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Control of Power, Torque, and Instability Drive using In-shot Variable Neutral Beam Energy in Tokamaks

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Abstract. A first-ever demonstration of controlling power and torque injection through time evolution of neutral beam energy has been achieved in recent experiments at the DIII-D tokamak [J. Luxon, Nucl. Fusion **42**, 614 (2002)]. Pre-programmed waveforms for the neutral beam energy produce power and torque inputs that can be separately and continuously controlled. Previously, these inputs were tailored using on/off modulation of neutral beams resulting in large perturbations (e.g., power swings of over 1 MW). The new method includes, importantly for experiments, the ability to maintain a fixed injected power while varying the torque. In another case, different beam energy waveforms (in the same plasma conditions) produce significant changes in the observed spectrum of beam ion-driven instabilities. Measurements of beam ion loss show that one energy waveform results in the complete avoidance of coherent losses due to Alfvénic instabilities. This new method of neutral beam operation is intended for further application in a variety of DIII-D experiments including those concerned with high-performance steady state scenarios, fast particle effects, and transport in the low torque regime. Developing this capability would provide similar benefits and improved plasma control for other magnetic confinement fusion facilities.

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In-shot variation of neutral beam energy has been applied in a tokamak plasma for the first time, and this capability is now being optimized for application in a range of DIII-D experiments. A recent experiment on the DIII-D tokamak [1, 2] demonstrated that it is possible to produce finely controlled evolution of neutral beam injected power and torque by adjusting the beam energy (i.e., the voltage at which the ions are accelerated prior to neutralizing and entering the device) in time. Time-dependent beam energies also led to changes in the drive of instabilities in plasmas that are similar except for the beam energy program. Neutral beams are a major auxiliary heating and current drive system for present tokamaks, and the system being built for ITER will be responsible for providing an injected power of 34 MW [3]. A sampling of the most recent worldwide effort to advance neutral beam technology and its application in magnetic confinement fusion includes: the creation of a new, detailed simulation code for the specific ITER beams [4]; modeling and experimental comparison of edge tungsten impurity density affecting beam deposition in JET [5]; using increased neutral beam heating to enable access to new plasma parameters regimes in the TCV tokamak [6]; and developing the capability to attach neutral beams to the complicated geometry of the Wendelstein 7-X stellarator [7].

Running a tokamak neutral beam system with time-variable energy is counter-intuitive since it will generally result in a reduction of the total power deposited into the plasma. A typical neutral beam ion source outputs power according to $P = \Pi V^{5/2}$, where Π is the perveance and V is the beam energy. The permitted range in operating perveance is narrow (this sets the beam focus and is typically less than $\pm 10\%$ of the optimum design value) and determined by the accelerator geometry and ion mass. This strong dependence on beam energy encourages operation at maximum energy throughout a plasma shot. In-shot variation of beam power has previously been achieved by altering the source current in MAST [8] and the beam line aperture in TEXTOR [9, 10]. Recent DIII-D upgrade plans focus on increasing the beam energy in order to input more beam power and current drive into steady state scenario plasmas [11]. Some of these scenarios exhibit reduced confinement linked to the existence of beam ion driven instabilities [12, 13], however, and there is a sizable collection of such instabilities that cause enhanced transport of injected beam ions [14] and reduce the effective heating and current drive from the beams. In a fundamental shift in thinking, the DIII-D neutral beams have been modified to vary their injection energy during plasma shots with the ultimate intention of tailoring the velocity space distribution of beam ions to produce continuously varying power and torque curves, and to temporarily reduce the drive for undesirable modes while remaining capable of reaching peak power input later in the plasma shot. The ability to conduct on/off modulation remains available and is not impacted by the changes required to achieve time-variable energy.

