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ABSTRACT

The neutral beam systems of DIII-D, a National Fusion Facility at General Atomics, are used both for heating the plasma, and as tools for plasma diagnostics. The spatial distribution (profile) and energy of the beam is used in the absolute calibration of both the Charge Exchange Recombination (CER) and Motional Stark Effect (MSE) diagnostics. The CER diagnostic is used to make spatial and temporally resolved measurements of ion temperature and poloidal and toroidal rotational velocities. These measurements are made by visible spectroscopy of the Doppler shifted He II (468.6 nm), C VI (529.1 nm) and B V(494.5 nm) spectral lines, excited by the charge exchange recombination events between the plasma ions and the beam neutrals. As such, the spatial distribution of the beam is needed for an absolute calibration of the CER diagnostic. MSE diagnostic measures the internal poloidal field profile in the plasma. MSE measures the polarization angle of the Stark broadned neutral beam D_α emission due to the $\boldsymbol{v}_{\mathrm{beam}} \times \boldsymbol{B}$ motional electric field. Again, the spatial profile of the neutral beam is needed for the absolute calibration of the MSE diagnostic.

In the past, the beam spatial profile used in these calibrations was derived from beam divergence calculations and IR camera observations on the tokamak centerpost target tiles. Two experimental methods are now available to better determine the beam profile. In one method, the Doppler shifted D_α light from the energetic neutrals are measured, and the full-width at half-maximum (FWHM) of the beam can be inferred from the measured divergence of the D_α light intensity. The other method for determining the beam profile uses the temperature gradients measured by the thermocouples mounted on the calorimeter. A new iterative fitting routine for the measured thermocouple data has been developed to fit theoretical models on the dispersion of the beam. The results of both methods are compared, and used to provide a new experimental verification of the beam profile.

INTRODUCTION

The eight (8) neutral beam systems at the DIII–D tokamak are employed for both plasma heating, and plasma condition characterization. A cut away view of a neutral beam system is given in Fig. 1. Calculations of the spatial distribution of neutral beam deposition, ion temperature measurements, and measurements of toroidal and poloidal field profiles, all depend on knowing the spatial evolution of the neutral beam profile.
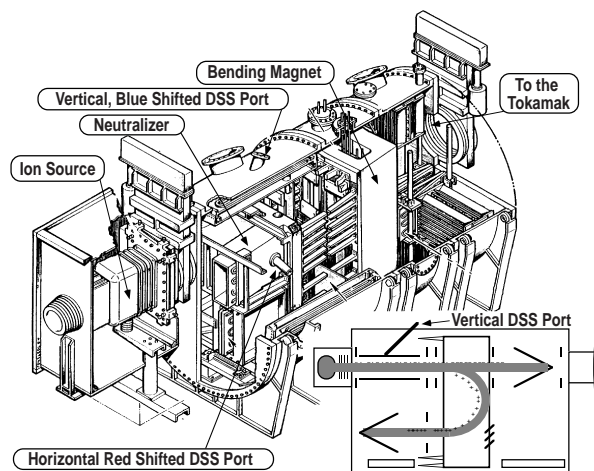

Fig. 1. Cut-away view of a neutral beamline.

At DIII–D, a neutral beam is formed by accelerating ionized deuterium to the desired energy (up to 80 kV), then neutralizing these ions in a gas filled neutralization cell. Accounting for losses, an 80 kV beam (at ~80 A) delivers ~ 2.5 MW to the plasma. The momentum of the energetic deuterium atoms and molecules carries them into the DIII–D tokamak vessel to interact with the plasma. The evolution of the beam's spatial distribution after the ions have passed through the accelerator grids is dependent on geometric dispersion. The spatial evolution of the beam can be predicted by knowing the physical dimensions of the system, and measuring the beam cross-section at some fixed position.

The geometric dispersion of the beam can be calculated since the distribution of beam particles in velocity space is Gaussian in nature. A sketch of the underlying mathematics for the dispersion calculation is presented. Two tools are available to measure the beam profile. The beam profile can be inferred from measuring its thermal footprint on the thermocouple array mounted on the beamline calorimeter, located 510 cm from the accelerator grids. The beam profile can also be devolved from the measurement of the Doppler shift of the D_α charge-exchange light in the beam neutralizer cell. The neutralizer cell is upstream of the calorimeter, and three collimators are situated between them. These collimators scrape-off the neutrals and ions that have strayed out of the beam path. Consequently, it is expected that the divergence angles reported by Doppler shifted spectroscopy be larger than those determined by fitting the thermal footprint on the beamline calorimeter. The entrance to the tokamak at 584 cm from the accelerator grids, is 74 cm from the calorimeter, and is connected to the calorimeter by the beamline drift-duct. The dimensions of the drift duct are sufficiently large, such that a well defined beam at the calorimeter will lose little to scrape-off in the drift duct. Hence, the measured divergence angle at the calorimeter is representative of the beam at the tokamak entrance.

