# Reduction in Neutral Beam Driven Current in a Tokamak by Tearing Modes

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(Received 11 February 1997)

Profiles of noninductive current driven by neutral beam injection into a tokamak have been measured and compared with theory. The driven current can be less than the theoretical prediction (by up to 80%) in the presence of islands driven by tearing modes. [S0031-9007(97)03551-5]

PACS numbers: 52.55.Fa, 52.50.Gj

Neutral beams are used on a number of tokamaks to heat the plasma and drive current [1–4]. High energy (typically 75 to 140 keV) neutral atoms are able to penetrate across the confining magnetic field of the tokamak and into the dense core of the plasma, at which point they become ionized and confined by the magnetic field of the tokamak. If the neutral beams are injected with a preferential direction relative to the magnetic field, an electrical current can result as the fast ions thermalize. This offers the possibility of generating the currents required to create and sustain the magnetic configuration of the tokamak by use of neutral beam current drive (NBCD). Increasing the plasma current using NBCD (ramp-up) would be a very useful demonstration for the engineering of a low-aspect-ratio tokamak, where the elimination of the conventional solenoid used to drive the current inductively would greatly simplify the design. Unfortunately, ramp-up has not been observed, in spite of the theoretical estimates which indicate it should be feasible. Understanding NBCD under ramp-up conditions requires understanding the fast ion dynamics at low plasma current and high neutral beam power.

The standard techniques for the study of fast-ion dynamics rely upon measurements of escaping neutral particles or fusion products (see review in Ref. [5]). For example, with deuterium injection the neutron emission is often dominated by fast ions fusing with each other and with the background thermal ions. The behavior of this signal is then sensitive to the deposition, slowing down rate, and confinement of the injected beam ions. The measured deposition profiles and thermalization rates agree (to within 20%) with classical predictions [5]. The confinement of beam ions is scarcely affected by short wavelength microturbulence [6], and diffusion coefficients of $<0.1\ \mathrm{m}^2/\mathrm{sec}$ are observed [5,7] in plasmas without long-wavelength magnetic field perturbations. In contrast, rapid beam-ion transport is observed in plasmas with large toroidal-field ripple [5,8] or magnetohydrodynamic (MHD) instabilities [5].

A previously unobserved, but equally useful, quantity for characterizing the fast ion distribution function in the presence of neutral beam injection is the profile of noninductive current. Although several experiments have clearly established the existence of beam-driven currents [1–4] there are no reported measurements comparing profiles of neutral beam-driven currents to those predicted by theory—due to the lack of reliable current profile measurements until now. (The earlier studies [1–4] compared external measurements of the loop voltage with expected values, but the predicted voltage is insensitive to spatial transport of the beam ions [8].) In this Letter, we present the first detailed measurement of the NBCD profile over a variety of conditions in a large tokamak. In addition, we report the first observation of the reduction in NBCD efficiency associated with islands near rational $q$ surfaces caused by tearing modes, establishing that measurements of the noninductive current give a new technique for diagnosing the behavior of fast ions. This reduction of NBCD efficiency has important ramifications for experiments which hope to ramp-up and sustain the plasma current noninductively using NBCD.

The experiments in this paper have been performed in the DIII-D tokamak and were designed to test the feasibility of plasma current ramp-up using NBCD and bootstrap current. Specifically, the ratio of inductive to noninductive current was systematically varied by programming the loop voltage $V_\Omega$, i.e., the toroidal $EMF$, and the normalized beta $\beta_N = \beta/(I/aB) = (2\mu_0\langle p\rangle a)/BI$ where $\beta = (2\mu_0\langle p\rangle)/B^2$ is the ratio of the volume-averaged plasma pressure to the magnetic field pressure, $B$ is the magnetic field strength, $a$ is the minor radius of the plasma, and $I$ is the total current in the plasma in MA. This method differs from the usual programming of the total plasma current in which the loop voltage is allowed to vary so as to maintain a preprogrammed plasma current.

These two parameters, $\beta_N$ and $V_\Omega$, were chosen for the following reasons. First, the quantity of inductive current varies monotonically with $V_\Omega$ at fixed $\beta_N$, and the behavior of the plasma in the limit of $V_\Omega \rightarrow 0$ can be studied to find the characteristics of ramp-up.