The neutral beam system has been modified such that the energy can be controlled with pre-programmed waveforms and will eventually allow real-time feedback control of energy. Neutral beam control circuitry processes the received waveform and adjusts both the ion source density (to maintain optimum perveance) and bending magnetic field (to redirect ions that fail to neutralize en route to the tokamak vacuum chamber) in addition to the accelerator voltage [15, 16, 17]. During the experiment shown here, the neutral beams were capable of injecting across an energy range of $\Delta V \leq 15$ kV with a slew rate of 20 kV/s or better. The accessible energy range is independent of the central beam energy, e.g., a central energy setting of 60 kV allows for a 52.5 - 67.5 kV range, while a central setting of 70 kV allows for 62.5 - 77.5 kV during the plasma shot. The beam energy waveforms can be tailored in a large number of ways, including the fixed power at variable torque example shown in Figure 1. All of the demonstration discharges featured an inner wall limited, elongated oval shape plasma with a central magnetic field of $B_T = 2.05$ T and plasma current that ramps to a flattop of 0.78 MA at 620 ms. Four different neutral beams were given energy waveforms between 60 - 80 kV [Figure 1(a)] such that the total injected power remains fixed at 6 MW [Figure 1(b)]. The result is a torque scan [Figure 1(b)] performed across nearly constant plasma parameters [Figures 1(c - e)].

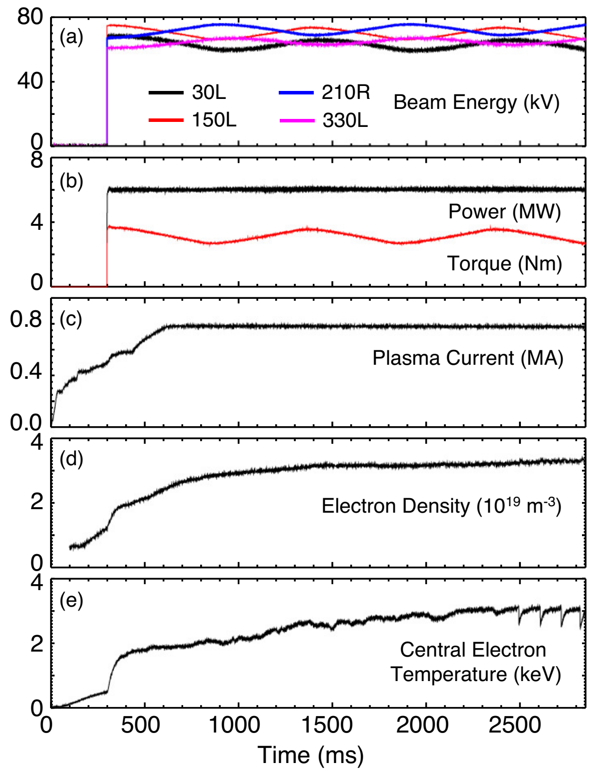

Figure 1. Time evolution of shot 166396: (a) energy of each of the four neutral beams that fired into this plasma, (b) total injected neutral beam power (black trace) and torque (red trace), (c) plasma current, (d) line-integrated electron density, and (e) central electron temperature.

The previous method for varying the beam torque at fixed energy was on/off modulation of the beams. In many circumstances, however, large instantaneous modulations in power and torque are undesirable. Figure 2 compares low torque beam waveforms for a modulation case and the variable energy case. The modulation case is from an experiment on QH-mode development at zero beam torque [18]. As seen in Figure 2, however, this zero net-torque condition is reached with a power modulation of 2 - 6 MW [Figure 2(a)] and torque modulation of -1 to +2 NM. Enabling beam energy variation allows constant beam power [Figure 2(a)] while also being able to vary the torque [Figure 2(b)], including crossing the zero torque level.

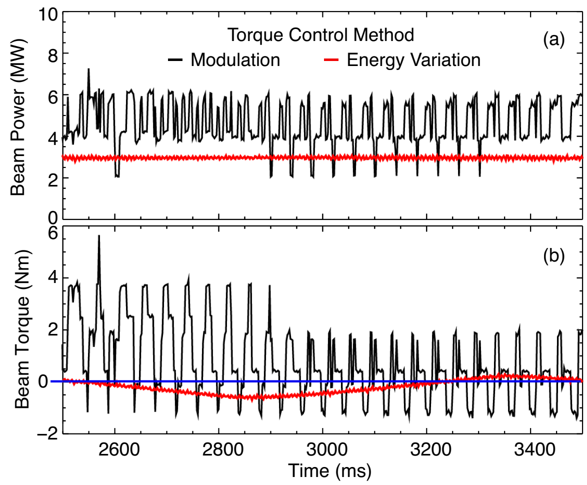

Figure 2. Comparison of the approach to zero beam injected torque between the modulation (shot 163520) and time-variable beam energy (shot 166396) methods. (a) Injected beam power, (b) injected beam torque.

