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Fusion Technology Institute
University of Wisconsin
1500 Engineering Drive
Madison, WI 53706

http://fti.neep.wisc.edu

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SPECTROSCOPIC STUDIES OF INTENSE ION BEAM PROPAGATION IN THE PBFA-II GAS CELL

J.E. Bailey, A.L. Carlson, D.J. Johnson, E.J. McGuire, T. Nash, and C.L. Olson

Sandia National Laboratories

Albuquerque, New Mexico

and

J. MacFarlane and P. Wang

University of Wisconsin

Madison, Wisconsin

We are studying the physics of ion beam transport on PBFA II by measuring time-resolved visible spectral emission from the gas cell. The initial goals are to perform a spectral survey, to measure the spectral-line intensities and widths, and to evaluate the potential for using this emission as a diagnostic for conditions in the gas-cell plasma. We have acquired spectra in the 4000 Å to 7000 Å regime excited by the transport of proton and carbon beams through 5 Torr argon gas. The nominal ion beam energy and current density at the spectroscopic line of sight are 6-7 MeV protons, 12-21 MeV carbon, and 10-50 kA/cm^2. The emission is dominated by n=4 to n=4 transitions in Ar II, with FWHM values typically 1-2 Å. We are investigating a variety of mechanisms which might contribute to the line profiles, including plasma Stark broadening, Stark and Zeeman splittings and shifts due to residual electric and magnetic fields, and opacity effects. The relative contributions of ion-impact and plasma electron collisional excitation are being evaluated using an LTE atomic model. Measured plasma properties will be incorporated into our understanding of beam transport.

Introduction

One requirement for inertial confinement fusion (ICF) with a light-ion beam driver is transport of the beam to the target[1]. Present experiments at the Particle Beam Fusion Accelerator II (PBFA II)[2] transport a mixed proton and carbon ion beam through a 12.5 cm, 5 Torr argon gas cell to the target. The acceleration voltage is typically 6-8 MV over a 15 nsec pulse, with a current density at the anode exceeding 5 kA/cm^2 and peak power densities on target of 5 TW/cm^2 protons. Injection of the beam into the gas cell causes rapid ionization and the resulting plasma provides charge and current neutralization for the beam.

This paper describes an initial investigation of the potential for using visible spectroscopy to study beam transport physics on PBFA II. Spectroscopic techniques could measure the plasma-electron density (n_e) and temperature (T_e), enabling inference of the plasma conductivity[3]. Spectral line profiles are sensitive to the presence of stray electric fields, possibly[4] arising during transport of non-uniform ion beams or from a breakdown in charge or current neutralization. Spectroscopic studies of ion-beam transport could also be useful for aspects of ion-driven ICF beyond the direct application to beam transport. We expect some dependence of the emission intensity on beam intensity, either because the beam itself generates the emission or because the electron excitation rates are highest where the beam intensity is highest[5]. If we spectroscopically determine this

relationship, then the light emission can be used to measure beam current uniformity during transport. It has also been proposed[6] to measure the beam divergence from the diameter of the light emission generated as a beamlet propagates through the gas-cell plasma.

An additional application is to use the spectral emission to study the heating of the plasma by the beam. The expected density ($n_e = 10^{17}$ cm^{-3}) and temperature (T_e= 1 eV) are far below the regime occurring in ICF targets. However, the slowing of multiply-ionized beams in plasma is an area of active research[7] and the deposition in the PBFA II gas cell plasma is ≈1-3 TW/gm, three orders of magnitude above the regime reported in recent heavy-ion beam-heating experiments[8]. Beam-heating experiments in the PBFA II gas cell are attractive because of the relative ease of visible spectroscopic diagnostics and the possibility of piggybacking on experiments with a different main objective.