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Second, $\beta_N$ empirically has been shown to govern MHD stability [9], and therefore it represents a limit on the amount of auxiliary power which can be applied for the purpose of driving current. The total bootstrap current is also directly proportional to $\beta_N$: $I_{\rm bs} \propto \beta_N B$, where profile and geometry effects have been ignored. For typical thermal energy confinement times which scale as $\tau \propto H[I/P^{1/2}]$ (where $H$ is a numerical factor of $\mathcal{O}(1)$ representing variability in the quality of confinement and $P$ is the auxiliary power for heating and current drive), the $\beta_N$ limit also limits the amount of power available for driving current to values $P < P_{\rm max} \propto [(\beta_{N,\rm max}B)/H]^2$. The driven current is $I_{\rm NBCD} \propto \eta(\beta_N B/H)^2$, where $\eta$ is an efficiency which can depend upon plasma parameters. The total amount of noninductive current is maximized at the highest $\beta_N$ possible without loss of confinement.

The data used in this Letter are from 20 discharges, representing a scan of $\beta_N$ from 1.2 to 2.2 and $V_\Omega$ from 0 to 200 mV (resulting in total plasma current from 0.2 to 1.0 MA and injected power from 2 to 15 MW). Typical time histories are shown in Fig. 1. In all cases, the discharges were initiated using conventional current programming to form a target plasma with a current of 500 kA; at 1.2 sec the switch to loop voltage control was implemented. In addition, $\beta_N$ control was also implemented at 1.2 sec by controlling the duty cycle of the neutral beams to keep a real-time estimate of $\beta_N$ constant. The dischanges then resistively relax over 4 sec. All discharges are $H$-mode, have a natural $H$-mode density proportional to plasma current (3 to 6 $\times$ $10^{19}$ m$^{-3}$), have an elongation of 2.0, a triangularity of 0.6, and a toroidal field of 2.0 T. Near tangential (tangency radii $R_{\rm tan}$ = 0.76 and 1.10 m), ~75 keV deuterium neutrals are injected in the direction of the plasma current.

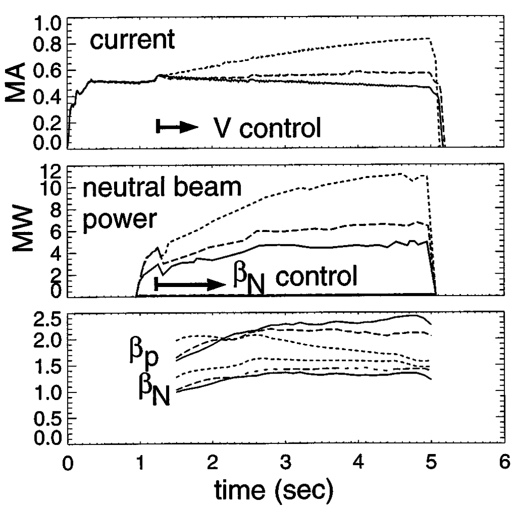


FIG. 1. Time histories of plasma current, neutral beam power, $\beta_N$, and $\beta_p$ for representative discharges with $\beta_N = 1.4 \pm 0.1$ and $V_\Omega = 50$ (solid), 100 (dashed), and 20 mV (dotted). Feedback control of $\beta_N$ control was implemented by modulating the duty cycle of the neutral beams.

The noninductive current profiles have been measured during three times intervals (1.5 to 2.5 sec, 2.5 to 3.5 sec, 3.5 to 4.5 sec) for each shot in this study. Magnetic reconstructions of the MHD equilibria are found using the code EFIT, constrained by 16 internal measurements of the poloidal field radial profile by motional Stark effect spectroscopy and by external magnetic probes [10,11]. For each time interval the loop voltage profile is calculated from time derivatives of the poloidal flux, and a time-averaged current density profile is calculated [12]. The long duration of each time interval greatly improves the accuracy of the calculation of the internal loop voltage (typically $\pm$20 mV locally). Measurements of the electron density, electron temperature, and carbon density profile are then used to calculate the neoclassical conductivity which, when combined with the loop voltage profile, determine the inductive fraction of the current density.

The theoretical predictions of the neutral beam current drive are made using the measured profiles. These same models are also used to estimate the neutron yield for comparison with theory. Several models for computing the fast ion distribution function have been used for comparison. These include the Monte-Carlo calculation of the fast ion current implemented in the TRANSP transport code [13], an asymptotic solution of the fast ion distribution function as implemented in ONETWO transport code [14,15], and the full solution for ion distribution function determined by the bounce averaged Fokker-Planck equation as implemented in the code CQL3D [16]. A comparison between the experiment and theory is shown in Fig. 2, for a case with no measurable MHD activity. The technique used to determine the experimental noninductive current is not able to distinguish between different types of noninductive current, thus the theoretical curves include both neutral beam and bootstrap currents. Note