An example of using time-variable beam energy to affect instabilities is shown in Figure 3. A pair of plasma shots both feature co-current, tangential beams injecting with a 10 kV swing as shown in Figures 3(a) and 3(b). The beam identified as 30L ranges between 71 - 81 kV while the beam identified as 330L ranges between 65 - 75 kV. The injected beam power oscillates between 3.5 - 4.5 MW. In one shot the power begins at its maximum value and in the other shot it begins at its minimum value. With a beam energy waveform period of 1000 ms, the total beam energy imparted to the plasma is the same in both shots. These shots are identical except for the beam programming and feature slowly increasing densities that remain below 3×10^{19} m^{-3} in the elongated oval shape. The measured neutron rates are compared with TRANSP [19] calculations of the classically expected rate (i.e., the rate in the absence of instabilities that increase beam ion transport) in Figure 3(c), where values below unity indicate that beam ion transport is greater than the expected value. The normalized neutron rate is reduced in the higher energy beam shot (166400), indicating that the beam ion confinement deviates more strongly from classical expectation compared to the shot featuring a lower initial beam energy.

Changes in the instabilities are displayed in the spectrograms of Figures 3(d) and 3(e). These plots show the cross-power of density as measured using two chords from an interferometer [20]. One chord is directed radially across the plasma while the other is oriented vertically. The resulting measurement therefore provides a wide survey of mode activity throughout the plasma. Figure 3(d) is from shot 166400 in which the beam power begins at its maximum value and the coherent modes are a mixture of toroidal Alfvén eigenmodes (TAEs, nearly constant frequency) and reversed-shear Alfvén eigenmodes (RSAEs, rapidly upward sweeping frequency) [21]. In shot 166401 shown in Figure 3(e), the beams begin at lower power and injection energies, and the

TAE activity in the time range of 300 - 700 ms is weaker than in the companion shot. After 700 ms, as the power increases in shot 166401, the RSAE activity persists while in shot 166400 it rapidly declines. This behavior is qualitatively consistent with the expectation that reducing the beam ion velocity (by reducing the injection energy) also reduces the number of energetic ions that can resonate with the Alfvénic modes. Importantly for tokamak experiments, this shows that beam power or energy can begin at a value that minimizes Alfvénic activity and maximizes beam ion confinement while still allowing for maximum power later in the shot, e.g., upon reaching a steady state period.