Our goals for the exploratory experiments reported here were to develop experimental techniques for acquiring time-resolved visible spectra from the PBFA II gas cell, to identify the dominant spectral emissions, and to evaluate the potential for using the spectra to measure physical quantities relevant to beam-transport physics. We obtained spectra in the 4000-7000 Å regime with spectral resolution up to 0.3 Å and time resolution of about 1 nsec. The dominant emission in this spectral regime is from Ar II 4s-4p and 3d-4p transitions. Analysis of these results using an LTE model to interpret line intensities and an atomic physics code to calculate the effect of electric fields on the line profiles has begun.

Experiment

A schematic diagram of the PBFA II applied-B ion diode[9] is shown in Figure 1. Ions are accelerated radially inward from the cylindrically-symmetric anode toward the target on axis. Typical voltage and ion currents (measured with Faraday cups located at the gas cell boundary) are shown in Figure 2 The spectroscopy diagnostic uses a lens at 4-cm radius to collect light from a 7-mm-diameter cylindrical line of sight . The light is coupled into a 400-μm-diameter radiation-hardened quartz fiber optic that transports the light 45 m to a remote screen room. There the light is injected into a 1-m Czerny-Turner spectrograph with a streak camera located in the focal plane to record a time-resolved spectrum. The streaked spectrograph characteristics are described in Reference 10. The time resolution is about 1 nsec. The spectral resolution is 0.7 Å and the range is 280 Å with a 1200 g/mm grating. Wavelength fiducials are recorded on each shot by injecting HeNe laser light into the spectrograph, rotating the grating a known amount, and re-triggering the streak camera. The film response is unfolded from the data using a calibration step wedge.

The timing of the streaked spectra with respect to other diagnostics is obtained using a fast plastic scintillator (BC-418, Bicron Corp) located near the diode to detect bremsstrahlung generated when the power pulse arrives at the diode. The light from the scintillator provides an optical fiducial on each streaked spectrum that can be compared with bremstrahlung recorded with the main PBFA II data acquisition system. Knowing the optical path lengths, we can relate physical quantities determined with spectroscopy to quantities determined with other diagnostics to within approximately +/- 2 nsec.

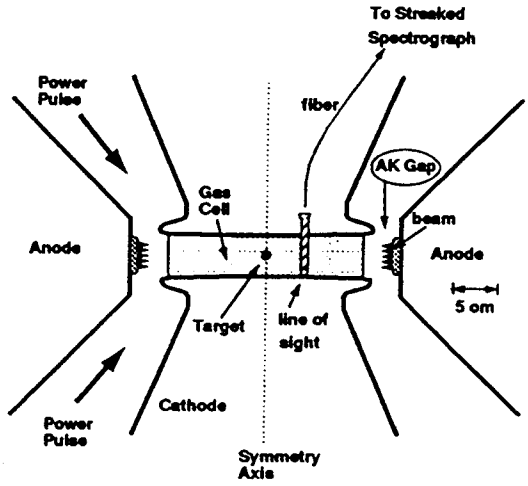

Figure 1. Schematic of the PBFA II ion diode.

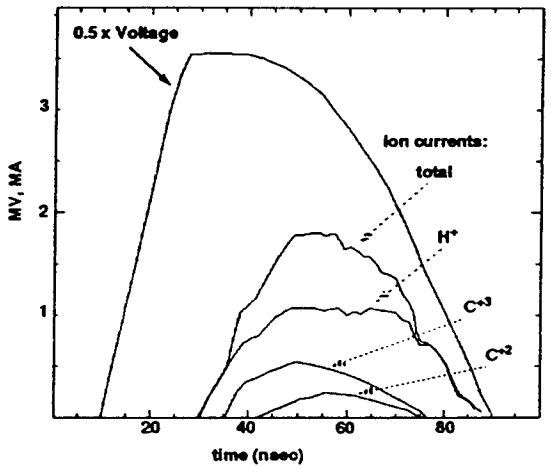

Figure 2. Typical PBFA II voltage and ion currents.

