminium, length 100 mm, linear diameter 8 mm
Buffer gases:	Helium, argon
Parameters:	$I = 4$ A, $U = 600$ V
Solid angle of observation:	10^{-6} sr
Area of observation:	Circular with 1 mm diameter

λ(nm)	Ion	Buffer gas	L(W m^{-2} sr^{-1})	Uncertainty
13.0	Al IV	Argon	0.87	±25%
16.0/16.2	Al IV	Argon	8.2	±25%
16.0/16.2	Al IV	Helium	6.5	±25%
23.7	He II	Helium	33	±20%
24.3	He II	Helium	93	±20%
25.6	He II	Helium	270	±20%
30.4	He II	Helium	1300	±20%
58.4	He I	Helium	2300	±20%

It might be interesting to note that the radiant intensity obtained in the He II Ly-α line from the hollow cathode is only three orders of magnitude less than the spectral concentration of radiant intensity of the BESSY storage ring (765 MeV, 100 mA) integrated over the 0.1 nm bandwidth of our monochromator at the same wavelength.

5. Conclusion

A differentially pumped high-current hollow cathode may be used as a source of intense line radiation in the VUV down to 13 nm. Stability and reproducibility are not yet completely satisfactory for its use as a transfer standard, but it may be appropriate for general survey work not requiring high precision radiance data.

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