**Near-Field Characterization of Hydrogen and Helium Operation on the TFTR
Diagnostic Neutral Beam**

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ABSTRACT

An Optical Multichannel Analyzer has been used to measure beam divergence and composition. This measurement is usually performed near the center of the neutralizer or beyond the magnet. In the past, these locations suffered difficult beam composition analysis and low light intensity, respectively. It has been determined that the light emission is relatively independent of neutralizer line density in the near field, allowing near-field measurements to overcome both difficulties. At optimum perveance, but under conditions of high gas throughput, the helium 1/e-divergence angle was measured to be 1.5° . Further investigation found that the divergence decreased with gas throughput down to 1.25° . Minimum divergences for the full-, half-, and third-energy hydrogen components were 1.1° , 1.2° , and 1.4° , respectively. Relative neutral hydrogen particle fluxes available for injection into TFTR are a function of perveance. At maximum perveance, the full-, half-, and third-energy atom fractions were 0.25 ± 0.04 , 0.5 ± 0.04 , and 0.25 ± 0.05 , respectively.

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INTRODUCTION

Ion temperatures in the Tokamak Fusion Test Reactor (TFTR) can be measured by charge exchange recombination spectroscopy.¹ A vital role in this measurement is played by the diagnostic neutral beam (DNB)² which provides the atoms with which the plasma ions charge exchange. Since central temperatures are of most interest, it is important to optimize beam operation for maximum plasma penetration. This requires operation at high voltage, with a large full-energy neutral constituency, and with minimal beam divergence. A previous effort to optimize DNB operation failed to quantify beam divergence due to the low light signal in the diagnostic target tank.³ Here, a line-of-sight in the neutralizer, 35 cm downstream of the accelerator, has remedied this problem. Similar spectroscopic measurements of beam composition on the TFTR heating beamlines,⁴ performed with lines-of-sight in the neutralizer, were hampered by cumbersome analysis that attempted to follow the evolution of all charged and neutral species and their conversion to excited neutrals. It can be shown that the beam composition measurement is simple if the line-of-sight is within a few mean free paths of the accelerator. It can be shown further that the measurement is insensitive to where in the neutralizer the line-of-sight is located.

Beam divergence has been measured for both hydrogen and helium beams. Minimizing divergence is important in maximizing both the transmission of the beam through the beamline and the on-axis particle flux in the tokamak. In addition, beam composition was determined for hydrogen operation.

I. EXPERIMENTAL APPARATUS

A 135 mm, $f/2$ camera lens was used to couple light from the beam into a 600 μm optical fiber.⁴ The beam was viewed in the neutralizer 34 cm downstream of the ion source with an included angle of 60° between the beam and the line-of-sight. The dispersive element in the system was a 60 cm ISA Czerny-Turner

spectrometer with an EG&G Princeton Applied Research Corp. (PARC) 1254E SIT vidicon as a detector.⁴ Light was integrated over the entire 300 ms beam pulse. Spectrometer wavelength was set to monitor the 6563 Å H α line for hydrogen operation or at 5876 Å (He I) for helium. Slit widths of 25 μ m and 10 μ m were used for hydrogen and helium, respectively.

II. ANALYSIS TECHNIQUE

Gas pressures, and hence available excitation target densities, are considerably higher in the neutralizer than at points downstream, resulting in greater signal to noise ratios when the measurement is performed in the neutralizer.⁵ Previous beam species computation in the neutralizer has been a tedious calculation taking into account the evolution of all charged and neutral species created in the neutralizer and the probability of conversion of each of these into an excited neutral. The computation is simplified when performed beyond the magnet after all charged particles have been removed and only full-, half-, and third-energy neutrals remain. Knowledge of the excitation cross sections for these three components is all that is necessary to determine the beam composition. Unfortunately the low background gas density yields low light intensity making the determination of beam divergence from line widths impossible.

Beam divergence, the 1/e angular half-width of a gaussian angular distribution, is computed from the widths of the Doppler-shifted lines:

$$\theta_{1/e} = \frac{\Delta\lambda_{1/e}}{\lambda_0} \frac{c}{v} \frac{1}{\sin \theta}.$$

$\Delta\lambda_{1/e}$ is the 1/e half-width of the Doppler-shifted line, λ_0 is the wavelength of the unshifted line, c is the speed of light, v is the velocity of the atom, and θ is the angle between the beam and the line-of-sight. In all cases, He⁰ and each of the three Doppler-shifted hydrogen lines (full-, half-, and third-energy H⁰), the 1/e

half-width of the gaussian line is computed as the quotient of the integral of the light intensity (after background subtraction) over the OMA channels encompassing the line and $\sqrt{\pi}$ times the peak intensity. For the half- and third-energy H^0 species, where there can be mutual contributions to the light intensity between the two lines, the areas were computed as twice the integral from the centroid out in the direction away from the companion half- or third-energy peak.

