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Initial study of the optical spectrum of the ISIS H^- ion source plasma[a)]

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The front end test stand is being constructed at the Rutherford Appleton Laboratory, with the aim of producing a 60 mA, 2 ms, 50 Hz, perfectly chopped H^- ion beam. To meet the beam requirements, a more detailed understanding of the ion source plasma is required. To this end, an initial study is made of the optical spectrum of the plasma using a digital spectrometer. The atomic and molecular emission lines of hydrogen and caesium are clearly distinguished and a quantitative comparison is made when the ion source is run in different conditions. The electron temperature is 0.6 eV and measured line widths vary by up to 75%. *© 2012 American Institute of Physics*. [doi:10.1063/1.3662959]

I. INTRODUCTION

A highly successful Penning-type H^- ion source has been operating on the ISIS pulsed spallation neutron and muon facility in the United Kingdom for over 25 years and is now being used on the front end test stand (FETS).[1] The demanding beam requirements for the FETS have driven ion source and associated power supply upgrades. However in order to simultaneously achieve a high current, low-emittance beam at high duty factors as well as maintaining long source lifetimes, the plasma must be studied in more detail. As such, an initial study of the optical spectrum emitted from the ion source has been performed with a view to understanding how varying the source parameters affect the plasma temperature and density. This should lead to optimal settings for the plasma to produce the desired ion beam.

II. SPECTROMETER

An EPP2000-UVN-SR-14 spectrometer from StellarNet[2] is used in the initial study since it has a wide detector wavelength range (200–1100 nm), reasonable pixel resolution (0.5 nm), plug-and-play universal serial bus (USB) operation and low cost. It is operated on the ion source platform which is biased to -65 kV relative to laboratory ground. A USB-over-fibre data transfer hub is used to send the signal from the high-voltage platform to the laboratory computer. The ion source plasma light is coupled to the spectrometer on the platform via a 2 m long, 600 μm core diameter optical fibre with a wide-angle lens attached.

III. EQUIPMENT SETUP

The ion source is mounted on a vacuum flange such that the 0.6 × 10 mm slit emission aperture faces down. The beam is brought to level with the rest of the accelerator and shaped to a round profile by a 90° dipole magnet.[3]

A schematic of the optical setup is shown in Fig. 1. The plasma light is studied by viewing a combination of the light emitted directly below the slit aperture, and the light created inside the source which is reflected off a polished extraction electrode assembly. Both direct and reflected light then pass through a quartz window on the ion source mounting flange and into the spectrometer's wide angle lens. A series of light transmission tests using a test lamp show no absorption lines from the quartz window or stainless steel extractor which could affect the measured ion source plasma spectra. The lack of direct line of sight into the plasma is a major drawback. Therefore, a system of fibre optic vacuum feedthroughs and in-vacuum mounts is being developed for future studies.

IV. DATA AQUISITION

LABVIEW code is written to continually monitor the intensity and full width at half maximum of specific spectral lines. The full spectrum can be recorded when required. The sub-optimal observation point shown in Fig. 1 meant CCD integration times of several seconds are required for good signal to noise. This is ideal for observing long-term changes, such as the ~30 min settling time of the discharge after varying gas flow rates, but meant that light variation within each 800 μs discharge pulse cannot be investigated. Integration times were limited to prevent intensity clipping by the 12-bit detector.

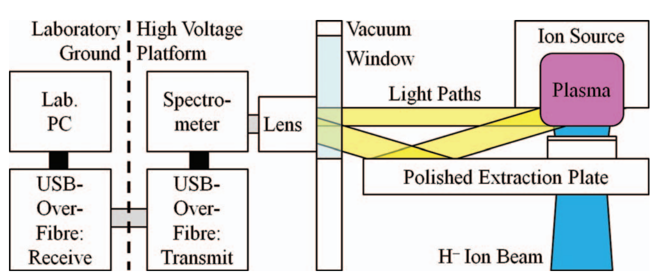

FIG. 1. (Color online) Equipment setup.

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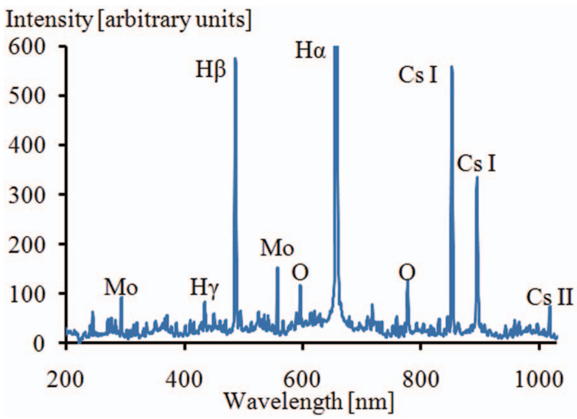

FIG. 2. (Color online) Typical emission spectrum. Scale adjusted for clarity: the H_α peak intensity is far higher at 3600.