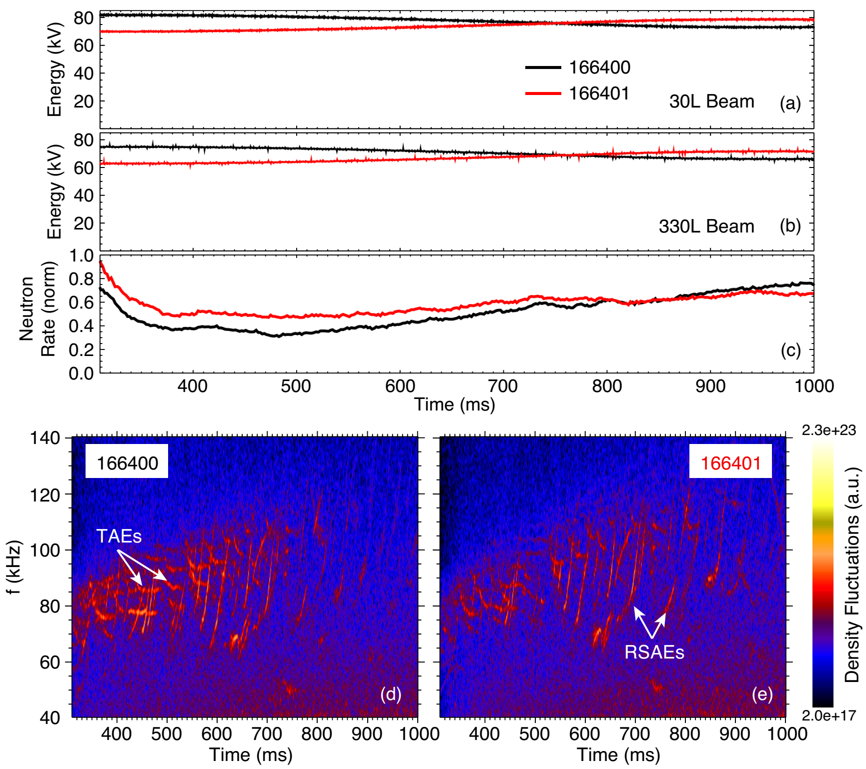

Figure 3. Comparison of shots using time-variable beam energy to alter beam ion instabilities. Energies from the co-current tangential beams identified as (a) 30L and (b) 330L. (c) Ratio of the measured neutron rate over the TRANSP-calculated classically expected rate. Cross-power of line-integrated electron density fluctuations from shots (d) 166400 and (e) 166401.

A final example of the changes manifested by time-variable beam energy is shown in Figure 4. These companion plasma shots feature a fixed injected beam power of 6 MW [Figure 4(a)]. The only change between these shots is that the energy waveforms of the four injected beams are flipped [Figures 4(b-e)]. Shot 166396 features two of the co-current tangential beams beginning at maximum energy and the other one beginning at lowest energy. In this shot, Figure 4(f) shows that beam ion losses are measured [22] at the frequencies of TAEs, RSAEs through a time of approximately 470 ms. Shot 166397, by comparison, flips the beginning status of the co-current tangential beams and nearly all of the coherent TAE and RSAE disappear [Figure 4(g)]. Changes in the beam ion loss due to the energetic particle-induced geodesic acoustic mode (EGAM) [23] are also apparent. The EGAM and coherent beam ion losses are commonly observed in DIII-D during the use of counter-current beam injection [24, 25]. Shot 166396 features the counter-current tangential beam beginning at its lowest energy and the EGAM-induced beam ion losses appear during this early stage and dissipate by 340 ms [Figure 4(f)]. These losses appear constant, albeit short-lived. In contrast, shot 166397 employs the counter-current beam beginning at its highest energy and the EGAM-related losses occur later in time and have a bursty appearance [Figure 4(g)]. The observed changes in the EGAM were not expected and efforts to understand or possibly predict this behavior are the subject of future experiments. While these particular beam ion loss characteristics may be created with some fixed value of beam energy, the utility of this time-variable energy beam operating mode is that it enables the design of plasma shots with a remarkable ability to adjust, or perhaps actively control, the amplitude of fast ion related instabilities and/or the fast ion transport they produce.

Future efforts to improve this mode of neutral beam operation include increasing the speed and energy range, and incorporating the ability to adjust the ion source current to produce more power at a given energy. Experiments seeking to study plasma dependencies on power or torque will be attempted with energy scans in place of modulated beams. While it is a major improvement to beam reliability to be able to scan power or torque without modulation, the lack of modulation can also be a major drawback. Important measurements of plasma ion density and rotation are often made using the beams as the source for active spectroscopy [26], which requires brief beam-off periods in order to acquire background levels. Such beam-off periods can be programmed into the energy waveforms as needed for these diagnostic purposes.

A wide operational parameter space is created by the availability of variable energy in seven DIII-D neutral beams. A selection of proposed plasma experiments and applications of this capability are provided here, and notes are made concerning whether the experiment intends to use beam energy in a yet-to-be-developed feedback mode.

