GA-A22183
CONF-9509238--4

**PLASMA ROTATION AND
THE RADIAL ELECTRIC FIELD
DURING OFF-AXIS NBI
IN THE DIII-D TOKAMAK**

RECEIVED
JAN 30 1996
STI

by

P. GOHIL, K.H. BURRELL, A.B. HASSAM,
and T.H. OSBORNE

DECEMBER 1995

MASTER

GENERAL ATOMICS

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED
ble

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, makes 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.

PLASMA ROTATION AND THE RADIAL ELECTRIC FIELD DURING OFF-AXIS NBI IN THE DIII-D TOKAMAK

by

P. GOHIL, K.H. BURRELL, A.B. HASSAM,*
and T.H. OSBORNE

This is a preprint of a paper presented at the Fifth
Workshop on H-Mode Physics, September 18-20,
1995, Princeton, New Jersey, and to be printed in
the *Proceedings*.

Work supported by
U.S. Department of Energy
Contract DE-AC03-89ER51114

*University of Maryland

GENERAL ATOMICS PROJECT 3466
DECEMBER 1995

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED
dlc

Plasma rotation and the radial electric field during off-axis NBI in the DIII-D tokamak

P Gohil†, K H Burrell†, A B Hassam‡ and T H Osborne†

† General Atomics, San Diego, California, USA

‡ University of Maryland, College Park, Maryland, USA

Abstract. Experiments have been carried out on the DIII-D tokamak to investigate whether off-axis NBI can: (a) drive significant perpendicular flow to lead to increased suppression of turbulence and improved confinement, and (b) be used to control the radial electric field profile. Measurements of both impurity ion poloidal and toroidal rotation profiles were made using charge exchange recombination spectroscopy. These experiments used a low current, low elongation ($I_p = 0.5$ MA, $\kappa = 1.2$) plasma whose magnetic axis was shifted 36 cm vertically upward from the vessel midplane and then shifted downward to be centered on the midplane later in the discharge. 10.7 MW of beam power was applied to maximize NBI effect whilst operating at low target densities and high temperature to minimize poloidal damping. Results from these experiments show a slight increase in impurity ion poloidal rotation velocity during the vertical shifted phase of off-axis NBI discharge. The toroidal rotation profile is more peaked during off-axis NBI. Both these effects lead to a change in the $V \times B$ contribution to the radial electric field during off-axis NBI.

Keywords. Fusion; tokamak; confinement; H-mode; DIII-D

Introduction

Stabilization of plasma turbulence by a sufficiently large radial derivative of the $E \times B$ plasma flow and the resulting improvement in confinement has been used to explain the L-H transition [1-3]. Further improvement in confinement in the VH-mode is associated with increased shear in the radial electric field E_r toward the plasma core [4]. The ability to control E_r and its derivatives across the plasma minor radius would significantly enhance efforts toward achieving even greater improvements in confinement. Theoretical studies have shown that imposition of a sheared plasma flow can suppress or stabilize plasma microturbulence [5,6]. Linear stability theory predicts that perpendicular flow beyond a critical flow shear v'_c can stabilize several tokamak microinstabilities for all wavenumbers [7,8]. Here $v'_c = C_s/L_s$, where C_s is the sound speed and L_s is the scale length of the magnetic shear [7]. Since the diamagnetic flow is small in the plasma core, the perpendicular flow is nearly identical to E_r/B . The perpendicular flow (and correspondingly, E_r) is dependent on both the poloidal plasma flow v_θ and toroidal flow v_ϕ . Shear in toroidal rotation leads to shear in E_r/B . Assuming momentum transport is diffusive, then the v_ϕ profile should be affected by off-axis NBI thereby modifying the shear in E_r/B . Poloidal rotation however, produces more perpendicular flow than toroidal rotation by a factor B_ϕ/B_θ where B_ϕ and B_θ are the toroidal and poloidal magnetic fields, respectively. Furthermore, since poloidal momentum is strongly damped by viscosity rather than diffusively, the poloidal rotation is more localized in the region of the beam deposition and so can produce more flow shear. However, since the poloidal momentum damping by viscosity is significantly stronger than the toroidal momentum damping greater effort must be made to both sustain the poloidal momentum drive and to carry out the measurement of the poloidal rotation. This paper describes experiments to determine whether off-axis NBI can be used to drive significant perpendicular plasma rotation and control the radial electric field.