V. GENERAL OBSERVATIONS

Figure 2 shows a typical observed spectrum from the ion source plasma. The strongest emission lines are of course from hydrogen and caesium. Trace amounts of molybdenum and oxygen sputtered from the ion source surfaces are also visible. The neutral caesium (Cs I) lines are almost as strong as the H_β. Additionally, there are no discernable high-energy (short wavelength) ionized caesium (Cs II) lines. This implies that ionized caesium rapidly binds onto the cathode surfaces before it can be further excited in the bulk plasma.

Without caesium, a pulsed discharge (PD) requires cathode surface temperatures greater than 1000 °C to thermally emit enough electrons to sustain the current demanded by the power supply (PS); typically 55 A. Caesium lowers the work function, meaning the cathode can operate at around 500 °C. The source will not operate immediately in pulsed, high current mode when turned on: the cathode must be warmed. This is achieved using a low current dc PS. From cold, the source may generate a dc discharge of ∼0.1 A. The PS drives a high voltage to try to supply the high demanded current: the plasma is in "high impedance mode." The initially low current is enough to slowly warm the cathode. As the cathode warms, more electrons are emitted and a higher current can be delivered. Over the course of ∼30 min, this positive feedback process heats the cathode enough to deliver a high current and for the PS voltage to drop. The plasma is now in "low impedance mode." The PD can now strike and is able to self-sustain the

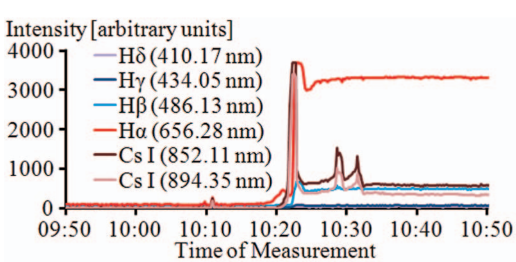

FIG. 3. (Color online) Change in line intensities during source startup. Caesium spikes at 10:30 are the breakdowns in the extraction system as it conditions to full voltage.

TABLE I. Spectral line data.

Emission Line	E (eV)	$A.g$ ($\times 10^8$ s^{-1})
Ha (656.28 nm)	12.09	7.938
Hb (486.13 nm)	12.75	2.694
Cs I (852.11 nm)	1.455	1.312
Cs I (894.35 nm)	1.386	0.5726

required temperatures, meaning the dc PS is no longer needed and is turned off.

The source temperatures increase approximately linearly during startup, whereas Fig. 3 shows that the light output hardly changes. The light intensity instead follows the discharge current, which starts to appreciably increase at the onset of low impedance mode at 10:15. Here, the plasma density drastically increases so higher rates of atomic excitation and spontaneous emission can occur.

In general, the low current dc discharge looks broadly white; whereas the PD looks red-pink as the neutral H_α light dominates. The sharp spike in caesium emission at 10:20 is when both dc and pulsed PSs are operating. Dialing down the dc PS lowers the Cs light to normal operating levels of ∼1/7th of the H_α emission. Once pulsed discharge operation is achieved, ∼30 min are required for the plasma (and extracted beam) to stabilize.

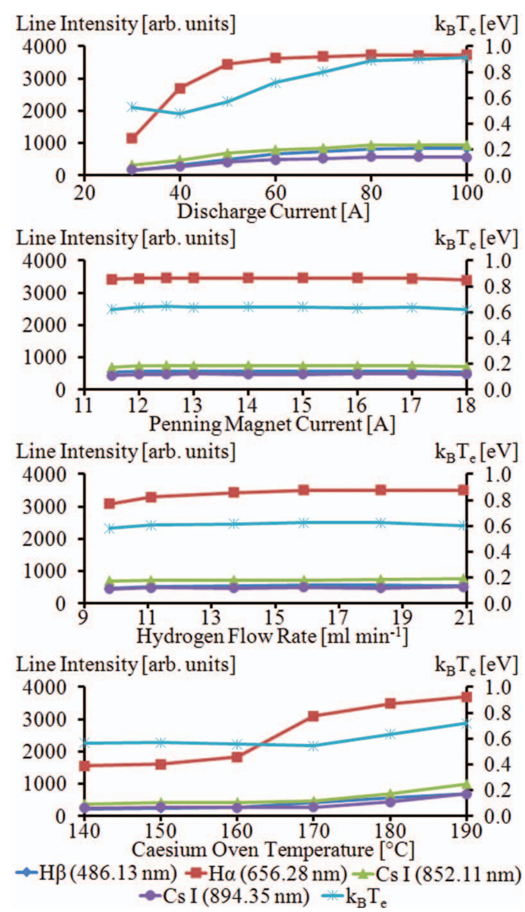

FIG. 4. (Color online) Change in emission line intensity and k_BT_e.