Measurements of beam profile were made with each of these techniques in conjunction with a beam transmission calibration measurement. The beam profile for the 150° beamline right beam is reported here with respect to the beam optics observed.

THEORY

Assuming that a neutral beam is made up of a set of Gaussian point sources at the accelerator grid. Those point sources each have a bi-Gaussian angular distribution in the perpendicular and parallel directions to the beam accelerator grids. The governing expression for the intensity of a single point source is:

$$I = I_0\, e^{-(\alpha/\alpha_0)^2}\, e^{-(\beta/\beta_0)^2} \tag{1}$$

where α_0 and β_0 are the 1/e fold divergence angles parallel and perpendicular to the beam accelerator grids. The neutral beam sources at DIII–D each have four 12 cm × 12 cm source modules stacked in vertical array. The upper and lower modules are canted towards the centerline of the beam flight path. The tilt in the outer modules is given by: $\theta = \tan^{-1}(3Y_0/4F)$, Y_0 is the half-height of the source, and F is the focal length of the beams (F = 10 m). The resultant expression for a point source is:

$$I = I_0\, e^{-(\alpha/\alpha_0)^2}\left\{ 2\, e^{-(\beta/\beta_0)^2} + e^{-[(\beta-\theta)/\beta_0]^2} \right.$$
$$\left. + e^{-[(\beta+\theta)/\beta_0]^2} \right\} \tag{2}$$

For small angles, Eq. (2) can be transformed into spatial coordinates by substituting $\alpha \sim \tan\alpha = (x-x')/z$, $\beta \sim \tan\beta = (y-y')/z$, and $\theta = (3Y_0/4F)$. Figure 2 shows the geometry in the $y-z$ plane.
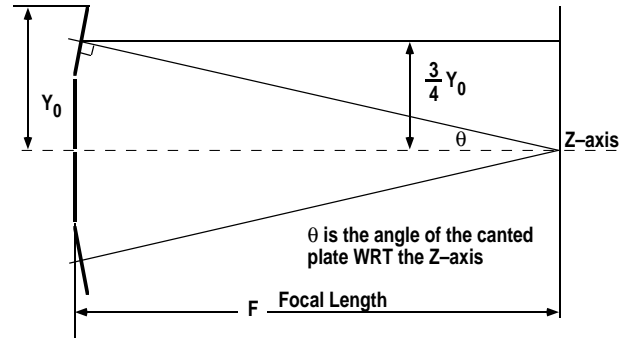

Fig. 2. Spatial relationships in the beamline.

Integrating expression (2) over both directions gives the governing expression for the spatial distribution of a neutral beam source:

$$\begin{aligned}
I(x,y,z) = &\, [I_t/(16X_0Y_0)] * [\mathrm{erf}\{(x+X_0)/a\} \\
&- \mathrm{erf}\{(x-X_0)/a\}] \\
&* [\mathrm{erf}\{(y+Y_0-d)/b\} \\
&- \mathrm{erf}\{(y+0.5Y_0-d)/b\} \\
&+ \mathrm{erf}\{(y+0.5Y_0)/b\} \\
&- \mathrm{erf}\{(y-0.5Y_0)/b\} \\
&+ \mathrm{erf}\{(y-0.5Y_0+d)/b\} \\
&- \mathrm{erf}\{(y-Y_0+d)/b\}]
\end{aligned} \tag{3}$$

where $\mathrm{erf}\{\}$ is the error function and $d = \theta z$. The divergence angles are found by finding the coordinates of the full width at half-maximum (FWHM) of the beam at a fixed axial distance, z. Expression (3) is used in curve fitting both the thermocouple data and the Doppler shifted spectroscopy (DSS) data.[1] A new C language algorithm, CALFIT, was written to curve fit the measured calorimeter thermocouple temperatures using Eq. (3).

