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Spectroscopic determination of the composition of a 50 kV hydrogen diagnostic neutral beam

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A grating spectrometer with an electron multiplying charge-coupled device camera is used to diagnose a 50 kV, 5 A, 20 ms hydrogen diagnostic neutral beam. The ion source density is determined from Stark broadened Hβ emission and the spectrum of Doppler-shifted Hα emission is used to quantify the fraction of ions at full, half, and one-third beam energy under a variety of operating conditions including fueling gas pressure and arc discharge current. Beam current is optimized at low-density conditions in the ion source while the energy fractions are found to be steady over most operating conditions. Published by AIP Publishing.

I. NEUTRAL BEAM OPTIMIZATION

A 50 kV, 5 A hydrogen diagnostic neutral beam (DNB) with 20 ms pulse provides local measurements of impurity ion emission through charge exchange recombination spectroscopy (CHERS) and of core-localized magnetic field through the Motional Stark effect (MSE). The DNB is used in low-field RFP discharges in the Madison Symmetric Torus and must provide a sufficiently bright, low divergence source of fast atomic hydrogen that the charge exchange emission from C^+ ions is comparable to background emission from electron impact excitation, and the Hα fine structure components are sufficiently resolved in the MSE spectrum. To meet these criteria, we require a beam current of 4–5 A and a large fraction of the beam neutrals to be at the primary energy of 50 kV. This energy maximizes the charge exchange cross section with C^+ and is sufficiently large to provide enough separation of the Stark components to determine the magnetic field. However, the DNB previously suffered from several deficiencies. The ion source failed to create a discharge reliably, the maximum beam current was reduced to below 4 A and was variable during a beam pulse, and the primary energy component varied from 60% to 80%. To correct these problems, the DNB was moved to a test stand which could provide greater availability and diagnostic access. We improved the reliability of the ion source by applying both a −3 kV pulse to an ignition tip near the cathode for 10 µs and a 900 V bias voltage across the cathode and anode for 3 ms to guarantee arc formation. We adjusted the beam by tuning the beam voltage, arc current, fuel line pressure, arc and high voltage module timing, and the magnetic isolation field to maximize the number of ions extracted at the full beam energy with a constant beam current. We introduced better high-voltage standoff in the power supply to achieve 50 kV without breakdown in the air. To verify the impact of these improvements, we measured electron density in the ion source and the fraction of each ion beam species. We determined the dependence of the ion source electron density under various conditions by measuring the Stark broadening of the Hβ line and the ions species fractions via the Doppler shifted Hα line.

II. SPECTROSCOPIC DIAGNOSIS OF THE NEUTRAL BEAM

Figure 1 shows the experimental setup for the ion source electron density and beam components measurement. The axial view is used to measure the ion source density and the view through a side port is used to measure the Doppler-shift spectrum. The spectrometer (Acton, SpectraPro-2500i) is equipped with an Andor iXon Ultra-897 camera which provides emission measurements with millisecond time resolution and 1800 g/mm grating for a spectral resolution of 0.012 nm/pixel. The full width at half maximum (FWHM) of the instrumental Gaussian broadening of spectrometer near the Hα and Hβ lines is 0.017 nm.

To help us understand the plasma conditions which optimize the extracted ion current, we measured the plasma density for a variety of control settings for the ion source. To have optical access to the ion source, we needed to remove the copper beam dump which prevented simultaneous measurement under beam formation conditions. The density is determined from the well-tested approximate formula:

\[ N_e [m^{-3}] = 10^{23} \times (w_x [nm]/4.8)^{1.46808} \]  

where \( w_x \) is the FWHM of the Stark broadening of the Hβ line. Compared with Stark broadening, the Doppler broadening is negligible and the instrumental broadening is about 15%–20% of the Stark broadening. The Stark broadening is determined from the Lorentzian contribution of a Voigt function fitting with the Gaussian component fixed at the instrumental function. For the ion source electron density measurement, the Hβ emission is not spatially localized but originates from the

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entire ion source area; thus, the measured electron density is weighted by the H\textsubscript{2} emissivity. We compared these density measurements with beam performance in later beam pulses with the beam dump in place.

For a hydrogen DNB, molecular ions such as H\textsuperscript{+}, H\textsuperscript{2+}, and H\textsubscript{2}O\textsuperscript{+} contribute to the extracted ion current as well as protons. Subsequent collisions in the neutralizer with neutral hydrogen gas will produce a composite beam of H\textsuperscript{+} and H\textsuperscript{0} with full, half, third, and 1/18 energy via charge transfer and dissociation.\textsuperscript{13,14} The fractions of beam particles at each energy are determined by measurement of their Doppler-shifted H\textsubscript{α} emission. These fractions are expressed in terms of the line intensities as\textsuperscript{6}

\begin{equation}
\frac{H\textsuperscript{+}}{H\textsuperscript{+}} = C\textsubscript{2}|I\text{obs}(E)/I\text{obs}(E)|, \\
\frac{H\textsuperscript{2+}}{H\textsuperscript{+}} = C\textsubscript{3}|I\text{obs}(E)/I\text{obs}(E)|,
\end{equation}

where I\text{obs} is the measured intensity, and C\textsubscript{2} and C\textsubscript{3} are the correction factors obtained by solving a set of ordinary differential equations\textsuperscript{3} of beam propagation through the neutral gas using experimental cross section data.\textsuperscript{15,16} These order-unity correction factors contain the neutralization efficiency of original beam ions and transition probabilities for spontaneous emission, and depend on the beam voltage and gas density of the neutralizer.