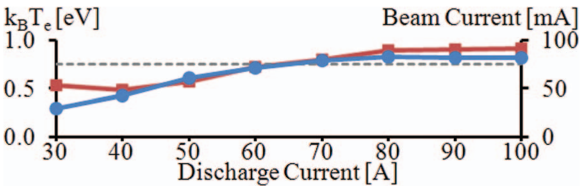

FIG. 5. (Color online) Electron temperature (squares); H^- affinity energy (dashed line); Extracted beam current (circles).

VI. VARYING ION SOURCE PARAMETERS

Optical spectroscopy is used to determine how the plasma temperature and density vary with source settings. The main adjustable parameters for the ISIS ion source are the pulsed discharge current, Penning magnetic field, and hydrogen and caesium flow rates. The caesium flow is controlled by altering the temperature of a heated oven.

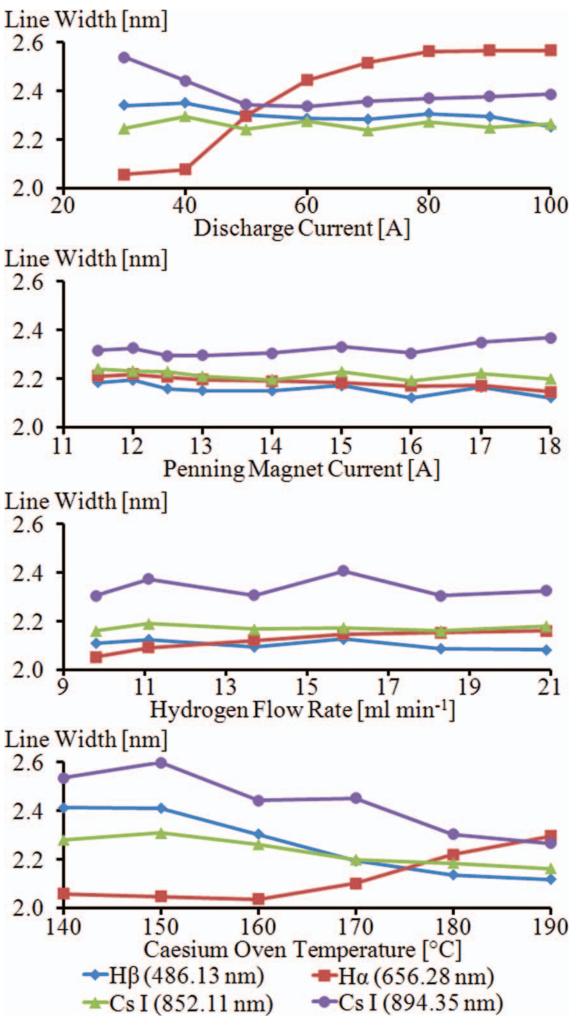

FIG. 6. (Color online) Change in observed emission line widths.

A. Electron temperature

Assuming local thermal equilibrium in the plasma, the electron temperature $k_B T_e$ can be determined using the ratio of light emission intensities I of two lines i and j with wavelengths λ from the same ionization state of an atom,[4]

$$k_B T_e = (E_j - E_i)/\ln\lfloor (A_j g_j I_i \lambda_i)/(A_i g_i I_j \lambda_j)\rfloor, \qquad (1)$$

where E is the excitation energy, A is the transition probability, and g is the statistical weight of each line;[5] given for a selection of lines in Table I. Figure 4 shows that the electron temperature varies around 0.6 eV depending on the source settings, agreeing well with measurements made at Los Alamos National Laboratory (LANL) on a scaled Penning ion source.[6] Figure 5 shows the importance of maintaining $k_B T_e$ below the H^- electron affinity energy of 0.75 eV.

Plasma density and hence extracted beam current tends to increase with discharge current. However H^- dissociation by high-energy electrons at discharge currents above 70 A saturates the beam current to 82 mA.

B. Ion temperature and electron density

Doppler and Stark broadening of emission lines can be used to determine the ion temperature and electron density in the plasma, respectively.[7] Figure 6 shows line broadening changes of up to 75% when source parameters are varied.

VII. SUMMARY

Optical spectroscopy provides a useful diagnostic link between discharge pulse oscilloscope traces and long-term electrode temperature measurements. This initial study has shown interesting features of the plasma's optical emissions. Future studies will use a high-resolution monochromator to further investigate line broadening.

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