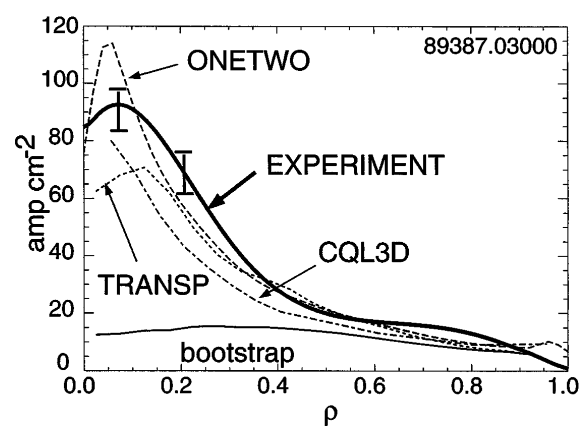


FIG. 2. The profile of measured noninductive current profile compared to various theoretical models of neutral beams current drive. The noninductive current is the combination of neutral beam driven and bootstrap driven currents; the theoretical estimate of the bootstrap portion is shown for reference.

that for $\rho < 0.3$, the main contribution to the noninductive current comes from neutral beams.

When $\beta_N$ is increased and magnetic fluctuations are observed the measured current drive can be considerably less than predicted by theory. Figure 3(a) shows a profile of the measured noninductive current profile and the theoretical predictions, illustrating that the discrepancy is over the entire profile.

Analysis of the MHD activity indicates that the fluctuations are due to magnetic islands in a rotating plasma. Using a newly installed heterodyne radiometer to measure temperature fluctuations inside the plasma, these low frequency (<50 kHz), coherent modes are found to be localized near rational $q$ surfaces as shown in Figs. 3(b) and 3(c). Charge exchange recombination spectroscopy measurements of the plasma rotation indicate that the modes are rotating at approximately the plasma rotation speed. Arrays of magnetic probes indicate that the mode numbers can vary, typically $m/n = 3/2$, $2/1$, or $5/2$, where $m$ is the poloidal mode number and $n$ is the toroidal mode number. The amplitude and phase profiles of the temperature fluctuations due to these structures are clearly indicative of magnetic islands. These plasmas show no high frequency activity characteristic of Alfvén eigenmodes.

The tearing activity limited the range of plasma pressure which could be reached. Transiently, $\beta_N$ could exceed four for discharges formed in this way; however, the steady-state $\beta_N$ limit caused by the tearing (for durations >1 sec) was less than 1.7. The tearing modes appear to be destabilized by the neoclassical bootstrap current effect in an otherwise conventionally stable plasma. Stability is estimated by an analytic formula (applied equilibrium reconstructions) which uses the true noncircular, finite aspect-ratio geometry [17]. These high $q_{95}$ ($> 8$) discharges are found to be conventionally stable for all resonant low $m$ and $n$ modes. Neoclassical helical bootstrap currents, in response to seed islands, can overcome the stability and reinforce the seeds if large enough, particularly at high $\beta_p$ as considered here [18]. The low density and high electron temperature ($\sim 2.5$ kV) used to optimize noninductive current drive reduces the collisionality, allowing the neoclassical destabilization to be more effective [19].

The disagreement between the experimental and calculated beam driven current density when tearing modes are present is due to the loss of fast ions rather than enhanced transport of current in the plasma. To study the current transport, as with particle and energy transport, one usually assumes that either the source or the transport coefficient is known and the other term can be evaluated from a flux-force relationship. Figures 2 and 3 are derived from the assumption that current diffusion (plasma conductivity) is known, while the sources (noninductive currents) are not. This is opposite to the usual approach taken for energy transport studies in which the sources are assumed known and the transport coefficients are determined. An equally plausible argument could have been made for an enhanced plasma resistivity due to tearing activity to explain the discrepancy. For this reason, an independent check has been made comparing the measured neutron signals with the predictions from the fast ion models. Figure 4 shows that neutrons are missing when the current drive is missing, independently validating the assumption of a missing source of fast ions.

A likely explanation for the radial transportation of the beam ions is that the tearing modes cause orbit stochasticity. Theoretically, magnetic perturbations can