- steady state scenario with $q_{min} > 2$ in which the beam energies are varied at fixed power to identify the minimum drive for Alfvén eigenmodes (pre-programmed)
- accurate control of beam torque profile allowing, for instance, to achieve null rotation profiles and directly study intrinsic torque (feedback) [27]
- creating a bump-on-tail distribution to study instability drive (pre-programmed)
- obtain beam-based motional Stark effect (MSE) data in plasmas featuring reduced energy beam injection by momentarily increasing beam energy to the 81 kV level needed for MSE (pre-programmed)
- minimization of counter-current beam prompt losses by controlling deposition in conjunction with applied error fields (feedback)

In summary, it has been shown that the newly developed operating mode of changing neutral beam energy during a tokamak shot provides a way to continuously

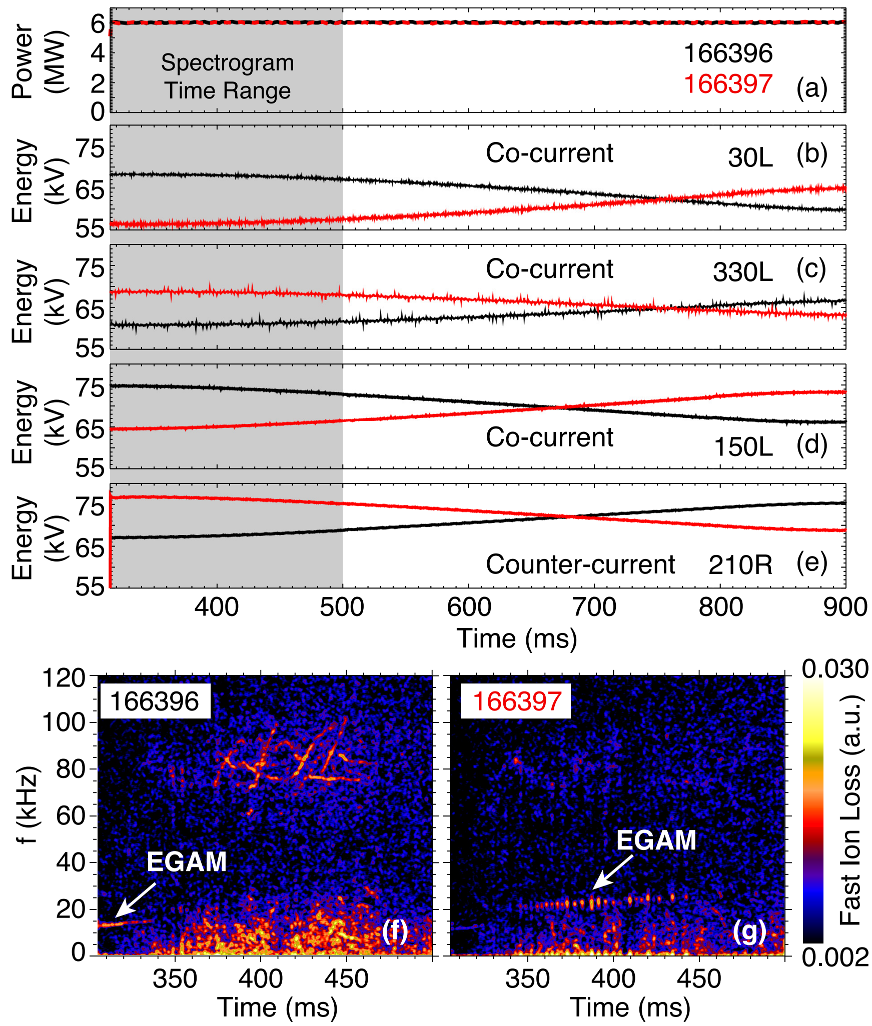

Figure 4. Comparison of shots with the same injected power and different beam ion losses. (a) Injected beam power (fixed at 6 MW). Injected energy for co-current tangential beams identified as (b) 30L, (c) 330L, (d) 150L, and counter-current tangential beam (e) 210R. Spectrograms of fast ion loss for shots (f) 166396 and (g) 166397.

adjust injected power and torque. Additionally, this allows for active control of the beam ion velocity space distribution, which in turn changes the drive of fast ion instabilities. Combining these three effects is proposed as a way to improve access to steady state scenarios in magnetically confined plasmas. Such a result may be achieved by tailoring the beam energy such that instabilities are minimized during the evolution of the magnetic equilibrium, allowing for maximum beam heating and current drive efficiency. Physics studies will be further advanced by allowing for well controlled scans in power and torque, including the ability to approach or deviate from a targeted parameter continuously.

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