$\Delta\lambda_{1/e}$ is the rms difference between this 1/e line width and the spectrometer/detector instrument function. At the slit widths used, the instrument functions were approximately 20% of the measured line widths, providing reasonable accuracy for determination of divergence. Accuracy for the divergence measurement is governed by the computation of the line widths and is $\pm 25\%$.

Hydrogen beam composition is based upon the evolution of the extracted H^+ , H_2^+ , H_3^+ beam toward full-, half-, and third-energy H^0 and H^+ , and their probability of excitation into a Balmer- α emitting state,^{6,7} as it traverses the neutralizer. Figure 1 shows the anticipated Balmer- α emission from each of the H^+ , H_2^+ , and H_3^+ branches of a 60 kV hydrogen beam as it traverses the neutralizer. Emission changes little in comparison to the line density through which the beam passes. For the case at hand, the line density to the line-of-sight is approximately $0.2 \times 10^{16} \text{ cm}^{-2}$. The uncertainty in the computation of beam species is determined by the uncertainty in the neutralizer line density. This uncertainty, approximately a factor of two, stems from the fact that the gas temperature in the neutralizer is anomalously elevated and not well known.⁸ Due to the insensitivity of the measurement to neutralizer line density, error bars are reasonable, 10% to 20%, with some component to component variation.

III. RESULTS

Figure 2 shows the results of a helium beam perveance scan at a constant accelerating voltage of 50 kV. Minimum divergence of 1.5° occurs at a perveance of $0.6 \times 10^{-6} \text{ A/V}^{1.5}$. At low perveance the plasma is underdense and the plasma/beam boundary too concave, resulting in poor beam quality. At high perveance the plasma is overdense, tending toward a convex plasma/beam boundary, and beam quality is equally poor. At optimum perveance, the boundary is sufficiently concave to give the beam an initial focus to balance the expansion due to the beam's positive space charge.⁹ Historically this relationship between beam optics and perveance has been well described by a parabola as in Fig. 2.¹⁰

At the conclusion of this scan the voltage to the ion source gas valve driver was varied and the effect of gas throughput on the divergence determined. As the pressure in the ion source and neutralizer was decreased, the Doppler-shifted line width, and hence the divergence, decreased. See Fig. 3. At the lowest pressure at which the ion source plasma generator would operate reliably at this time, the divergence reached its lowest value of 1.25° .

Figure 4 shows the results of a hydrogen beam perveance scan at an accelerating voltage of 59 kV. Again the least square fit is parabolic. Divergences for each of the three hydrogen components were measured. Optimum perveance occurs at approximately $1 \times 10^{-6} \text{ A/V}^{1.5}$ regardless of component. Divergences of the full-, half-, and third-energy neutrals were 1.1° , 1.2° , and 1.4° , respectively. Based on Child-Langmuir law scaling it would be expected that the difference in perveance between helium and hydrogen would be between a factor of two ($\sqrt{4/1}$) and $1.15 (\sqrt{4/3})$. The actual ratio is 1.67, in agreement with a weighting based on the measured extracted ion fractions (50% H^+ , 35% H_2^+ , 15% H_3^+).

Figure 5 shows the results of the species measurement during the scan of Fig. 4. The calculation of beam composition yields the fractions of the extracted H^+ , H_2^+ , and H_3^+ . The atomic neutral fractions in Fig. 5 were inferred from the ion fractions assuming an equilibrium gas cell. Shown are the calculated injected

fractions of full-, half-, and third-energy neutrals as a function of beam current. These values are in good agreement with the earlier measurements.³

When this assessment was initiated, normal DNB 60 kV hydrogen beam operation was at 12.5 A, the lowest perveance run. This prior operation was based on measurements performed by the Lawrence Berkeley Laboratory (LBL) during their initial ion source qualification runs. Subsequent to the LBL qualification, the original field-free arc/filament plasma generator was replaced with an axial-cusp bucket with an internal rf antenna,² yielding greater reliability and plasma uniformity. By increasing the current to 14.5 A the divergence decreased by approximately 30%, the full-energy fraction of the beam increased by 25%, and the total beam current increased by 16%. The central beam power density deliverable to the center of the plasma was, therefore, increased by a factor of two. The improved plasma uniformity and freedom from density fluctuations, as a result of the rf plasma generator, is thought to be responsible for the improved divergence at the higher current.

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Figure Captions

Figure 1. The fractions of Balmer- α emission from a hydrogen beam as it propagates down a neutralizer.

Figure 2. Helium beam perveance scan at 50 kV. A parabolic least square fit is indicated.

Figure 3. Helium beam divergence as a function of the ion source gas valve driver voltage.

Figure 4. Hydrogen beam perveance scan at 59 kV showing the divergence of the full-, half-, and third-energy atoms. Parabolic least square fits are indicated.

Figure 5. Calculated full-, half-, and third-energy neutral fractions available to TFTR as a function of beam current.

FIG. 1

FIG. 2

FIG. 3

FIG. 4

FIG. 5