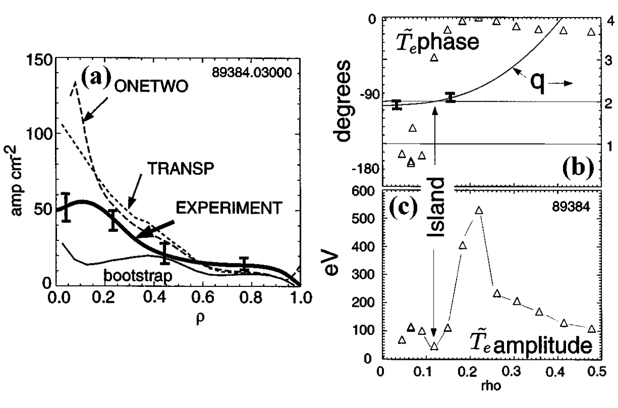


FIG. 3. (a) The same as Fig. 2, but for a case with a tearing mode at 22 kHz. Magnetics indicates that the mode is $m/n = 2/1$ and is stationary in the rest frame of the rotating plasma. (b) The phase of the perturbation indicates an inversion at $\rho = 0.12$ corresponding to $q = 2$. (c) The amplitude of coherent perturbation of the electrons temperature from the tearing mode. Note that the maximum perturbation is near the outer edge of the island as expected.

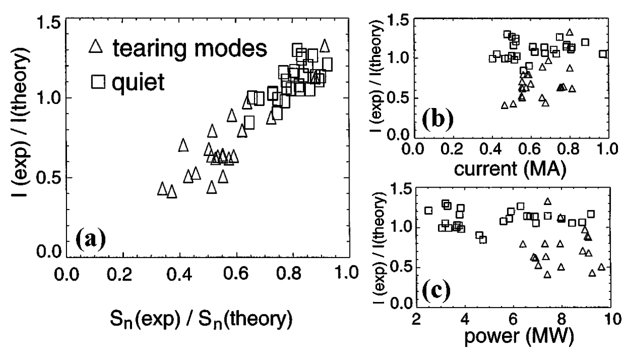


FIG. 4. Driven current discrepancy versus (a) neutron discrepancy, (b) plasma current, (c) neutral beam power. $I_{\rm exp}$ is the integral of noninductive current measured inside $\rho > 0.35$, and $I_{\rm theory}$ is the same quantity predicted by the transport code ONETWO. $S_n(\exp)/S_n(\text{theory})$ is the ratio of the total measured neutron rate to the predicted neutron rate using the same fast ion model as for the current drive estimation. Each data point represents a 1 sec long average of the experiment and a 1 sec transport simulation. △ represents tearing fluctuations observed on external Mirnov coils; □, no measurable fluctuations on external Mirnov coils (small signals may be seen on ECE).

beat with harmonics of the orbital motion, producing chains of secondary islands in phase space [20,21]. If the width of the magnetic island and the width of the harmonic island exceed the distance between rational surfaces, orbit stochasticity ensues. For the conditions of Fig. 3, the large beam-ion gyroradius makes the harmonic island width relatively large ($\delta\rho \simeq 0.06$), the magnetic island is large ($\delta\rho \simeq 0.10$), and the strong shear in these low-current plasmas makes the distance between rotational surfaces relatively small ($\delta\rho \simeq 0.14$), so the overlap condition [Eq. (11) of Ref. [21]] is satisfied. Thus, rapid transport of circulating beam ions is expected.

The results in this paper illustrate how difficult ramp-up will be for sources with current drive efficiencies similar to NBCD as implemented on DIII-D. This demonstration is complicated by the intricate coupling of current drive efficiency, confinement, and MHD stability: The quality of confinement and MHD stability limit the amount of power which can be injected into the tokamak to drive current. A possible ramp-up scenario is to form a discharge noninductively [22] and then to increase the current drive power until the discharge is near, but not above the $\beta$ limit. If the noninductive current exceeds the plasma current at this power level, then the plasma current will increase. Since this ramp-up scenario implicitly requires high $\beta_p$, it appears that they are always susceptible to neoclassical tearing modes driven by bootstrap currents and thus have relatively low steady-state $\beta$ limits. The tearing modes not only impose a relatively low $\beta$ limit, but also reduce the efficiency of current drive by reducing the fast ion confinement. This loss of NBCD due to fast particle losses is a more serious limit on ramp-up than the thermal confinement scaling arguments outlined in Politzer [23].

Several possibilities exist for improving upon the experiment presented in this Letter and making ramp-up feasible. First, the efficiency of current drive could be increased. Increasing the current drive efficiency by decreasing the density and increasing the electron temperature may have the deleterious side effect of further decreasing the stability against island formation due to the decrease in collisionality. Second, a reduction in plasma energy confinement relative to $H$-mode confinement would allow more power to be injected for driving current before reaching the $\beta$ limit. And finally, the $\beta$ limit for tearing modes could be improved by carefully tailoring the current and pressure profiles during ramp-up.

This is a report of work sponsored by the U.S. Department of Energy under Contracts No. DE-AC03-89ER51114, No. DE-AC05-96OR22464, and Grant No. DE-FG02-92ER54139.

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