OPTICAL-EMISSION STUDIES IN THE ION-FOCUSED REGIME

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Y. P. Chong, Simon S. Yu, J. A. Masamitsu,

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T. J. Fessenden and D. S. Prono

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Lawrence Livermore National Laboratory

University of California

Livermore, California 94550

ABSTRACT

The utility of optical emissions for diagnostic purposes in the ion-focused regime is explored. Two possible uses of the emissions are examined: (1) The time delay of 337.1-nm emissions relative to 391.4-nm emissions is observed to scale with the beam-neutralization time; (2) Emissions at 391.4 nm may determine beam-current density at the front of the beam.

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I. Introduction

It has been shown that optical diagnostics are viable monitors of an electron beam pulse travelling in high pressure gas.¹ We present here studies of optical emissions at very low pressures; namely, in the ion-focused regime.² This region, below 1 Torr, is of great interest regarding conditioning and centering of an intense relativistic electron beam. Measurements presented here were made on the Experimental Test Accelerator (ETA).³ Specifically, a study of the effects of electric field and beam current density on emissions of nitrogen at 337.1 nm and 391.4 nm is described.

II. Experimental Description

Optical measurements on ETA were made at the end of the accelerator, 14 cm after the gas entry foil which is located between beam current monitors No. 9 and 10 (Fig. 1). Emissions were measured through side ports. A photometer viewed the west port while a monochromator measured intensities through the east port via a periscope. Quartz vacuum windows were placed on extended arms 38.1 cm away from beam chamber center line in order to reduce darkening caused by beam radiation.⁴

The monochromator setup is shown in Fig. 2. A focusing mirror (focal length 3 ft., diam 6 in.) viewed the ETA beam through a 2 in. diam quartz vacuum window, located 48.3 cm from beam axis. The image was relayed at one-to-one magnification through an optical periscope out to the exterior of

the ETA pit and focused with a second focusing mirror onto the entrance slit (0.5 mm wide, 1 cm long) of a monochromator (ISA Model H-20, linear dispersion 4 nm/mm). The resolution of the monochromator was less than 3 nm. The exit slit was imaged onto a photomultiplier tube shielded in a lead pig. Single microchannel plate (MCP) R1194U or tandem type MCP (R1294U) photomultipliers from Hamamatsu TV Company, Ltd. provided sufficient gain ($10^3 - 10^6$) with very fast risetimes (≤ 300 ps). The detected light pulses were monitored on a Tektronix 7104 scope. The monochromator as well as necessary electrical equipment were placed inside an electromagnetic shield room.

Reflective mirrors in the periscope oriented the beam axis parallel to the monochromator entrance slit (Fig. 2). Since the beam diameter was typically 1.5 cm, the monochromator viewed only a fraction of the beam. This permits spatial resolution in the radial direction.

III. Electric Field Effect on Emissions at 337.1 nm and 391.4 nm

A. Measurements and Results

Measurements were made using the monochromator setup with a 6 kA current into the nitrogen gas. The time history of line emissions at the beginning of the beam pulse was measured and compared for these two bands (Fig. 3). In particular, the difference in the onset of these line emissions was plotted as a function of pressure from 40 to 160 microns (Fig. 4). The time difference

$$T_D = T_0(337.1 \text{ nm}) - T_0(391.4 \text{ nm})$$

was observed to decrease with pressure.

B. Discussion

Figure 5 shows excitation cross-section versus electron energy as measured by Borst and Zipf⁵ and Imami and Borst.⁶ We observe that emissions at 337.1 nm are initiated only by slow secondary electrons (< 1 keV). At low pressures, the large radial electric field at the beam front accelerates the beam-generated secondary electrons to the 10 - 100 keV range. In this regime, only the 391.4 nm emission, excited primarily by the beam electrons, is observed. Emissions at 337.1 nm begins to appear only when sufficient ions have been created to short out the radial electric field. The rate for ion generation is proportional to pressure. The neutralization time, as indicated by the delay of 337.1 nm onset, is therefore expected to vary inversely with pressure.