Results

The first PBFA II gas-cell spectra were acquired with a survey grating to enable us to identify the dominant emission features.An experimental survey spectrum with ~ 3 Å resolution is compared to known[11] Ar II wavelengths in Figure 3. Essentially all of the lines can be accounted for by emission from Ar II. We are investigating possible reasons for the lack of Ar I emission, including changes in the ionization distribution and excited state populations as a function of the plasma and beam parameters. We did not yet explore the ultraviolet wavelengths where any bright emission from Ar III would be located.

Spectral surveys were also performed to look for emission from beam ions as they traveled toward the target. This search was prompted by the possible measurement of beam current and/or beam divergence (through the line Doppler broadening). No beam emission was observed in these experiments, presumably because although the current densities are high, the cross sections for recombination and electron capture followed by radiative decay are low. This does not preclude success with such measurements in the vacuum ultraviolet regime, where emission is expected to be brighter.

A sequence of lineouts as a function of time from PBFA II shot #4659 is shown in Figure 4. We used high spectral resolution (0.3 Å) to enable line profile measurements. The emission is first observed when the proton current reaches 400 kA, approximately simultaneous with the onset of carbon beam current. The Ar II intensities grow for ~ 25 nsec, then rapidly decrease and disappear over the next 10 nsec. Some of the experimental lines are blends of several transitions and thus a detailed line-fitting method must be used to measure the widths. While this work is in progress, we made an initial measurement wherever possible by measuring the half width of partially-resolved features and multiplying by two. The 4348 Å 4s-4p line width grows from 0.9 Å

at t = 48 nsec to ~ 2 Å at t = 57 nsec. The rest of the lines have widths that grow from ~ 0.8 to ~1.4 Å during the same time period. These values can only be regarded as approximate until we take the line blending into account more accurately using a line-fitting procedure. However, the qualitative features are correct, i.e., the line widths double during the power pulse and the 4348 Å line is systematically wider.