The divergence angle can be measured by viewing the D_α light in the neutralizer cell in a direction transverse to the path of the beam. Figure 3 illustrates the relationship between the beam divergence angle α_0 and the Doppler shifted spectroscopy viewing angle ϕ. The divergence angle is related to the width of the fitted Gaussian by the relationship:
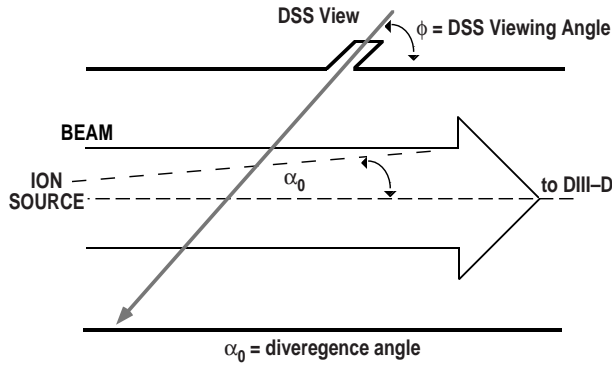
Fig. 3. Estimation of the divergence angle from DSS measurements.

$$\cos \alpha_0 = 1 - 2(u * w)^2 / E(1 - \cos^2 \phi) \tag{4}$$

where $u = (0.102$ Å/pixel$)/6.771$, E = energy of the beam particles, and w is the FWHM width of the peak.[2]

The expression for beam optics is the beam perveance, $p = I_{\text{beam}} / [V_{\text{beam}}]^{3/2}$, this expression is dependent beam current I_{beam}, and beam energy V_{beam}. There is for each beam system an optimum perveance for beam transmission. It is expected that a beam is best focused at the optimum perveance setting, and that its divergence angle should be at minimum.[3,4] The optimum perveance setting corresponds to the maximum transmission efficiency and power output for the beam

MEASUREMENT AND RESULTS

In conjunction with a series of measurements to quantify transmission on the 150° beamline right beam system, measurements for calorimeter temperature distribution and the Doppler shifted spectroscopy were made. The beam was held to a fixed accelerator voltage of 74.3 kV. The beam optics was varied from below optimum perveance (~2.70 μperv) to an above optimum perveance (~3.20 μperv) in ~0.05 μperv steps. Beam pulses were fired into the calorimeter at each perveance setting. Each beam pulse was of 1 s duration. The beam pulses were spaced at 10 min intervals to allow the calorimeter cooling circuit to remove the energy deposited by the previous pulse. During the pulse, the D_α charge exchange light in the neutralizer cell was recorded for beam species and vertical beam divergence characterization. At 2 s after beam turnoff, the calorimeter thermocouple temperatures were read for thermal footprint characterization.

The measured thermal foot print on the calorimeter is used by the program CALFIT to iteratively solve Eq. (3). CALFIT takes initial guesses for the values of α_0 and β_0, finding the best fit by using a chi-squared least squares fitting routine.[5] The fitted beam profiles in the

perpendicular direction for the 150° beamline right beam as a function of perveance and location on the calorimeter plane is presented in Fig. 4.
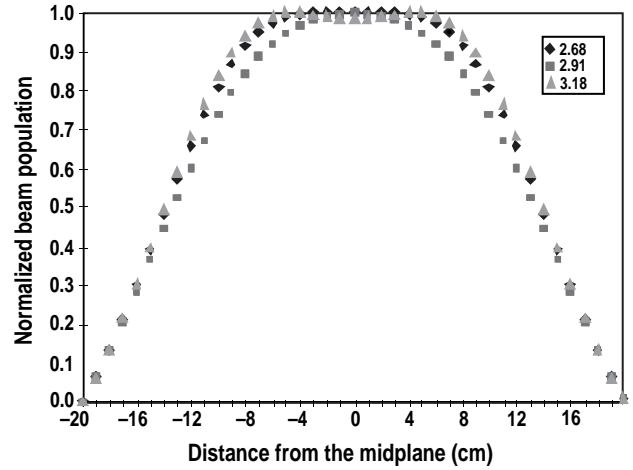

Fig. 4. Beam profile as a function of beam optics.