A simple model based on a straight cylindrical beam predicts that for complete neutralization ($F = 1$)

$$P \times T_D \approx 1, \quad (1)$$

where P is pressure (Torr) and T_D is the time delay in the onset of the two bands (nsec).

Figure 6 shows the experimental values of $P \times T_D$. The data is consistent with the predicted pressure scaling. Its magnitude falls slightly below 1 ($F \sim 0.8$).

IV. Beam Current Density Measurement From 391.4 nm Emission

A. Preliminary

At the pressures relevant to the IFR, the rate equation for 391.4 nm emission is given by

$$\frac{dN}{dt} = \left(\frac{J_b}{e} \right) N_g \sigma - AN \quad (2)$$

Here

N = population of upper state

J_b = beam current density

N_g = gas density

A = radiative decay coefficient

σ = cross-section for excitation of upper state by beam electrons.

Although Eq. (2) looks similar in form to rate equations for high pressure regimes, three differences are implicit: (1) In Eq. (2), the electric field term (proportional to $v(E/p)$) which plays an essential role in much of the high pressure regime is absent. This is due to the fact that secondary electrons in strong runaway do not produce significant emissions. (2) The source term in Eq. (2) comes only from direct beam ionization, in contrast to high pressure models where the ionization term includes effects from beam excitation as well as excitation by the cascading secondaries. (3) At high pressures, collisional quenching is the dominant loss term. At low pressures, it is negligible.

The signal intensity S is given by

$$S = \pi a^2 h \nu \bar{A} N$$

where

a = beam radius

ν = frequency of radiation

$\bar{A}$ = transition probability for the band in question

N = density of upper state

h = Planck's constant.

Therefore,

$$\left(\frac{dS}{dt} + AS \right) = J_b \quad (3)$$

B. Measurements and Results

Using the monochromator setup, the time history of the 391.4 nm band was measured during the early part of the beam pulse (Fig. 3). The signal intensity and its rate of increase were determined. The quantity within brackets in Eq. (3) was plotted versus time. Figure 7 shows the results for three pulses compared to the signal measured by a target-wire x-ray diagnostic developed by E. J. Lauer.⁵ The data were taken at pressures of 80 and $100 \mu\text{N}_2$. Each optical data curve is normalized to the x-ray value at $t = 6 \text{ ns}$. Very good agreement is seen for times up to 8 ns. This is a much better agreement than expected in view of the different z locations.

V. Conclusion

At low pressures in the IFR, light emission at 337.1 nm is observed to occur later than that at 391.4 nm which is excited primarily by energetic beam electrons. This time delay is seen to scale as the beam neutralization time with pressure, showing the electric field behavior at beam head.

Light emission at 391.4 nm shows promise as a measure of beam current density at beam head, based on a comparison to another diagnostic, target-wire x-ray.

Present measurements are preliminary and further study is highly desirable.

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Figure 1 - Beam line observation region

Figure 2 – Schematic: monochromator setup

$I = 6 \text{ kA}$
80 microns
Nitrogen

PMT risetime = 0.5 ns

$T_0(391.4) = 2.8 \text{ ns}$

$T_0(337.1) = 10 \text{ ns}$

$$T_D = T_0(337.1) - T_0(391.4) = 7.2 \text{ ns}$$

Figure 3 - Onset time of 337.1 nm and 391.4 nm compared

Figure 4 - $T_D = [T_0(337.1 \text{ nm}) - T_0(391.4 \text{ nm})]$ vs pressure

Figure 5 - Cross sections vs electron energy for the excitation of the 337.1 nm and 391.4 nm bands of nitrogen

Figure 6 - Pressure x time delay (T_D) vs pressure (microns)

Figure 7 - Beam current density measurements from probe wire x-ray signal ($z = 45$ cm) and optical signals ($z = 14$ cm) compared