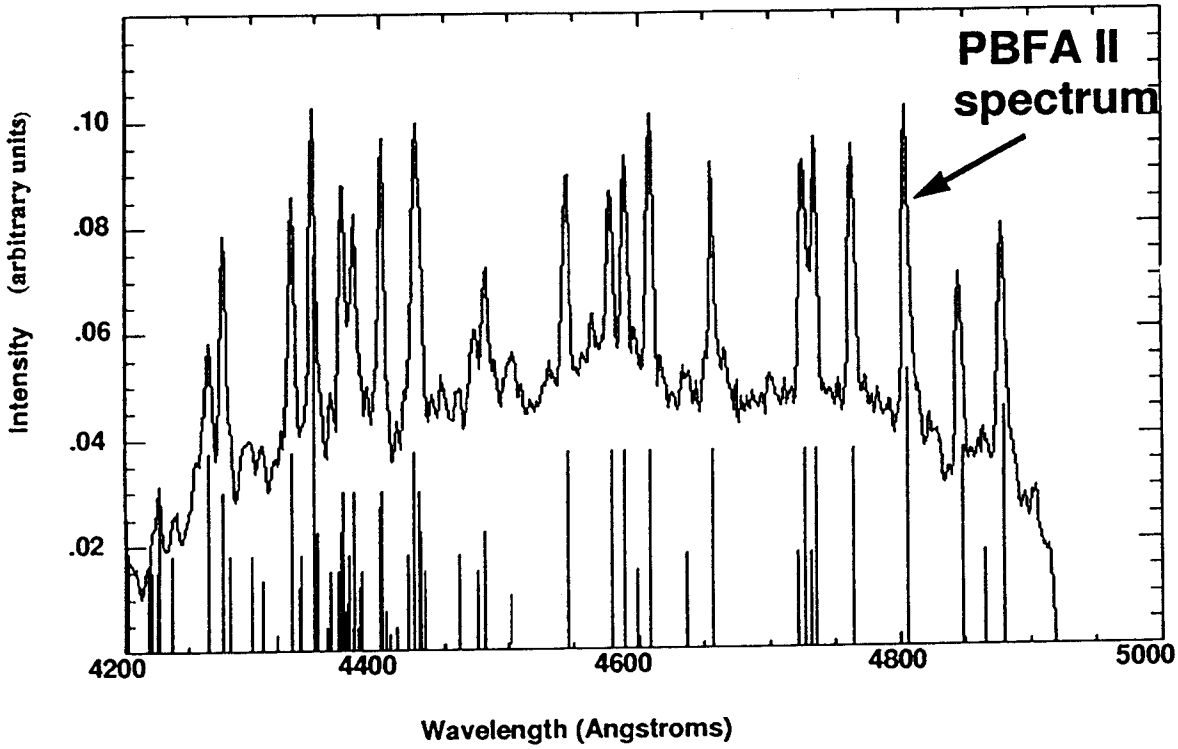

Figure3. Experimental survey spectrum (top) compared to known Ar II wavelengths (bottom). The line intensities in the bottom spectrum are from Ref. 11 and don't necessarily reflect the experimental conditions.

Discussion

The initial breakdown of the argon gas and the subsequent ionization involve complicated processes[1, 12], including beam ion-impact ionization, electron avalanching, and collisional ionization by thermal and secondary electrons. Although detailed hydrodynamic simulations are required to model these processes, we can make initial estimates following the approach in Reference 3, using the measured beam parameters and analytic equations to determine approximate bounds on n_e. Calculations for similar conditions[12] indicate that the expected electron temperature and density are ~1-2 eV and 10^{16}-10^{17} cm^{-3}, respectively The electron density produced by ion impact ionization during the first 10 nsec of the beam within the spectroscopic line of sight is ~ 10^{16} cm^{-3}. Also, assuming that the energy deposited by the beam is invested in electron temperature and ionization and neglecting radiation losses and ohmic heating by the return current (see Ref. 3), we find $n_e < 1.7 \times 10^{17}$ cm^{-3} at t= 39 nsec and $n_e < 3 \times 10^{17}$ cm^{-3} at t=44 nsec. These values can be compared with electron densities obtained from the spectroscopic measurements.

As described above, the experimental fwhm values range from 0.7-2.0 Å. Instrumental and Doppler broadening are negligible. The Stark widths[14] for these transitions are all approximately 0.32 Å for $n_e = 1x10^{17}$ cm^{-3} and $T_e = 1$ eV. If Stark broadening dominates, we expect all the line widths to be roughly the same. In fact, the 4348 Å 4s-4p line is significantly wider. We believe this is because the 4348 Å line width is modified by the opacity, which is a factor of 5 greater for this transition (assuming LTE among the excited states and using the oscillator strengths in Reference 15). The agreement for the other widths indicates they are not modified by opacity, since the optical depth varies by an order of magnitude. If we assume that Stark broadening is the dominant broadening mechanism for these lines, then the electron density is $2.4x10^{17}$ cm^{-3} at t= 40 nsec and it rises to about $5x10^{17}$ cm^{-3} during the pulse.