Experimental Results

Experimental conditions were optimized for driving poloidal rotation with off-axis NBI, and

and for attaining the critical velocity shear v_c' . That is, to reduce poloidal damping, increase the factor B_ϕ/B_θ , and obtain the best tangency of the beam centerline to the magnetic flux surfaces of the vertically shifted plasma. Since poloidal damping is strongly viscous, damping is reduced by operating at low target electron densities and high plasma temperatures. In order to obtain good off-axis NBI, the magnetic axis of the plasma was vertically shifted 36 cm upward from the horizontal axes of the neutral beams, which are located along the horizontal midplane of the DIII-D vacuum vessel as shown in figure 1(a). The diverted deuterium plasmas were operated at a plasma current $I_p = 0.5$ MA, toroidal magnetic field $B_T = 2.1$ T, major radius $R = 1.78$ m, minor radius $a = 0.58$ m, elongation $\kappa = 1.2$, plasma volume $V_p = 13$ m³, and Ohmic target densities $\bar{n}_e = 1.0 \times 10^{19}$ m⁻³. Total deuterium neutral beam power was 10.7 MW for these experiments with the neutral beam cross-section being 0.30×0.10 m (FWHM) for the height and width, respectively. Neutral beams were injected into the lower part of the plasma for up to one second after which point the magnetic axis of the plasma was vertically displaced downward quickly (within 50 ms) to the central on-axis NBI position [see figure 1(b)] so that measurements could be made by diagnostic systems imaging along the vessel midplane. Reference plasma discharges were obtained with the applied NBI centered on the magnetic axis of the plasma throughout the discharge which was similar to figure 1(b). These plasmas were operated with the neutral beams continuously centered on the magnetic axis throughout the shot with no vertical plasma motion. Plasma shape and position were monitored throughout the discharges with results from an magnetohydrodynamic (MHD) equilibrium code EFIT [9], using data from numerous magnetic probes around the vessel incorporated with results from the motional Stark effect (MSE) diagnostic system [10].

Charge exchange recombination (CER) spectroscopy was used for measurements of impurity ion toroidal and poloidal rotation profiles as well as ion temperature profiles [11]. Since CER measurements are made along the axes of the neutral beams, plasma rotation measurements were made both off- and on-axis during the displaced and centered plasma positions, respectively, in the same discharge. These measurements were then compared with CER results from the purely on-axis NBI discharge. The CER chords used comprised typically seven tangential chords and six vertical chords. Measurements were made on the C VI spectral line at 5290.5 Å. The temporal resolution for these measurements was 2 ms. The best spatial resolution of 1 to 2 cm for the central CER chords was obtained with unshifted plasma. The spatial resolution degraded for measurements on vertically shifted plasma, more so for vertically viewing chords since they sampled a larger range of magnetic flux surfaces within the vertical dimension of the neutral beam.

Figures 2(a) and 2(b) show toroidal rotation profiles for the on-axis and off-axis NBI cases, respectively. Solid curves are spline fits to data points for various times in figure 2(a) and for the 3050 time in figure 2(b). Toroidal rotation profiles with on-axis NBI are broad particularly because of the small dimensions of the plasma relative to beam dimensions in comparison to normal DIII-D discharges. The toroidal rotation profile with off-axis NBI, however, is more peaked despite the peak of the neutral beam deposition profile being at $\rho = 0.4$. Data points in figure 2(b) move closer to the plasma core with increasing time as plasma is shifted downward to its central position [see figure 1(b)]. Slowing down times for beam ions was about 90 ms for the primary beam species as determined by a 1-1/2 D transport code, ONETWO [12]. Consequently, since the vertical shift of the plasma was completed in about 50 ms together with the number of beams being reduced from five to two beams, the effect of the beams on the plasma is substantially reduced during this phase. Also, profiles of electron density, electron temperature, and ion temperature did not change during the dynamic shift of the plasma.

