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# Prompt, Collisionless Toroidal Momentum Balance With Short Neutral Beam Pulses in DIII-D

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**Abstract.** In electron cyclotron heated (ECH) H-mode discharges with neutral beam injection (NBI) pulses short compared with the fast ion scattering or slowing times, or the momentum confinement time, it is observed that the plasma stores all the angular momentum delivered by the NBI torque impulse. Source computations with the Monte Carlo code TRANSP show that approximately 90% of this torque impulse is delivered via the collisionless fast radial current injection process during a pulse, so that the plasma acquires the balancing toroidal acceleration through ion electric field drift motion. The measured radial profile of the toroidal momentum increase matches the source, the computed torque impulse profile. We measure the bulk ion toroidal acceleration in helium discharges, as well as that of the primary impurity, carbon. These two species show a common acceleration, consistent with an incremental velocity due to electric drift motion. On this timescale the plasma responds as a dielectric. The acceleration measurements are consistent with the neoclassical value of the dielectic constant, as computed from measured quantities.

## I. Introduction

We report experimental measurements of the balance between the increase in toroidal mechanical momentum and the torque impulse from short neutral beam injection (NBI) pulses, called “blips”, in DIII-D. The blip timescale is short compared with the collision time of the fast ions injected by NBI, so it is a collisionless process for momentum injection. We use the TRANSP code [1] to compute the NBI source profiles of particles, torque, and energy, using 5,000 particles. No significant change is found when doubling the particle number. The TRANSP results show that in the time of a 10 ms NBI blip about 90% of this torque impulse is delivered by the so-called $\vec{J}_{\rm fast} \times \vec{B}$ effect [2]. This $\vec{J}_{\rm fast}$ is the radial fast ion current due to the separation of the newly ionized NBI ion from the accompanying electron, averaged in time over the first poloidal orbital transit.

The measurements are made in ECH generated H-mode discharges which have small sawteeth and small edge localized modes (ELMs). The bulk ion is helium, so that charge exchange recombination spectroscopy (CER) [3] is used to measure the bulk ion velocity and hence the plasma momentum when coupled with a measured density profile. Pairs of identical discharges are taken to measure both the $He^{++}$ velocity, $\vec{V}_{\rm He}$, and that of the primary impurity, $C^{6+}$, $\vec{V}_{\rm C}$.

The discharge parameters are: $a/R$ = 0.60 m/1.70 m, $\kappa$ = 1.8, $B_{\rm T}$ = -1.75 T (opposite to $I_{\rm p}$ direction), $\bar{n}_{\rm e} \approx (4\text{-}5)\times10^{19}/\text{m}^3$, $T_{\rm e}(0) \approx 2$ keV, $T_{\rm i}(0) \approx 1.5$ keV, and $q_{95}$ = 2.7-3.5. A typical flux surface contour plot is shown in Fig. 1, together with the poloidal projection of the electron cyclotron heating (ECH) vacuum ray trajectories. The flux surface radial coordinate is the normalized toroidal flux, $\rho$. The nominal 2nd harmonic EC resonance for the 110 GHz gyrotrons is indicated by the primarily vertical line. The total ECH power is approximately 2 MW, on continuously. The Ohmic heating power is ~1 MW. Neutral beam injection (NBI) from two sources is used in a 10 ms blip, with total instantaneous power 4.8 MW. The full $D^0$ beam energy for one source is 81 keV, and 75 keV for the other, injected in the direction of $I_p$, that is, co-injection. The guiding center projection of two prompt NBI ion orbits are shown, with starting points marked by an X. One starts outboard (trapped) and contributes an inward $\vec{J}_{fast}$, while the other starts inboard (passing) and contributes a smaller outward $\vec{J}_{fast}$, due to the collisionless orbital excursions in ρ.

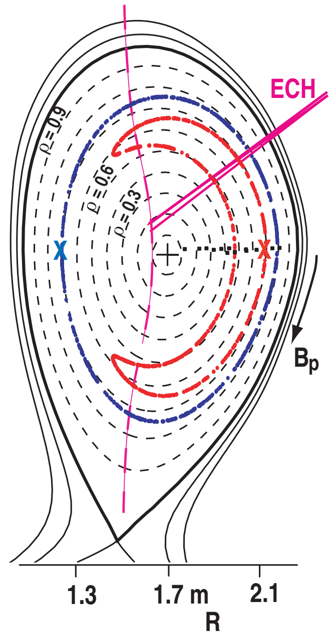


Fig. 1. Cross section of LSN discharge. Two prompt NBI orbits are indicated. Small squares show the location of some CER measurements.