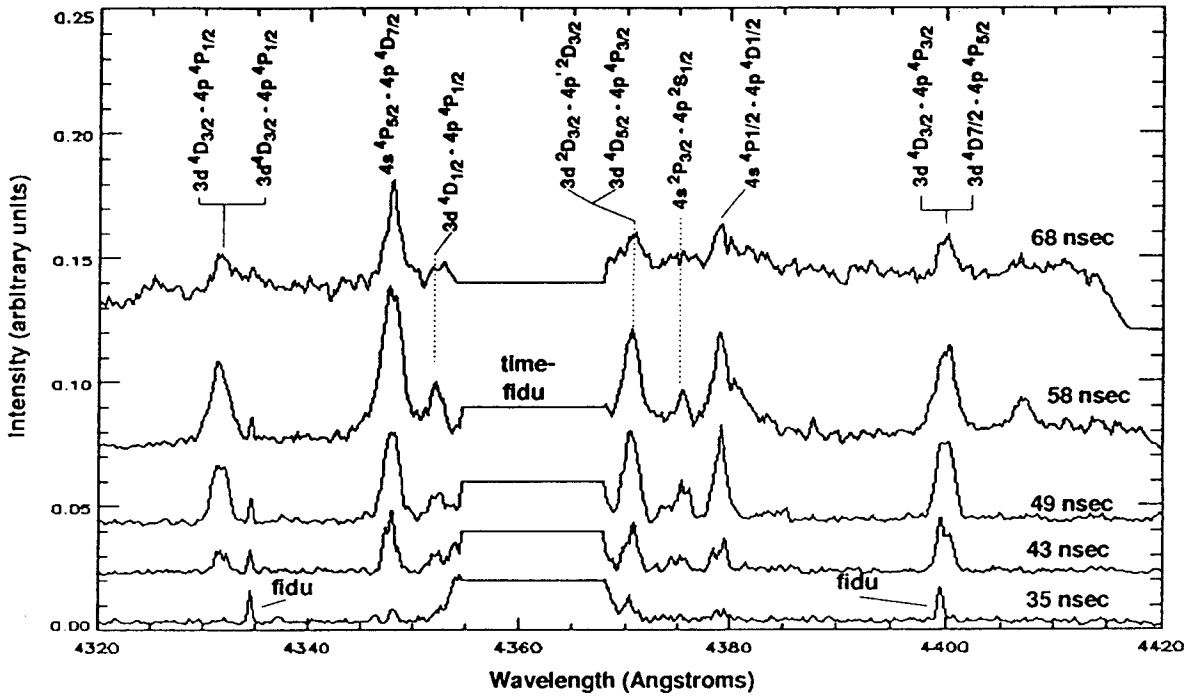

Figure 4. Sequence of lineouts from a high-resolution PBFA II gas cell spectrum. The times correspond to the electrical signals shown in Figure 2.

The electron density determined assuming the lines are Stark broadened is a factor of two higher than the upper bounds determined from the simple energy balance arguments. One possible explanation is that either the actual ion current is higher than indicated by the Faraday cups or that the timing of the spectra is in error by about 5 nsec. A second possiblity is that the stopping power appropriate to hot plasma, rather than cold gas, must be used to determine the energy deposition. Finally, other broadening mechanisms must be considered. For example, if stray electric fields do exist in the plasma because of transport of a non-uniform ion beam, the resulting distribution of Stark shifts may increase the apparent line broadening. Estimates for the peak field to be expected under these conditions are 100 kV/cm[4]. Code calculations of the Stark shift for the argon lines under such fields are in progress.

Atomic physics modeling is required for the quantitative interpretation of the line intensities. An atomic model for argon was constructed (see Reference 16 for details) and used to determine that an LTE analysis is satisfactory for the conditions in these experiments. The model predicts that Ar II is the dominant charge state for T_e = 2-3 eV. The calculated line center optical depth for the 4348 Å Ar II 4s-4p line is $\tau \approx$ 3-10, while the other lines have $\tau < 1$. This qualitatively agrees with the experimental observation that the 4348 Å linewidth is opacity broadened. A quantitative effort to compare experimental line intensities and widths to model-generated synthetic spectra is in progress.

The model was also used to compare the excitation rate due to ion impact excitation to the electron collisional excitation rate. The total ion impact excitation rate for protons and carbon is about the same, since the carbon ions have a lower particle current but a higher cross-section. For the conditions in this experiment, the electron collision and ion impact rates are comparable if $n_e \sim 1\text{-}3 \times 10^{17}$ cm^{-3} and $T_e \sim$ 2-3 eV. Thus, determination of which rate dominates requires an unambiguous measurement of the electron density and temperature. It may also be necessary to include effects of a non-thermal secondary electron distribution in the model.

In summary, these experiments have demonstrated that it is possible to acquire spectra from the PBFA II gas cell with good signal to noise and high spectral and temporal resolution. The visible spectra are dominated by Ar II lines with fwhm ranging from 0.7 - 2 Å. The interpretation of the experimental spectra is in progress, with potential for measuring n_e, T_e, and stray electric fields. These parameters can then be used to determine the mechanism responsible for populating the excited states and to improve our understanding of beam transport physics.

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