III. EXPERIMENTAL RESULTS AND DISCUSSION

The extracted ion beam current is either limited by space-charge for-ces or emission. For the space charge limited case, the extracted ion current can be calculated from the Child-Langmuir law: \(I\text{cl} \propto U^{3/2}/d^2\), where \(d\) is the approximate gap width between the electrodes and \(U\) is the potential drop. For the emission limited case, the extracted ion current depends on ion source plasma density \(n\text{e}0\) and temperature \(T\text{e}\) as \(I\text{B} \propto n\text{e}0T\text{e}^{1/2}\). In optimizing the extracted ion current, we found that it increased with grid voltage as expected for space-charge-limited current, but also increased with the arc current in the cathode, and current in the magnetic isolation field coil. These latter two parameters are related to the formation of the plasma at the extraction electrode and their effect on ion current suggests that some type of emission-limited effect plays a role in determining the ion current. We also varied the gas pressure in the gas valves used to fuel the discharge and found that the beam current was reduced at higher pressures. Figure 2 shows the beam current at different fueling pressure and arc current. The error bars depict the beam current variation during the beam pulse. In order to understand the beam behavior, we measured the electron density in the ion source while varying these operational parameters. The measured electron density at different fueling pressure and arc current is shown in Figure 3. The error bars depict the density variation; the fitting error is within 8%. The density ranges from \(2.3 \times 10^{20} \text{ m}^{-3}\) to \(4.5 \times 10^{20} \text{ m}^{-3}\) which is consistent in magnitude with the expected operation.\textsuperscript{17} It increases with fueling gas pressure, but unexpectedly decreases with arc current. We also find that the density decreases with increased magnetic isolation field strength and the highest constant extracted beam current is achieved for low density conditions. Since we expect greater extracted beam current with \(n\text{e}0\), it may be that \(T\text{e}\) is changing as well. We would expect \(T\text{e}\) to increase with arc current and magnetic isolation field due to greater input power and longer confinement time of the primary electrons. This dependence may also suggest that the shape of the ion sheath at the extraction grid apertures, which is also called the plasma meniscus,\textsuperscript{18} is optimized at lower \(n\text{e}0\).

We also checked what effect these varying plasma conditions have on the beam energy fractions through measurements of the Doppler-shift spectrum. A typical spectrum of a 50 kV beam observed at 44° to the beam line is shown in Figure 4. The...
FIG. 4. Spectrum of hydrogen Balmer alpha lines emitted by a 50 kV beam. The four blue shifted lines emitted by beam neutrals and protons originate from \( H^+ \), \( H_2^+ \), \( H_3^+ \), and \( H_2O^+ \) in the plasma source.

FIG. 5. Temporal evolution of ion species for a 50 kV, 20 ms hydrogen beam.

FIG. 6. Temporal evolution of ion species of the DNB before optimization.

observation angle is determined by equating the Doppler-shift of the full energy component with the beam energy determined from the grid voltage.

Since the gas line integrated density in the neutralizer and test chamber is estimated at the range of \( 10^{15} \) m\(^{-2}\)–\( 10^{16} \) m\(^{-2}\), the C\(_2\) and C\(_3\) at the beam voltage 30 kV–50 kV are estimated to be 0.52–0.4 and 0.36–0.28 with line density of \( 10^{10} \) m\(^{-2}\). With these correction factors, the ion species ratios of the beam are estimated from the measured line intensity ratios. The temporal evolution of the original ions species of a 50 kV, 500 A arc current, and 20 ms hydrogen beam is shown in Figure 5. The error bars depict the fitting errors. In addition, the uncertainty in the experimental cross section data\(^{14–16}\) is 15%. The average ratio of beam ion species with full, half, and one-third energy is 75%:20%:5% and is relatively constant over the beam pulse, leading to the decrease of \( H_3^+ \). Although the extracted ion current, and full energy component, the anticipated CHERS signal will increase by 20%–30% and the separation of Stark components will increase by about 10%.

IV. SUMMARY

The DNB has been improved by correcting arcing problems in the power supply and optimizing the extracted ion current by operating the beam at 50 kV, 500 A arc current and 60 kPa–70 kPa fueling gas pressure, creating a steady 4 A beam current with low variation during the beam pulse and full energy ion fraction of 75%. Although the extracted ion current is higher at lower fueling gas pressure, the variation during the beam pulse is the lowest at intermediate gas pressure. Density measurements in the ion source revealed that ion extraction is maximized under low density conditions which are thought to affect the shape of the ion sheath at the extraction grid.

SUPPLEMENTARY MATERIAL

See the supplementary material for figure numerical data.

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