## II. Collisionless Momentum Balance

The measured bulk $He^{++}$ toroidal velocity, $\vec{V}_{\phi He}$, is shown in Fig. 2 for 3 times after NBI initiation at $t$ = 1800 ms. Measurements are made only during NBI since charge exchange recombination (CER) requires NBI. The velocity profile is driven up in the direction of $I_p$ due to the collisionless NBI torque. The times are midpoints of the CER 1 ms averaging times. Although $\vec{V}_\phi$ undergoes a zeroth order change, there is no change in the pressure profile; the temperature and density profiles are unchanged, except for small ELM-induced activity. This is because the blip deposited NBI energy is only ~2% of the plasma thermal energy. The initial $\vec{V}_\phi$ profile is due to the intrinsic rotation, that obtained with no auxiliary momentum input which is measured by the initial CER time window, as we have described [4,5]. For our purposes we need only measure the change in velocity due to NBI, i.e. driven acceleration.

The instantaneous torque profile from TRANSP is shown in Fig. 3. Both the total torque, η(ρ), and the collisionless torque, $\eta_f(\rho)$, are shown; the frictional torque is $\eta(\rho) - \eta_f(\rho)$. This is near the midpoint of a NBI blip, computed using the details of NBI in DIII-D and the measured kinetic profiles and the specific equilibrium. The momentum confinement time is ~100 ms, much longer than the 10 ms blip, estimated from the response to multiple blips.

Neglecting NBI friction, momentum transport, and any radial electron current, the toroidal momentum equation [2], with allowance for multiple ion species, $i$, becomes

$$\sum_i M_i n_i \frac{\partial}{\partial t}\langle R V_{\phi i}\rangle = \sum_i \langle \vec{j}_i \cdot \vec{\nabla}\psi \rangle \quad , \qquad (1)$$

where ψ is the poloidal flux function, and the magnetic field, $B$, is defined as $\vec{B} = [I(\psi)\vec{\nabla}\phi + \vec{\nabla}\phi \times \vec{\nabla}\psi]/R$. Here, $\langle\cdot\rangle$ represents a flux surface average. On the blip timescale,

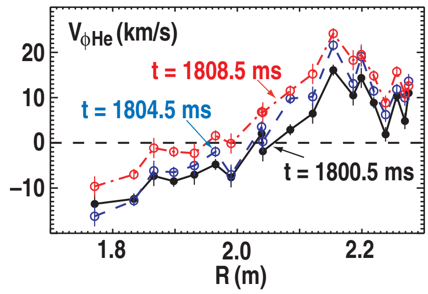


Fig. 2. Toroidal velocity profiles during NBI blip.

the plasma responds as a dielectric to the injected NBI current, with the neoclassical dielectric constant $\kappa_{NC} = 1 + c^2/V_{Ap}^2$ [6], where $c$ is the speed of light and $V_{Ap}$ is the Alfvén velocity using the local poloidal magnetic field, $B_p$. Maxwell's equation for the electric field becomes

$$\frac{\partial}{\partial t}\left\langle \vec{E}\cdot\vec{\nabla}\psi \right\rangle = \left\langle \vec{j}_f \cdot \vec{\nabla}\psi / \kappa_{NC} \right\rangle \qquad \varepsilon_{NC} = \kappa_{NC}\varepsilon_0 \quad , (2)$$

and the momentum equation can be written

$$\sum_i M_i n_i \frac{\partial}{\partial t}\left\langle RV_{\phi i}\right\rangle = -\left\langle j_f \cdot \vec{\nabla}\psi \right\rangle$$
$$= -\left\langle R\vec{j}_f \times \vec{B}_p \right\rangle \cdot \hat{\phi} \equiv \eta_f(\rho) \quad . \qquad (3)$$

We apply Eq. (3) to the measured data by assuming two nucleons per electron, and using the measured electron density profile. We assume a common $\partial\left\langle RV_\phi \right\rangle/\partial t$ for each species, based upon the electric drift nature of the acceleration. The flux surface average is done assuming the angular frequency, $\omega_\phi = V_\phi / R$, is a flux function. The source torque is given as a flux surface average by TRANSP. We numerically compute the local impulse, $\int dt\eta(\rho,t)$, and use Eq. (3) to predict the local velocity change.

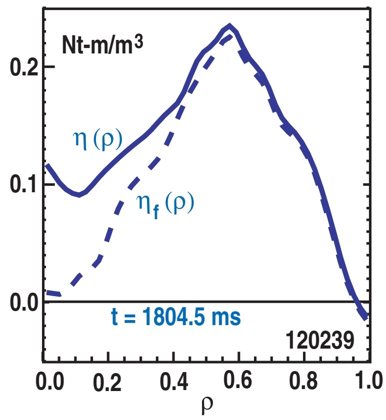


Fig. 3. Instantaneous total, and collisionless, $\eta_f(\rho)$, torque profiles from TRANSP.