Figure 5 shows the 2.91 perveance calorimeter temperature data overlaid with the fitted beam temperature profile on the y-axis of the calorimeter. The fitted curve is derived from iterative fitting of the beam intensity integral (Eq. 3) to the measured temperature data from the calorimeter thermocouple array.
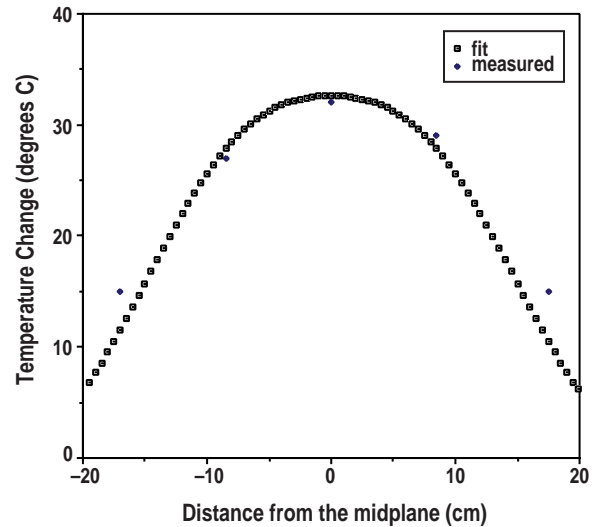

Fig. 5. Temperature distribution at the y-axis of the calorimeter.

A broad vertical profile is measured. On average, the vertical FWHM at the calorimeter is approximately 26 cm wide.

The divergence angle in the vertical direction is devolved from the Doppler shifted spectroscopy data, using

a software instrument created at General Atomics.[2] A comparison of the vertical divergence angle inferred from calorimeter temperature profile fitting and Doppler shifted D_α spectroscopy as a function of beam optics for the 150° beamline right beam is presented in Fig. 6.
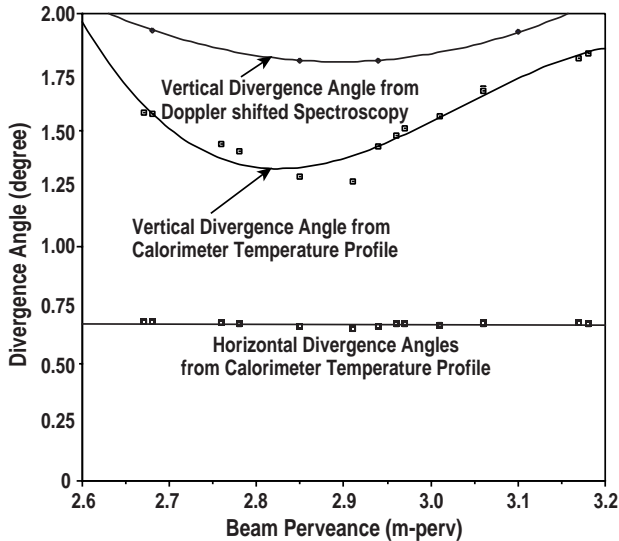

Fig. 6. Divergence angles as a function of beam optics.

The fitted data indicates that best optics setting for the 150° beamline right beam occurs between 2.85 μperv and 3.00 μperv. As expected, DSS measures higher values for the vertical divergence angle. The best vertical divergence angle from the calorimeter temperature profile fit is 1.30^o. The horizontal divergence angle from the calorimeter temperature profile is insensitive to beam perveance, and is typically $\sim 0.662^o$. The beam profile at best perveance for the 150° beamline right beam at the entrance to the tokamak is characterized by inserting these divergence angles into Eq. (3). The FWHM is ~26 cm in the vertical direction. Figure 7 presents the vertical beam profile at best optics at the entrance of the tokamak.
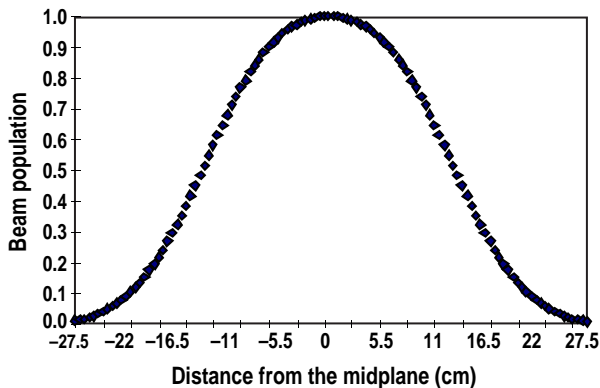

Fig. 7. Fitted beam profile at best optics at tokamak entrance.

SUMMARY

Measurements for curve fitting the profile of the 150° beamline right beam were made by curve fitting its thermal footprint on the beamline calorimeter, and observing its Doppler shifted D_α emissions. These independent measurements indicate general agreement for the vertical divergence angle. These measured values are in agreement with previous measurements for these values.[2,3] The beam profile at the entrance to the tokamak was calculated based on the measured divergence angles. These measurements contribute to the absolute calibration of several important plasma diagnostics.

ACKNOWLEDGMENTS

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