Figure 3 shows the C VI poloidal rotation profiles for the on-axis NBI and off-axis NBI cases, respectively. There is a slight increase in poloidal rotation during off-axis NBI compared to the on-axis case for $\rho > 0.4$. This difference is only observed during the shifted plasma and by 3050 ms the poloidal rotation profiles are similar. Therefore, viscous damping of poloidal rotation is substantial over a timescale of 50 ms. There is a change in the $V \times B$ contribution to the radial electric field between on-axis NBI and off-axis NBI cases as can be seen in figure 4. The $E_{V \times B}$ component is broad with on-axis NBI as a result of the strong contribution of the toroidal rotation profiles. However, the off-axis NBI case has a much more peaked profile as a result of more peaked toroidal rotation profiles and greater influence of the poloidal rotation. Therefore, it is possible to affect the radial electric field profile with off-axis NBI. The estimated value of v_c'

(to within a factor of 3) for these conditions is $4 \times 10^5 \text{ s}^{-1}$. The experimentally determined value of v' from figure 4(b) is lower at $9 \times 10^4 \text{ s}^{-1}$ at $\rho = 0.6$ at 3000 ms. Results from the far infra-red (FIR) scattering diagnostic [13] indicate broadband turbulence averaged over the plasma core and edge is slightly reduced (less than a factor of 2) during off-axis NBI when measured after the discharge is moved to its on-axis position relative to turbulence observed on the purely on-axis NBI discharge. No large improvement in global thermal energy confinement times was observed as the times were 40 and 37 ms for off-axis and on-axis cases, respectively.

In conclusion, changes in C VI toroidal rotation and poloidal rotation profiles and $V \times B$ contribution to the radial electric field have been observed during off-axis NBI discharges compared to on-axis NBI discharges. Slight changes in broadband turbulence were observed. However, the level of poloidal momentum drive is not sufficient to lead to a significant increase in confinement time. Future experiments will need to impart greater poloidal torque and further reduce the large viscous poloidal damping as well as requiring more definitive plasma rotation measurements by making very fast (in less than 50 ms) dynamic shifts of the plasma.

Acknowledgments

This is a report of work sponsored by the U.S. Department of Energy under Contract No. DE-AC03-89ER51114 and Grant No. NDE-FG05-86ER5.

References

- [1] Burrell K H 1992 *Plasma Phys. and Contr. Fusion* **34** 1803
- [2] Groebner R J et al. 1993 *Phys. Fluids B* **5** 2343
- [3] Gohil P et al. 1994 *Nucl. Fusion* **34** 1057
- [4] Osborne T H et al. 1995 *Nucl. Fusion* **35** 23
- [5] Biglari H et al. 1990 *Phys. Fluids B* **2** 1
- [6] Zhang Y Z and Mahajan S M 1992 *Phys. Fluids B* **4** 1385
- [7] Hassam A B 1991 *Comments Plasma Phys. and Contr. Fusion* **14** 275
- [8] Hassam A B et al. 1993 *Phys. Fluids B* **5** 2519
- [9] Lao L L et al. 1990 *Nucl. Fusion* **30** 1035
- [10] Rice B W et al. 1995 *Rev. Sci. Instrum.* **66** 373
- [11] Gohil P et al. 1992 *Fusion Engineering* **2** 1199
- [12] Pfeiffer W W et al. 1985 *Nucl. Fusion* **25** 655
- [13] Rettig C L et al. 1993 *Nucl. Fusion* **33** 643

Figure 1. Shape and positions of plasma during off-axis NBI (a) at 3000 ms and (b) at centered position after downward shift of plasma at 3050 ms. Also shown is the region of predominant NBI.

Figure 2. C VI toroidal rotation profiles for NBI discharges: (a) on-axis, (b) off-axis. The beams come on at 2000 ms for both cases. Times in (b) are before, during, and after downward shift of plasma to the central position shown in figure 1(b).

Figure 3. C VI poloidal rotation profiles for NBI discharges: (a) on-axis, (b) off-axis. The positive rotation corresponds to rotation in the ion diamagnetic drift direction.

Figure 4. $V \times B$ contribution to radial electric field for NBI cases: (a) on-axis, (b) off-axis.

GENERAL ATOMICS

P. O. BOX 85608 SAN DIEGO, CA 92186-9784 (619) 455-3000