MEASUREMENT OF NEUTRAL BEAM PROFILES AT DIII-D

by
HENRY CHIU

AUGUST 1998

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

MASTER

AUGUST 1998
DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, make any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.
DISCLAIMER

Portions of this document may be illegible electronic image products. Images are produced from the best available original document.
MEASUREMENT OF NEUTRAL BEAM PROFILES AT DIII-D

by
HENRY CHIU

This is a preprint of a paper presented at the 13th Topical Meeting on the Technology of Fusion Energy, June 7–11, 1998, Nashville, Tennessee and to be printed in the Proceedings.

Work supported by
U.S. Department of Energy under
Contract No. DE-AC03-89ER51114

GENERAL ATOMICS PROJECT 3466
AUGUST 1998
MEASUREMENT OF NEUTRAL BEAM PROFILES AT DIII-D

Henry Chiu
General Atomics
P.O. Box 85608
San Diego, California 92186-5608
(619) 455-3169

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 broadened neutral beam Dα emission due to the $\mathbf{v}_{\text{beam}} \times \mathbf{B}$ 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 Dα 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 Dα 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 Dα 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:

\[ I = I_0 e^{-\left(\frac{\alpha}{\alpha_0}\right)^2} e^{-(\beta/\beta_0)^2} \]  

where \( \alpha_0 \) and \( \beta_0 \) 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 x 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 (\( F = 10 \text{ m} \)). The resultant expression for a point source is:

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

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

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

\[ I(x,y,z) = \left[ \frac{I_0}{(16X_0Y_0)} \right] \left[ \text{erf}\left(\frac{x + X_0}{a}\right) - \text{erf}\left(\frac{x - X_0}{a}\right) \right] \left[ \text{erf}\left(\frac{y + 0.5Y_0}{b}\right) + \text{erf}\left(\frac{y - 0.5Y_0}{b}\right) \right] \]  

where \( \text{erf} \{ \} \) 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. 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 Dα 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 \( \alpha_0 \) and the Doppler shifted spectroscopy viewing angle \( \phi \). The divergence angle is related to the width of the fitted Gaussian by the relationship:
Heifry Chiu

MEASUREMENT OF NEUTRAL BEAM PROFILES AT DIII-D

Fig. 3. Estimation of the divergence angle from DSS measurements.

\[
\cos \alpha_0 = 1 - 2(u * w)^2 / E(1 - \cos^2 \phi)
\]  

(4)

where \( u = (0.102 \, \text{Å/pixel})/6.771 \), \( E \) = energy of the beam particles, and \( w \) is the FWHM width of the peak.\(^2\)

The expression for beam optics is the beam pervance, \( p = I_{\text{beam}} / V_{\text{beam}}^{3/2} \), this expression is dependent beam current \( I_{\text{beam}} \), and beam energy \( V_{\text{beam}} \). There is for each beam system an optimum pervance for beam transmission. It is expected that a beam is best focused at the optimum pervance setting, and that its divergence angle should be at minimum.\(^3\)\(^,\)\(^4\) The optimum pervance 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 pervance (~2.70 μperv) to an above optimum pervance (~3.20 μperv) in ~0.05 μperv steps. Beam pulses were fired into the calorimeter at each pervance 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 \( \text{D}_\alpha \) 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 footprint on the calorimeter is used by the program CALFIT to iteratively solve Eq. (3). CALFIT takes initial guesses for the values of \( \alpha_0 \) and \( \beta_0 \), 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 pervance 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 pervance 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.\textsuperscript{2} A comparison of the vertical divergence angle inferred from calorimeter temperature profile fitting and Doppler shifted D\textscript{\alpha} spectroscopy as a function of beam optics for the 150\textdegree beamline right beam is presented in Fig. 6.

The fitted data indicates that best optics setting for the 150\textdegree beamline right beam occurs between 2.85 m-perv and 3.00 m-perv. 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\textdegree. The horizontal divergence angle from the calorimeter temperature profile is insensitive to beam perveance, and is typically -0.662\textdegree. The beam profile at best perveance for the 150\textdegree 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.

ACKNOWLEDGMENTS

I would like to express my gratitude to Mr. J. Phillips for his help with the diagrams, setting read times on the calorimeter thermocouple array, and help in C-code compiling in the ACCESSWARE environment. Much gratitude is extended to the neutral beam operating staff at DIII-D, in particular Ms. B. Scoville and Mr. M. Madruga. Finally, I like to thank Dr. R. M. Hong for his suggestions and encouragement.

This is a report of work supported by the U.S. Department of Energy under Contract No. DE-AC03-89ER51114.

REFERENCES