In Fig. 4 we plot the difference in measured $\Delta V_{\phi He}$ between the first and last measurement times in a single NBI blip. Also shown is the predicted change in the toroidal velocity profile due to the impulse, and using both the total torque density $\left(\Delta V_{\phi\eta}\right)$ and only the prompt torque density $\left(\Delta V_{\phi\eta f}\right)$. The agreement demonstrates that the absorption of the NBI momentum in the region 1.9 < R < 2.2 is predominantly through the $\vec{J}_{fast} \times \vec{B}$ mechanism. The measurements closer to the magnetic axis indicate that frictional torque is important in this region. The difference near the plasma boundary (ρ=1) is observed in the dataset, where turbulence or ELMs may be affecting the ion orbits and hence the dielectric response.

In a matched pair of discharges we measure both $\Delta V_{\phi He}$ and $\Delta V_{\phi C}$. These are compared in Fig. 5, where the CER channel locations are plotted using the mapped ρ values. Other than the one outlying difference at $\rho \cong 0.46$, we see that the velocity change for the bulk ion species and the small minority carbon species are equal within the measurement uncertainties, consistent with a velocity change due to the electric field precession of trapped ions.

We find good agreement between the total toroidal momentum change and the total computed torque impulse, i.e. the

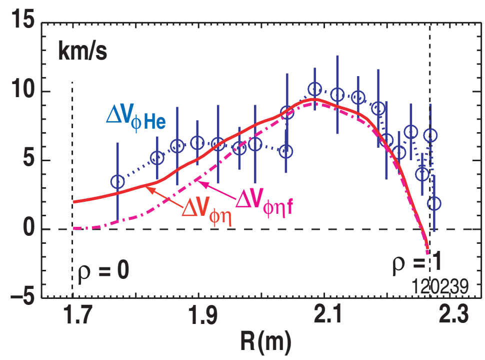


Fig. 4. Profile of the measured toroidal velocity difference during a NBI blip, and the predicted difference using the impulse computed from TRANSP for the total torque density (solid) and the collisionless torque density (dot-dash).

volume and time integrals of Eq. (3). The dataset consists of five pairs of matched discharges with a total of 19 NBI blips. The agreement is good for the momentum change during a blip, using either the measured $\Delta V_{\phi He}$ or the $\Delta V_{\phi C}$ for the plasma velocity increment, due to the common prompt acceleration.

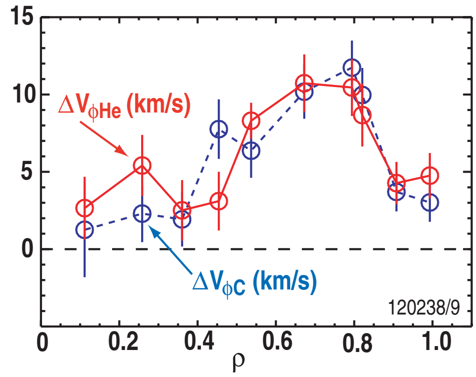


Fig. 5. Toroidal velocity difference, that is, acceleration, for $He^{++}$ and $C^{6+}$, measured in separate, matched discharges.

## III. Discussion

On this short timescale we find that the plasma responds to the NBI torque impulse consistent with neoclassical physics. The torque input is collisionless and the plasma responds through a dielectric polarization current. The effect of the NBI $\vec{J}_{fast} \times \vec{B}$ torque has been reported in JET for the total integrated momentum change, based upon the difference in timescales of momentum and energy response [7]. Here, we have measured this response in the radial profile as well.

The 1 ms CER integration time, $\tau_{CER}$, is longer than the bulk ion-ion collision time, $\tau_{i\text{-}i} \sim$ 0.3 ms, so we expect local velocity space relaxation between the passing ions and the precessing trapped ions. On the measurement timescale the plasma is predicted to respond with the neoclassical polarizability [6]. Indeed, Eqn (2) and (3) are satisfied by plasma velocity $\partial V_\phi / \partial t = \left(1/B_p\right) \partial E / \partial t$ with a plasma dielectric of $\kappa_{NC}$. Using the TRANSP determined $\left\langle \vec{j}_f \bullet \vec{\nabla}\psi \right\rangle$ in Eq. (2) and an electric field response measured by $\Delta\vec{E} = -\Delta\vec{V} \times \vec{B}$, we obtain agreement with $\kappa_{NC}$ computed from the measured $(c/V_{Ap})^2$ across the profile, when $\Delta\vec{V}$ is corrected by $\eta_f/\eta$. (There is little change in the pressure profile to affect $\Delta\vec{E}$.) The only lack of agreement with $\kappa_{NC}$ is at the edge.

There is no statistically significant value of a poloidal acceleration $\Delta\vec{V}_p$ that emerges from the measurements, so $\Delta E = \Delta V_\phi B_p$ and thus $\kappa_{NC}$ and collisionless momentum balance are equivalent. A nonzero value of $\Delta V_p$ indicates a dielectric constant other than $\kappa_{NC}$, to satisfy momentum balance. Given a shorter measurement time, $\tau_{CER} < \tau_{i\text{-}i}$ we expect to find such a result, where the passing and trapped populations respond independently and can be considered as two dielectric species in Eq. (1).

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